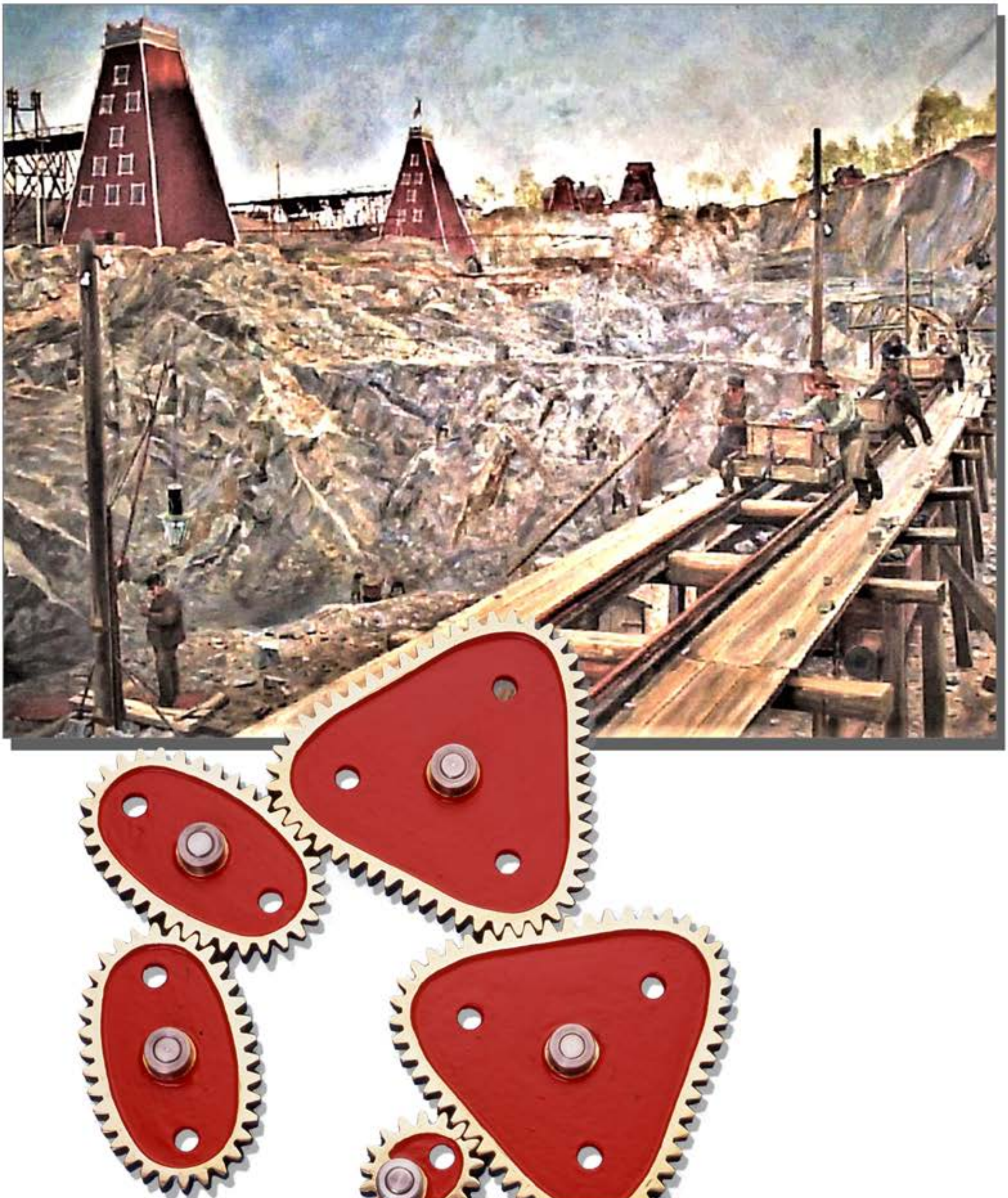
1922 VBIK 1922 2022



Technology development in Västerbergslagen

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in
Västerbergslagen
1922 – 2022

VBIK
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Preamble

Per Krainer

How did the Titanic sink?
Was it because the phosphorus-rich ore came from Grängesberg? The ore from the mine in Grängesberg dating back to the 15th century has a composition containing phosphorus. Too much phosphorus in finished iron causes that it becomes brittle and cracks, especially when it is cold. During the latter part of the 1800s, it was true that phosphorus could be driven out of the melt using the Thomas process, but it wasn't until the 1960s that Grängesberg's mine could deliver a phosphorus-free product for the iron works. Investigations have shown that the steel in the Titanic contained so much phosphorus that it could affect the quality of the steel.

How many mercury-arc valves are at the bottom of Lake Väsman?
Russian industrial espionage led to the dumping of valves in Lake Väsman. During the second world war an HVDC transmission in Germany fell into the hands of Russia. That facility was copied and then put into use in 1951. It was called the Moscow-Kashira transmission. It didn´t work and the knowledge, that the capricious ion valves could backfire, was limited in Russia. SÄPO warned ASEA of the risk that the Russians could steal industrial secrets and that led to the fact that vital parts, which were not intended to fall into the wrong hands, were dumped in Lake Väsman at night.
Source: Gunnar Engström NLT 28/8 2000.

What happened to the secret development of a fusion reactor in the -50s?
One day in 1958, two professors came from Uppsala into the high-voltage laboratory in Ludvika under great secrecy and wanted help in simulating energy production like in the sun. They had an idea of a process that with cheap fuel would solve the earth's energy production for all time. How did it go?

What did Hannes Alfvén (Swedish Nobel laureate) think about the bombing of Nagasaki and Hiroshima?
VBIK's Chairman, Engineer Stenkvist, introduced Hannes Alfvén, who gave a lecture in front of 300 people in Ludvika on October 29, 1945. 25 years later he received the Nobel Prize in Physics. The subject of the evening was the extraction of the energy of the atom core and during the lecture listeners like Engineer Uno Olsson and Dr. Uno Lamm got the chance to ask adequate questions. Hannes Alfven was against the utilization of nuclear energy in the form of fission of uranium atoms both for use as a nuclear weapon and as an energy source. On the other hand, he was positive to developing nuclear fusion, where hydrogen atoms under high pressure and temperature are brought together to form helium atoms, which happens under strong generation of heat. The development of nuclear fusion is currently underway in France, the USA, Germany, Japan and South Korea. Will this method generate energy and forever solve the world´s increasing need for energy at a low cost and without significant radioactive waste?

What is the difference between the development process now and then?
How was it that Dr. Uno Lamm was developing HVDC for more than 20 years, without any plant being sold? Could it happen today? Uno Lamm led the development of HVDC at ASEA from 1929 to 1954 when the first transfer from Västervik to Gotland was put into operation. ASEAs management thus invested money in development for 25 years without any result during this time. Is

it possible that such a long time of development with private financing could have taken place today without the company management stopping the work, because there was no guarantee that the development would succeed?

How could Smedjebacken's Walsverk survive the extinction of iron mills?
Had there been a rolling mill and steel mill in Smedjebacken, if a 15-year-old boy hadn´t traveled from Medelpad to Stockholm in 1788? And why did he, as a 72-year-old wholesaler and city major, buy Hagge Bruk? How could the rolling mill and the steel mill in Smedjebacken make it through the "death of iron works", which affected most of them in an area in the middle of Sweden , called Bergslagen? Why is the name Wenström so associated with the technology development in this area? Jonas Wenström is considered a pioneer for development of the three-phase system, while his father, Wilhelm Wenström designed the first rolling mill and the rail rolling mill in Smedjebacken. Could it have been the turner at Nyhammars Bruk, Staffas Johan Andersson, who invented the universal rolling mill?

Some of these questions will be answered, others will be speculations in this publication, describing a century of events out of an engineering and social perspective.

A historic review
It all really started somewhere in present Africa 1.8 billion years ago. There and then the foundation was laid the for the epoch at the time that put Grängesberg and Bergslagen on the map. The mineralization's in the so-called Bergslagen have, since their discovery between the 15th and 17th centuries, paved the way for industrialization in Ludvika and the surrounding area.

From the time Hans Christian Ørsted discovered a connection between magnetism and electricity in 1820, until 100 years later, when the Västerbergslagen Engineering Society was formed, a lot has happened. Jonas Wenström's short but significant life and the Thomas process were enormously important for the development around Ludvika. The Thomas process made it possible for large parts of the ore from Grängesberg to be used and Jonas Wenström contributed to Hällsjön's electrical power transmission. The connection between the electricity industry and the mining industry grew strong in the late 1800s and early 1900s. This is not least reflected in the guidelines that were presented at the constituent meeting of the Västerbergslagen Engineering Society on June 8, 1922, at 19:00. *"The interest that in state government, has been shown for "electrical engineering in mining", would be apt to give an association of preferably minning and electrical engineers an immediate and current importance".*

At the time when ASEA was formed in 1883, Ludvika was an industrial community which from the middle of the 19th century was disappearing and a replacement industry was developing. The way people were living in those days was different from today. Mining drove the development towards electrification and an electrical business was started in 1900. And 16 years later ASEA Västerås took over that business. World War I is being fought 1914-1918 and in 1919 Ludvika was granted its city privileges. Women got the right to vote in 1921. It was during that time the Västerbergslagen Engineers´Club was formed. Over a century since then, close to 1,000 lectures have been given and between 20,000 and 30,000 visitors have acquired great knowledge of the subject. Considering the scope and purpose of the association of these engineers, this sociaty has undeniably had a considerable part of this development.

Introduktion

Per Krainer

Mines in Grängersberg

Here, part of the story is retold, among other things, when it all started, how technology developed and how society grew together with the big company. The mine in Grängesberg has been a central part of the local industrialization. Here we get an insight into some major business leaders, how the war affected the need of iron ore and how a crack limits future mining. The mine had early restrictions on how much phosphorus the ore could contain. Before the 1880s, there was no technology to remove the phosphorus from the finished steel and that made the steel becoming brittle, which the customers did not want. In the 1960s, it was possible to extract the phosphorus before it ended up in the blast furnace, thus making the phosphorus into a resource in the form of fertilizer. What is happening today is that private companies intend to enrich the ore from the old sand reservoir in Grängesberg, which contains phosphorus in the form of apatite. The apatite can also bind rare sorts of earth minerals in the form of monazite and allanite. Future will tell if there will be any recycling of the old sand reservoirs. It is undeniably time for a so-called circular economy.

Electrical power transmission with alternating current

At the end of the 19th century, interest increased rapidly within Bergslagen's mining and quarrying industry to use the new electric power technology, e.g., for operating pumps and fans. In 1893, the world's first commercial electric power transmission with three-phase alternating current was put into operation from Hellsjön's power station to Grängesberg. The facility was built by ASEA and was developed from Jonas Wenström's three-phase patent. Elektriska AB Magnet was founded in Ludvika in 1900 and came after a couple of changes to be bought by ASEA in 1916. The Ludvika facility then received responsibility for transformers and power transmission equipment. During the first half of the 20th century, the power grid in Sweden was expanded at a rapid pace with increasing voltages. ASEA in Ludvika rapidly met the increasing technical requirements, including the building of new high-voltage and high-power laboratories. With a fruitful technical collaboration with the state-owned Vattenfall. In 1952, a world record was set in Sweden with the new voltage of 400 kV, which was needed for the long lines from the upper Nordic area. ASEA continued to be at the forefront of technology and participated in the expansion of AC voltage grids with increasingly higher voltages in various places in the world. The merger with Brown Boveri in 1987, when ABB was formed, made the company stronger on the world market. Power transformers, shunt reactors, circuit breakers and other high voltage equipment developed in Ludvika, often have a unique and world-leading performance. Since 2020, ABB's power transmission business has been sold and is now part of the newly formed company Hitachi Energy.

Electric power transmission with direct current

The development of power transmissions with direct current with low voltage began in Sweden in 1889 in the mine at Illmyra with 10 kW for motor operation. In 1954, the world's first transmission with high voltage mercury-arc valve plants was taken into operation for transmission of power to

Gotland in the Baltic Sea, 20 MW @ 100 kV.

The first commercial power transmission system from Ludvika, which only used thyristors (unlike mercury-arc valves they don´t backfire and are non-toxic), was taken into operation in 1976/77 and brought power between Norway and Denmark.

A pilot plant with transistors (IGBT) in a power transmission between Hellsjön and Grängesberg demonstrated in 1996 HVDC transmission with greater flexibility than with thyristors, including black start and islanding.

A power transmission for 12,000 MW @ ±1,100 kV is currently in operation and at another location a meshed network of four HVDC stations has been installed. Much of the development within HVDC has taken place in Ludvika, and the Ludvika unit within ASEA/ABB/Hitachi Energy has over the years always had a share, higher than 50% of the HVDC market. Members of the Västerbergslagen Engineering Society have via many lectures repeatedly been able to follow the world-leading development.

Tap changer

Ludvika and later ASEA were probably the first in the world to develop the possibility of regulating the voltage during transformation. The first tap changers were used for melting iron and were manually regulated at low power. As the distribution networks grew, the demands for regulation increased. The tap-changer is today a central component in the power grids. The various mechanical solutions developed over more than 100 years have been ingenious and fascinating. Those of us old enough to remember Tekniskt Magasin that was broadcast on TV up until the late 1980s may remember the vignette on that program in which Uno Olsson's non-circular gears appeared. This principle of a constant and smooth feeding speed and a variable output speed driven

Uno Olssons orunda kugghjul vinjett i programmet Tekniskt Magasin. Finns att beskåda i entrén på Hitachi Energy Components i Ludvika

by non-circular gears, was a central feature of the tap-changer for several years. This principle with non-circular gears was later replaced with geneva drive, a gears mechanism that translates rotational motion into intermittent rotary motions.

Sweden's first experimental reactor for fusion energy

In 1951, the United States detonated the first hydrogen bomb. This led to the idea of being able to utilize the fusion power that develops at one detonation of hydrogen bombs only for peaceful purposes in above all the United States and the Soviet Union. In Sweden, too, scientists had this idea, among other things at the University in Uppsala. In 1958, two professors decided to make a first practical attempt to create fusion and ordered the equipment they needed from ASEA in Ludvika. They wanted to create a plasma of heavy hydrogen, deuterium, trapped in a magnetic field, heated to a temperature of about 100 million degrees. The equipment from Ludvika was delivered to the university in Uppsala. When energizing the equipment, a plasma string was established in a toroid, held in place by electromagnets. Due to the low resistance of the plasma string, high losses were obtained in the circuits that fed the plasma current and due to insufficient temperature to achieve fusion of the hydrogen atoms, that fused into helium, was not achieved. However, these initial attempts have been followed by continuous research since then, with the aim to establish an inexhaustible source of energy with low risk and low waste. More about this research in chapter ”Nuclear fusion - cheap, safe energy or unattainable dream”

An industrial saga without a really happy ending.

Morgårdshammar has an absolutely fantastic history behind it from a Swedish perspective. The company is a respected name in its industry and is regarded with the greatest respect all over the world. Two products overshadow everything else in the company’s 166-year history today. Ernst von Zweigbergk’s universal rolling mill in the 1870s and Erik Norlindh’s two unique, world-class patents, the seatless roller pair and above all the roller drawer. These innovations from Morgårdshammar were and still are the Rolls Royce in the rolling mill industry.

From the start in 1856 and 120 years later, Morgårdshammar has been extremely successesful, characterized by visions and determination that quickly took it to the forefront not only in Sweden but also in the rest of the world. Morgårdshammar’s largest customers have been the mines and the ironworks. Mining and rolling mills were the main product areas. Although Morgårdshammar specialized in tailor-made solutions for mines and ironworks, they also developed their own products such as milk separators and boat engines.

As a dominant industry in a small community, Morgårdshammar maintained functions for civil society such as apprentice schools for forestry and agriculture and these were self-sufficient in electricity through the construction of its own power station. The term ”Morgårdsandan“(the Morgårdshammar spirit) got a concrete manifestation when their ice hockey team in the 1960s sensationally reached the top series.

Morgårdshammar is today owned by the Italian group Danieli and still operates for the manufacture of equipment for rolling mills. The competition over the last 50 years from developed industrial nations as well as developing countries have meant that the business has shrunk and today the factory is consisting of around 50 employees.

From Smedjebacken Rolling Mill to Ovako.

When this is written, in 2022, 170 years have passed since the 31-year-old mill owner Axel Nordlander at Hagge mill was becoming increasingly convinced that the rolling mills that started in the country would be a difficult competitor to the tilt hammer. He convinced a couple of other mill owners that they together should build a rolling mill. They chose to build it in Smedjebacken which had good relations with Stockholm via Strömsholm’s canal. On the 15th of September 1856, the first rod was milled and with the area’s veterinarian as head of the mill, it took the works 10 years to become the country’s largest rolling mill steel producer.

A lot happens in 170 years. In history, of course, there are difficult times during depression and world war. But there were also many forward-looking investors, together with successful development steps, that helped Smedjebackens Walsverk from 1856 to avoid ” the death of iron works ” and become a supplier of quality steel within The Ovako Group.

Mining over time

Mining in its simplest form is considered to have started about 40,000 years ago, while mining today goes back to about 9,000 years. In the beginning it was relatively soft metals that were mined and through various treatments were formed into tools and weapons. As time went on, they began to apply so-called fire-setting, which means that you heat up the rock by making a fire close to it and then pour cold water on it so it cracks. In this way hard metals such as iron could be extracted. Crucial for mining is the possibility of pumping water from the mines. Winches and Archimedes screw came into use but with modest efficiency.

Since the 10th century China had used black powder and in the 13th century this powder came to Europe and was then used for military purposes. It was not until the 17th century that drilling and blasting with black powder began to be used in mining. At the end of the 19th century, Alfred Nobel produced dynamite and since then drilling technology has also developed.

The are many mines in Bergslagen and they have been of great importance to Sweden.

Hybrit and H2GS are two new projects in Northern Sweden to produce carbon dioxide-free sponge iron by using green hydrogen made from renewable electricity.

SUM is a project to achieve sustainable mining underground.

ReeMAP is a project for recycling, among other things, rare earth metals.

The project ”Green copper” aims to recycle an increasing proportion of the copper that has already been produced.

In the mine, that Nordic Iron Ore aims to open in Blötberget, there will be electric mining trucks that get their electricity from lines in tunnel ceilings like trolleys in cities. These electrical machines are then remotely controlled from ground level with very few people underground. This means that the power requirement of ventilation can be significantly lowered. Possibly it may be relevant with so-called cut-and-fill to reduce landfill by, among other things, enrichment sand in the ground level.

Nuclear fusion - cheap safe energy or unattainable dream

Will fusion energy be able to be exploited by humanity and offer cheap, safe, inexhaustible energy source without any emissions? Or is the dream of catching the sun in a donut just a dream? For the past seventy years, the researchers have sought in vain to imitate the fusion that is in the sun. The message has always been that fusion energy will be able to be utilized for humanity within 30 years. ITER, the huge research facility currently being built in Cadarache in France for SEK 200 billion is the latest step in finding out whether it is possible to tame the natural forces and convert the energy to be used in a conventional coal plant.

Merging of two hydrogen atoms into helium is a form of fusion. When it comes to fusion, neutrons and energy are released in the form of heat that can be used to operate a steam turbine/generator in the same way as today in a coal power plant. Fusion does not form any long-lived isotopes that require storage for many thousands of years before the radioactive radiation has been reduced to harmless levels. Furthermore, a fusion power plant is designed in such a way that the reactor cannot suffer an uncontrolled atomic fission that would cause such high temperatures that the reactor core melts down, and radiation is spread uncontrollably in the environment, which happened in Chernobyl and Fukushima.

Research is conducted today along two different principles. One principle is based on enclosing a plasma stream that is held in place by electromagnets in a toroid and transfers liberated energy at fusion to the walls of the toroid. The energy is used to drive a conventional steam turbine. According to the other principle, a concentrated amount of multivalent hydrogen atoms is bombarded with a laser and a sufficiently high temperature is reached, which means that the hydrogen atoms are fused into helium and the energy thus released is used to drive a conventional steam turbine.

The Grängesberg Mines – A historical view

Bengt Andersson

Grängesberg mines have been worked since the 15th century.

The Grängesberg ore mainly consists of phosphorus-rich iron ore. Smaller ore tracts, mainly south and west of the main ore, are phosphorus-poor. The main ore is about 1.2 km long and 80 to 100 meters wide and runs in a south-north direction. The phosphorus-rich ore gave brittle substandard steel that easily broke at cold temperature. The ore therefore had to be mixed with low-phosphorus ore in the smeltery to obtain durable steel.

It was determined by the Iron Office's regulations how large content of phosphorus-rich ore from Grängesberg the smelteries in the area were allowed to have in their blast furnaces. It was mainly the local miners with their sons and servants who in the summer mined ore for their needs and transported the ore to their smeltery in the winter. The miners produced in the autumns the necessary charcoal in so called piles, as well as the lime needed for iron production. The smelteries were operated during the spring when the snow melted. Then the water in streams and rivers could drive the water wheels, which drove the blowers and transportation tracks at roasting ovens and blast furnaces. The low-phosphorus ores were mined during the 17th and 19th centuries until almost none was left.

During 1850 - 1855, the Bessemer method was invented, with which the produced steel could be separated from phosphorus with the help of oxygen and lime. This was blown through the melt and the phosphorus could then be skimmed off from the iron. A refined method, and adapted to industrial use, came in 1870–75 and was called the Thomas process. Large containers, converters with ducts for air / oxygen supply, could be used industrially in a simpler way. The method was developed in Sweden by Edsken's mill, west of Hofors, which was then moved to Högbo. This method was then used by Sandviken's steelworks and in parallel also by Uddeholm in the Värmland steelworks. The skimmed Thomas phosphate became a coveted soil improver.

The open pit in late 19th century Painting: Axel Ljungstedt

In this way, the Grängesberg ore became sought after, especially after the Prussian war between the German states and France, the Franco-German war. During the reconstruction of the armies and cities, it was discovered that iron ore began to run dry in Europe and England. They then began to search for ore in northern Europe. The largest deposit that was mined in the Nordic countries at that time was the large Grängesberg field. The large companies that mined the ore in Grängesberg were Stora Kopparbergs Bergslags AB and Klotens mill, east of Kopparberg. The head of Stora Kopparbergs Bergslags AB and its iron ore site was Anders Erik Salwén. He lived at Laxsjö Mill between Grangärde and Stora Tuna and in Klotens Bruk Sir Ernest Cassel was a major partner. These men now found that it was possible that the Grängesberg mine could become a large export mine.

There was a railway down to Oxelösund. Many railways had been built during the 1870s and through FLJ, Frövi-Ludvika Järnväg AB, Hult-Köpings Järnväg AB to Valskog and for the last portion OFWJ Oxelösund-Flen-Wästmanlands Järnväg AB the port on the Baltic coast was reached and the ore could be transported by boat down to Europe . The railways later became TGOJ. Other companies that took iron ore from Grängesberg were Säfsnäsverken in Strömsdal, Gravendal, Ulriksberg and Annefors in Fredriksberg.

In 1893, exports of ore had reached such a volume that Salwén and Cassel formed Grängesberg's Joint Administration for all mines in the Grängesberg field. They thus merged their mines and focused on as efficient mining as possible.

In 1893, electric power had also come to the mines as three-phase alternating current from the power plant that the Administration built in Hällsjön, about 13 km east of the Mining Field. In 1896, they had reached such a point that Grängesbergsbolaget was formed with Salwén as head of the Grängesberg facilities.

Until now, the miners had wandered weekly to their work in Grängesberg from their homes in the forests around the community. It was the sons and servants of miners and homeowners who walked to the mine on Sunday afternoons and back home on Saturday afternoons. During the weeks, people lived in large barracks with 30 to 50 residents together in a large room. The barracks were run by a powerful lady. It was not the healthiest working life. Cassels, with a model from England, was eager for the company to build workers' housing according to the English model.

Klotens Mill built the first workers' housing north of the field at Norrmalm. The first miners' housing that Grängesbergsbolaget built was Stora Hagen in 1896 and then Källfallet, Laxtorp and at a time into the 20th century Grotfallet and others. These were buildings called Hälleforshus.

Salwén was a community builder and Grängesberg became a distinct Brukssamhälle where the company was responsible for the social service. The company built homes for miners, supervisors and white-collar workers. Also hospital, sanatorium, epidemic building and laundry rooms were built. Salwén was also a municipal politician and chaired the Grangärde parish council and ensured that the municipality and the mining company built schools and public institutions. That the workers being able to take their families with them and move to the miners' homes, society got a much calmer social environment. A state church was built in 1892 and several independent church buildings and sobriety rooms / lodges and workers' rooms in the community.

Cassel's concert hall.

Cassel was responsible for the capital for the investments and it was, at that time, a large donation of SEK 250,000 to a Foundation for the Miners in Grängesberg. For the money, according to the donation letter, a bathhouse was to be built, which was completed in 1898, a sports field and a concert hall with a park around it. The concert hall would have a large auditorium for concerts and theater, a reading room (library), a banquet hall for family / association / general ceremonies, halls for teaching, in technical subjects for the miners' boys, and lectures.

Cassel's building was ready for inauguration on January 12, 1900 and the keynote address was given by Bishop Johan August Ekman in Västerås Diocese.

The only restriction that Cassel wrote in his donation letter was that the room could not become a preaching room.

A few years later, a school kitchen was also built for the miners' daughters who would learn to cook nutritious food for their families. Cassel's intentions were, as evidenced by preserved drawings, that it would become a People's House. But the miners did not accept this as they had a workers' premises in the northern part of the community at the current Gruvarbetarbacken. The board of the foundation initially consisted of salaried employees at Grängesbergsbolaget. They were not willing to lend Cassel's to the miners' agitation meetings, for example during the great strike of 1909, so it took a few years before the miners accepted the building as a House of Culture as it was intended to be.

The iron ore mines flourished before major wars, when armies were being built, and during the wars and after the wars when bombed-out cities were to be rebuilt and armies re-emerged. This was the case during and after the First World War 1914 - 1918. A little calmer in the 20s but in the 30s Germany would equip its armies to take revenge after the losses during the

First World War and Hitler wanted revenge. During that time, production in Grängesberg was in full swing with large deliveries to Germany and Central Europe.

Grängesbergsbolaget had built up its own fleet so that it could deliver the ore on its own vessels. During both the First and Second World Wars, the ore fleet lost many boats that were torpedoed both in the Baltic Sea and on the North Sea and the Atlantic. During the wars, ore was also transported from the Lapland mines via Narvik in Norway.

During the 1930s, there were long periods of layoffs at the mines. At that time, many miners took the opportunity to build their own homes in their spare time with the support of the mining company. One example is the residential development at Björkås.

The Second World War from 1939 - 1945 were turbulent times in Grängesberg with demands for deliveries to Germany and many of the miners called up in the Swedish defense forces. After 1945, it had been hoped that the demand for ore would be great, but the reconstruction in Europe did not take off. The victorious powers Russia, England, France and the United States were facing the division of the losing Germany and it took time. The UN was formed in the autumn of 1945, but it did not help. The United States came with Marshall Aid in 1948 but it was still sluggish. The Korean War in 1950 to the armistice in 1953, only then the construction of the war-torn countries began and then came the great demand for iron ore. Grängesberg flourished, new miners' homes were built and in general there was a lot of construction in the community, various homes HSB, Riksbyggen and individually owned homes.

Demand for ore was high and new annual records of mined ore were broken year after year.

During the latter part of the 1960s, a lot of work was done to get a low-phosphorus product to sell on the market. The laboratory in Stråssa worked partly with grinding and flotation of the ore and making cold-bound balls. After grinding, a very fine-grained material was obtained where, with the aid of a flotation process, the ore grains could be separated from the apatite grains which contained phosphorus.

Flotation meant that several different chemicals were used, which partly attached to the ore grains and sank in the flotation apparatus and partly a chemical which attached to the apatite grains and lifted these grains. The apatite grains could be skimmed off at the surface of the apparatus and then dried and used as phosphorus in soil improvers in the fields and also as feed for cattle.

After the flotation, the ore grains were a very fine material, such as flour, and which had to be sintered before brought into the blast furnace and the most common method was to make ball sinter with the help of oil. The laboratory in Stråssa worked on developing a method with cold-bonded balls where the binder bentonite was used on the ball plates. These bullets were then stored in a large high pocket and in ball storage halls of very large dimensions 50 x 180 meters. This method was not as profitable as had been hoped, but these bullets were marketed until the mine closed.

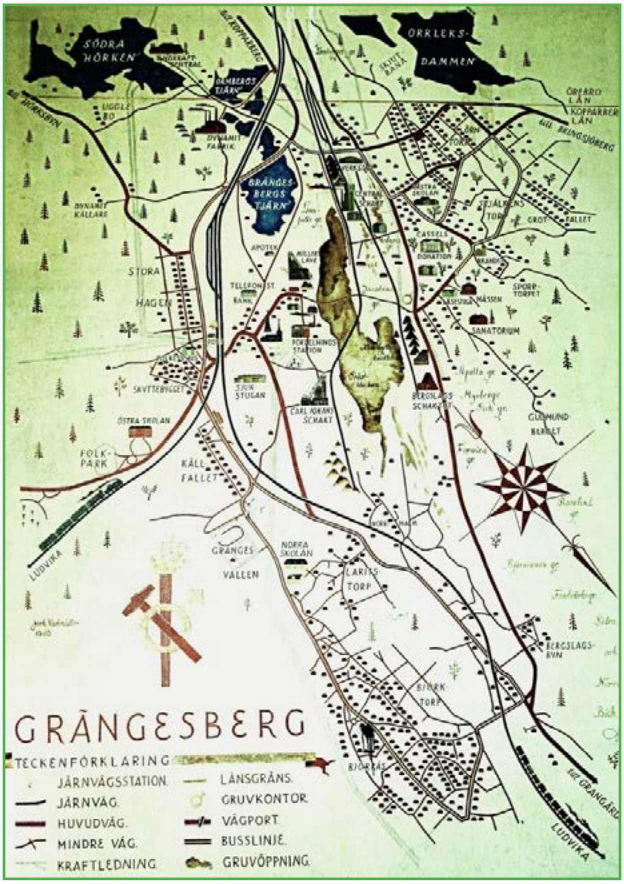
During the mid-1970s, a crisis arose in the commercial steel industry. The shipyards that used a lot of commercial steel and the car industry wanted lighter products for both their cars and trucks. The large ironworks were then Gränges in Oxelösund, Stora Kopparberg in Domnarvet and the state's NJA in Luleå. In order to save as much of the commercial steel as possible, the state initiated a major relief operation so that Sweden would not be without ordinary commercial steel. The state formed Svenskt Stål AB (SSAB) in 1977 and took over the listed steelworks from Gränges, STORA and Staten but also Gränges and STORA's iron ore mines. Gränges had iron ore mines in Grängesberg and Stråssa. STORA had mines in Blötberget, Håksberg, Dannemora and Vintjärn. The Vintjärn mine was closed down by STORA and other mines were transferred to SSAB. In the early 1980s, the mines in Stråssa, Blötberget and Håksberg were closed down due to unprofitability. The blast furnaces were shut down in Domnarvet and it became only a rolling mill. In Oxelösund and Luleå, the metallurgy was retained and the rolling mills and the railworks in Domnarvet were moved to Luleå. During the 1970s and until 1990, competition was very potent from new iron ore mines that could load iron ore from large surface deposits such as Brazil and Australia, and freights to Europe were relatively cheap. The iron ore was sold in US dollars and it was difficult to compete for the smaller Swedish mines. Those who managed the competition were the larger mines in Norrland.

Myller's pithead with enrichment plant and Tybo wash plant. Paintings: Ragnar Salwén.

SSAB kept the mine in Grängesberg until 1989 and the State took over the Dannemora mine and closed it down at the same time. Grängesberg's community had 6,500 inhabitants in the 1970s but gradually decreased during the 70s and 80s to 3200, which is the number of inhabitants at present. Society has seen how Spendrup's brewery is expanding and taking over as the largest employer in the Grängesberg. But also a number of smaller companies are now active in the community and several of the residents commute to ABB / Hitachi in Ludvika, among other places.

The mine's impact on town

The spread of mining operations in mining towns means that communities can move their buildings and public facilities, as is currently the case in Kiruna and Malmberget in Lapland. It has also happened



Map in the railway station building's waiting room from 1940, painted by Jerk Werkmäster

of shops, hotels, bank buildings, hospitals, a church and a cemetery. The FLJ railway was built between the mine and the large pitheads on the suspension wall. A little further east, the BJ railway was built as well as the central road through Grängesberg, which was drawn past the central Byxfickstorget. FLJ first had to be moved east out parallel to the BJ line and new stations were built.

In 1940, the railways were moved to their current location with a common station building and the large new ore railway station south of the mine was put into operation. During the 1930s, the mining facilities began to be moved to the west side of the mine. The first one built there was Dillner's pithead later called the Central Shaft. The Southern enrichment plant was put into operation and all the mining facilities were gradually moved to the western side of the mine. A new hospital was built in the 1930s, the cemetery was moved in the 1950s as well as the bank, many shops and the hotel. It was a major intervention in society when the railways, the national road and the pitheads on the east side were demolished.

in Grängesberg. Until 1900, the ore was mainly mined from the open pit, which was called Skärningen with a railway yard north towards Norrmalm, Kloten's railway yard. But between 1900 and 1910, the ore had to be mined underground. Grängesberg's ore body fell in a slope of about 70 degrees to the east, and in such a way that the facilities built during the first years of the 20th century such as Myllers pithead and Karl Johan's pithead with concentrators and workshops came to lie on the so-called hanging wall.

This meant that the buildings were undermined when the mine was dug toward the depths. Not only mining buildings were built east of the mine but also a number

In order to arrive with the BJ line, the Mission Congregation Church had to be demolished and a new one built further up to the east. New pitheads were added on the west side. Jakobina 1945 and Risbergsfältet 1956–57 which replaced Höga Visan's downpipe shaft which followed the slope of the ore body.

In 1974 an earthquake occurred in Grängesberg and a movement started and intense investigations took off. It was found that there was a fault which, after investigations,

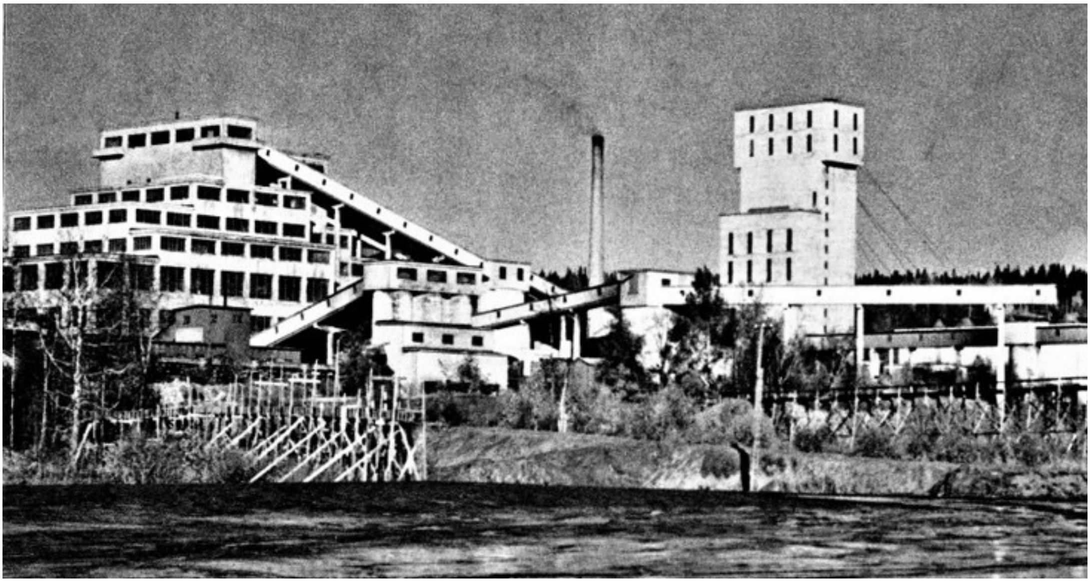


Photo of Southern enrichment plant and Dillner's pithead in the 1950s.

turned out to extend in a north-south direction a little further up on the eastern slope up towards Öraberget. Some houses were cracked and had to be demolished and the fault also reached the surface under Spendrup's Brewery. This meant another move of the infirmary towards Björkås and a new Church was built for the Church of Sweden towards Kyrkbacken along the national road towards Ludvika.

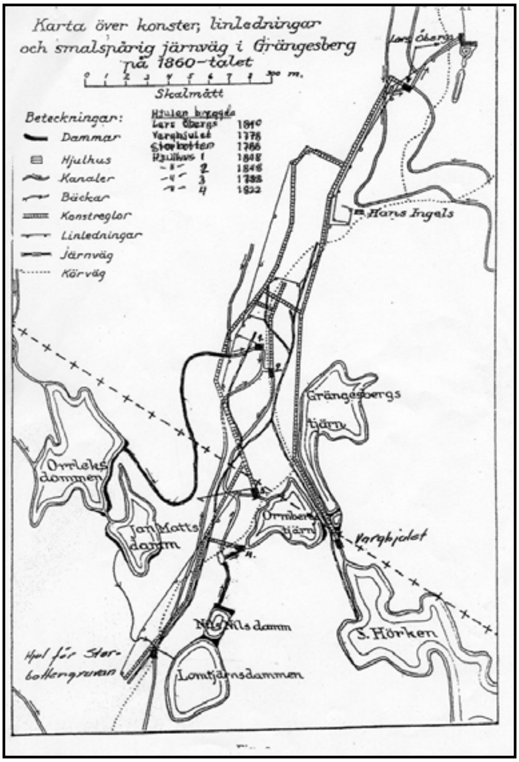
The fault slopes westwards down towards the ore body and passes it at the level of about 650–700 meters. The ore body also has a displacement. During the 1980s, the last ten years the mine was in operation, the eastern "hanging wall" moved 10 cm closer to the mine and it also sank by about 10 cm. These movements ceased when the mine was filled with water after closing. This movement would certainly occur again if the mine reappears. If this happens, it is estimated that after about 10 to 20 years of mining, the railway, national road and central Grängesberg will have to be moved again.

Energy supply to the mines in the Grängesberg region for 400 years.
Originally, the ore for iron production was produced by human hands before aids such as water power in various ways replaced human labor. That applied from producing bog ore to underground ore mining.

At the large Grängesberg field, which began to be worked on a larger scale during the 1600s and 1800s, the ore body went up to the surface so that drainage of water collected in the open pits could be diverted out of the mining site. The ore could be transported out of the mine by hand or by horse power. If the ore had to be lifted to the ground surface, horse-drawn winches would be used.

Polhem's water wheel (art wheel) came at the beginning of the 18th century. The first in the Grängesberg area in 1721 for Björnberget's mines and the wheel was placed below Örabergsdammen with flatrod systems up to the mine for pumping water out of the mine. There the ore did not reach daylight, but slightly deeper than for the rest of the Grängesberg field itself. The water wheels could also lift the ore out of the mine with cable lines to the pitheads at the ground lavel.

At the Grängesberg mines’ ore field, 7 water-powered art wheels were built that drove the articulations, mainly for pumping water. There was also a line winch for ore hoisting. These Polhems facilities were built between 1788 and 1848 and were used right up to the 1910s. In order to get water to the art wheels and the washing plant facilities, an extensive system of canals and dams was built in the forests around Grängesberg. It is estimated that 45 km of canals were built to collect water for the artificial wheels. A large steam engine, Stora Maskin, was acquired in order to strengthen the operation of the flatrod systems in the event of a lack of water. It was built in the



Map of art canals and waterwheels in the 1860s. Sources: Pictures by Örjan Hamrin and Artificial Canals by Grängesbergs Hembygdgille.

southern part of Ränngruvefallet. It came from the USA and was shown at the World Exhibition in Paris in 1878 and came to Grängesberg in 1879 and was demolished in 1930. The last art wheel was taken out of service in 1911.

The Polhem equipment began to be replaced in 1893 by three-phase alternating current from the power stations that Grängesberg’s Joint Administration built at Hällsjön in 1893, Enkullen in 1898 and Lernbo in 1899. In 1911, Mockfjärd’s (Lillstupet) power station was built in collaboration with Stora Kopparbergs Bergslags Aktiebolag, which then needed power for the newly built Domnarvets Järnverk.

These four power plants supplied the power to a distribution station in Grängesberg which ensured that the various mines in Grängesberg received the electricity they needed. There are remains of that distribution station which can be seen within the mining area west of the old church grounds. One of the art wheels located south of the Dalporten viaduct was reconstructed in the 1990s. As a reserve a steam power station was built at Grängesberg Bay by Södra Hörken. In an emergency, the station could supply the mines in the event of a failure to the long lines from the power stations.
In order to get the electrical equipment needed in the mines, Grängesbergsbolaget was involved in starting the Elektriska Aktiebolaget Magnet in 1900 in Ludvika together with the mines and sawmills in Västerbergslagen.

Power transmission with alternating current

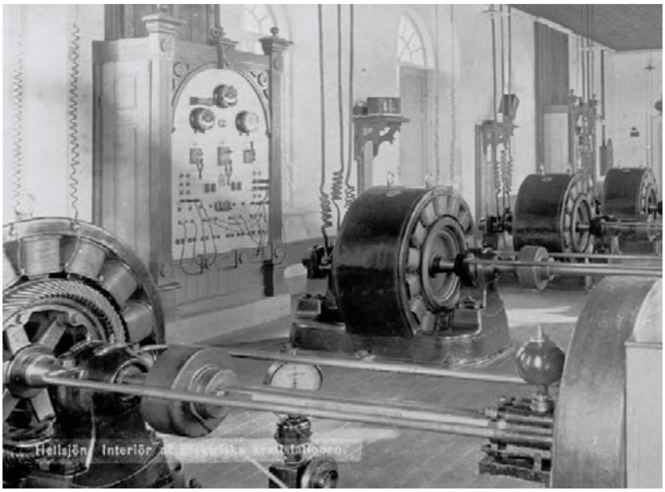
Carl Ejnar Sölver

Early electrification, the birth of ASEA

The use of electricity gained momentum during the last decades of the 19th century, with the United States and Germany as leading countries. The first applications were lighting systems, which mainly used direct current, generated in dynamo machines. This worked fine, but it was quickly realized that direct current was not suitable for greater transmission distances than a few km. The heat losses in the lines became too large, and there was no method to increase the voltage to reduce the current and thus the losses.

Alternating current has the advantage of being able to be converted from one voltage level to another in a transformer, and this made it possible to use high voltage (and thus low current) to transmit the power over longer distances. At first it was difficult to design efficient generators and motors for alternating current, but this problem was solved around 1890 when three-phase systems were introduced, where the three alternating currents had mutually different phase angles. The sum of the three phase currents was zero, and therefore no return conductor was needed. This was a big advantage because it reduced the cost of the lines. One of the inventors was Jonas Wenström, who received a Swedish patent for this technology in 1890.

The emerging Swedish electric power industry gained early customers in Stockholm, and to a large extent in Bergslagen. Here were future-oriented steel and mining companies as well as pulp and paper industry, all of which needed large power resources in their production. In 1883, Elektriska Aktiebolaget was founded in Stockholm, which focused on direct current and lighting systems. A main product was the dynamo machine, which had just been developed by Jonas Wenström. The interest expanded in the coming years to alternating current technology, and the company was transformed in 1890 into Allmänna Svenska Elektriska Aktiebolaget, ASEA. In connection with this, it was decided to move all its operations to Västerås.



Interior from Hellsjön's Power Station.
Photo: Albin Andersson, Tekniska museet.

The power transmission Hellsjön-Grängesberg

The industry's interest in three-phase AC systems increased rapidly. Grängesbergsbolaget was a strong driving force, and ASEA's very first installation was the Hellsjön-Grängesberg power transmission, which was put into operation in 1893. Four three-phase generators with a total power of 344 kVA were installed in the hydro-power station. The generator voltage 260 V was transformed up to 9500 V, and the energy was transferred via overhead line to the consumption sites in Grängesberg. The transmission distance was 14 km, and Jonas Wenström's patent was behind the constructions. This was the world's very first commercial three-phase AC power transmission! Later, the Hellsjö system was strengthened with the hydropower stations in Enkullen in 1897, and Lernbo in 1899.

Even today, original interiors remain in Hellsjön's Power Station - here the doors to the switchgear room. Photo: Tommy Hjort

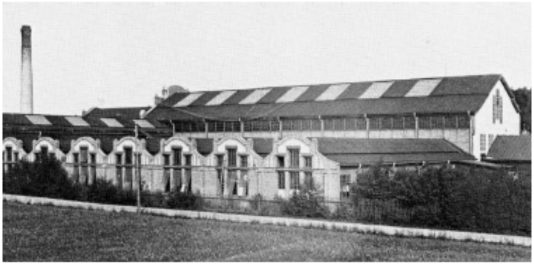
Prior to the Hellsjön – Grängesberg electric power transmission, local water wheels provided power for the hoists and pumps of the mines. The power was transmitted mechanically with flatrod or cable systems. The water wheels were replaced in 1877 by a central steam engine located approximately where Västra skolan is today. Mechanical transmissions have very low efficiency, about 10%. Therefore, they could only be used for short distances, 1 - 2 km at the longest. The electric power transmission is estimated to have had about 70% efficiency and thus meant a paradigm shift.

Electrical industry in Ludvika

Until around the middle of the 19th century, Ludvika Bruk had an extensive production of wrought bar-iron, with the forges concentrated at Ludvika stream. The hydropower was used partly to drive the bellows to the hearths, and partly to drive the forge hammers. The iron ore was taken from the area's mines, and converted into semi-finished pig iron in the blast-furnaces, such as Norhyttan, which were scattered in the surroundings. The pig iron was then remelted in the hearths of the forges, whereby the carbon content decreased, and could be hammered out to the wrought bar-iron which was the end product. The mill owner lived at Ludvika Manor, in the immediate vicinity of the business.

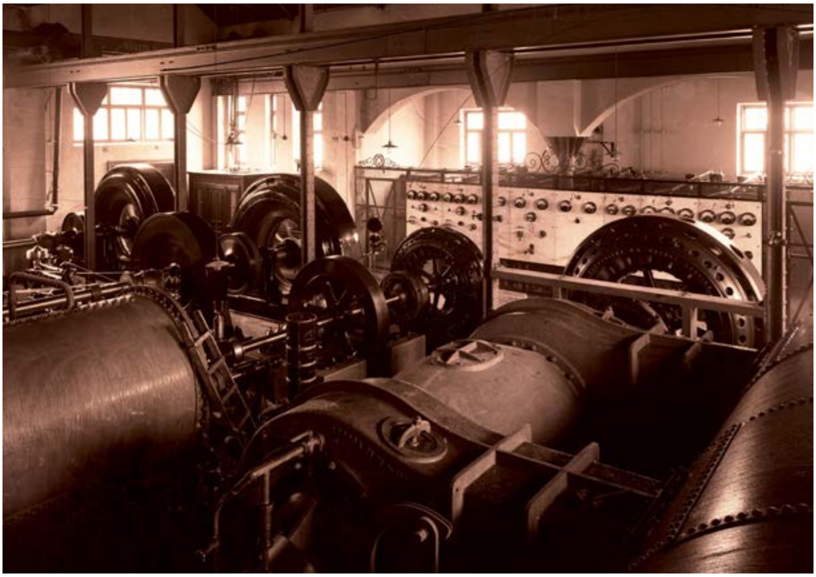
However, new methods would completely transform iron and steel production. Rolling mills replaced the traditional forges, and new steel processes (Bessemer, Martin) caused market prices to fall sharply. Ludvika Bruk was too small and capital-weak to be able to keep up with this development. Mill owner Carl Roth tried to maintain the mill's profitability for as long as possible, but was gradually forced to close down iron handling. In this situation, he partly invested in completely new businesses. Among other things, a steam sawmill was built at the shore of Lake Väsman.

What became absolutely crucial for Ludvika's future was Roth's initiative for a completely new industrial operation, Elektriska Aktiebolaget Magnet. This was exactly right at the time. It had been a boom for the electrical engineering industry during the latter part of the 1890s, and there was a rapidly growing market for electrification of Bergslagen's mines and industries. Grängesbergsbolaget became the largest shareholder, and a constituent general meeting was held on June 30, 1900. Richard Göransson with experience from the German electri-



Elektriska Aktiebolaget Magnet's new premises at Ludvika. Photo: Hitachi Energy

city industry was employed as CEO. New premises were built at a rapid pace, and the company started with deliveries as early as 1901. From the beginning, the company had the ambition to have a wide range of products for customers in Bergslagen: power transmissions, electrical equipment for rolling mills and mineral processing, hoists and locomotives for the mines.



Interior from Ludvika Power Station, with the lighting unit in the middle. The control panel shows the four fields for the three-phase units. Photo: Västmanlands Läns Museum.

Around the same time, Roth began to exploit Ludvika stream for electricity. For this project, he received practical help from Grängesbergsbolaget, which of course had its own experience from the Hellsjön-Grängesberg power transmission. The power station in Ludvika was started up in October 1901. It was originally equipped with four three-phase units for motor power, each of 400 horsepower and 40 Hz, and a single-phase unit for lighting, 250 horsepower and 100 Hz. The electrical equipment was delivered from Magnet's brand-new factory. A few years later, Roth continued by exploiting Lake Väsman's tributaries in Finnmarken. The small hydropower stations Sunnansjö, Loforsen, Vännebo and Nyhammar were added in 1910 - 1915.

Merger with ASEA

In the years after the turn of the century, the boom changed into a recession. Elektriska Aktiebolaget Magnet, like ASEA and other companies in the industry, had difficulties to fill their workshops with orders, and also suffered from problems with frequent changes of senior staff. In 1906, the difficulties led to Magnet merging with a couple of its Swedish competitors. The new company was named Förenade Elektriska Aktiebolaget. As a result of the merger the engineers A Grönwall, Axel Lindblad and O Stålhane resigned, and formed Aktiebolaget Elektrometall to test their inventions regarding production of pig iron by electrical means. Experiments were made at Ludvika Bruk, with power from Ludvika Power Station, but the business moved to Domnarvet a few years later. Förenade Elektriska was reorganized in 1908 into NFEA, Nya Förenade Elektriska Aktiebolaget. Then, in 1916, NFEA was bought by the expanding ASEA. In connection with this, the major structural rationalization that was to be permanent for the future was carried out: ASEA in Ludvika got responsibility for transformers and power transmission equipment, while ASEA in Västerås got responsibility for rotating machines. The merged company was now on par with the best in the world. It had a strong position in the Swedish domestic market, and also began to seek out export markets.

Construction of regional power grids in Sweden

The introduction of three-phase alternating current made it possible to exploit waterfalls that were at a great distance from electricity consumers. The construction of power stations and lines required large investments, and special power companies were formed at the beginning of the 20th century, in which the large industrial and municipal power consumers were important partners. The former local electricity grids grew into power grids of regional size with around 100 km distribution radius. The increasing transmission distances went hand in hand with rapidly increasing transmission voltages. In connection with the construction of the power station in Trollhättan, the Swedish state also made its entrance as owner and commercial power producer: Kungl. Vattenfallstyrelsen, better known as Vattenfall, was established in 1909.

When Trollhättan's power station was inaugurated in 1910, it was a Swedish record both in terms of the generator power of 40 MVA and the transmission voltage 50 kV, and the electrical equipment was supplied by ASEA. Subsequently, Vattenfall quickly built Porjus power station in Lule river, to supply the ore fields in the north and the railway to Narvik with electric power, and Älvkarleby power station in the lower Dalälven. In both these cases, the voltage 70 kV was used in the connected networks. The other power companies also expanded rapidly. An example is the privately and municipally owned Sydkraft, which built four power stations in Lagan, and fed the power from there on a 50 kV line. A few years later, the regional electricity networks around Trollhättan and Älvkarleby had grown so strongly that Vattenfall wanted to interconnect them. This resulted in a transmission line ”Västra stamlinjen” with the new record voltage 130 kV. The line was put into operation in 1921, and the voltage was then the highest in Europe.

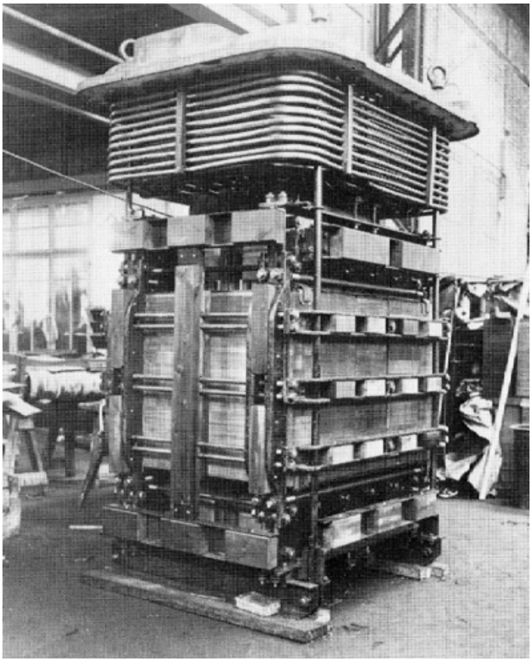
Development of the network frequency

Today, in large areas, the electricity grids are interconnected and maintain the same frequency, usually 50 Hz or 60 Hz. Other frequencies are used for train traffic and in a few cases, for historical reasons, in industries. In the late 19th and early 20th centuries, most networks were run in what is known as island operation, without contact with any other major network. In island operation, the network operator is solely responsible for correctly regulating frequency and voltage. This cannot be done without considerable rotating mass in the power station units.

When it was supplemented with the hydropower stations Enkullen and Lernbo, the Hellsjö system still had a frequency of 70 Hz. When the power station in Mockfjärd later was built together with the company Stora Kopparberg, it was the intention to connect the Hellsjö system with Mockfjärd and also

Stora Kopparberg's existing power system around the lower Dalälven. It was then chosen to use the latter system's frequency of 60 Hz, and the Hellsjö system was rebuilt around 1910 to fit this frequency.

For Ludvika Kraftstation, 40 Hz was chosen, probably because the customers would then not be able to make the power companies compete against each other. The 40 Hz frequency is good because it gives higher starting torques in motors than higher frequencies, but it gives rise to flicker in arc lamps. These were used in the early 20th century for lighting in public, commercial and industrial contexts. For this purpose, a lighting machine was therefore chosen which gave 100 Hz. In homes, filament



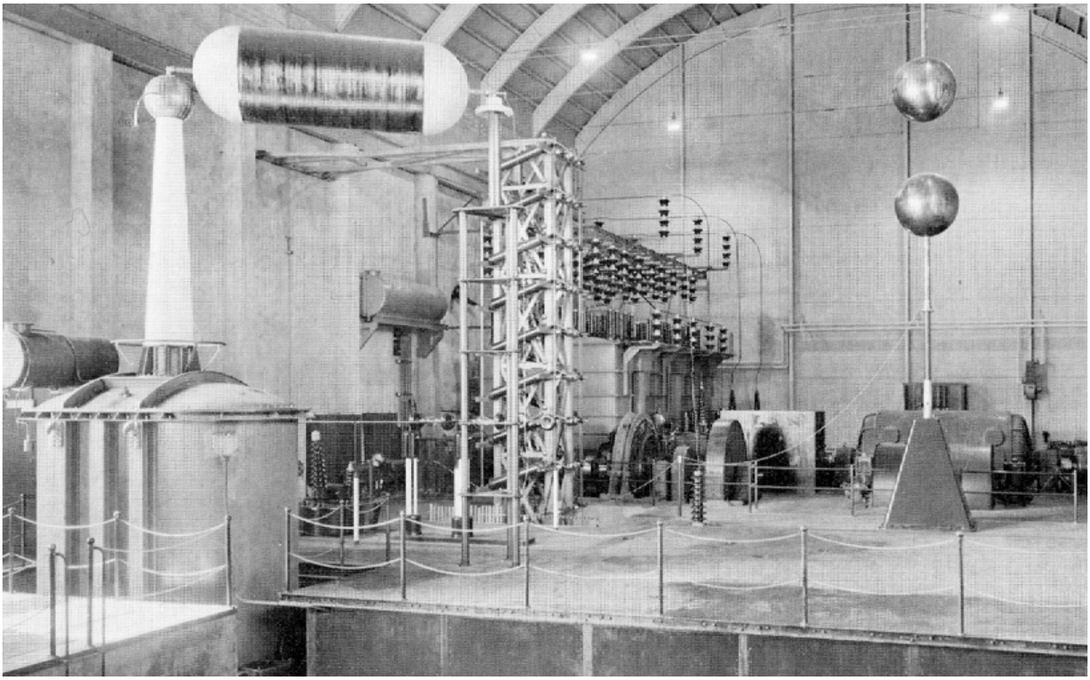
77 kV transformer for Älvkarleby power station supplied by Nya Förenade Elektriska Aktiebolaget in Ludvika in 1914. Photo: Hitachi Energy

lamps were used from the beginning and these worked well at 40 Hz. Loforsen, Nyhammar, Vännebo and Sunnansjö hydropower stations were later built and connected to the 40 Hz system.
The earliest units in Trollhättan, Porjus and Älvkarleby had a mains frequency of 25 Hz.

By the end of the 1920s, the construction of the national power grid, which had a frequency of 50 Hz, had reached our regions. The power companies then chose to connect to this network because it offered both accident and dry year reserves. Some conversions were required in the short term and gradually the turbine-generator units were replaced with those that were optimized for operation at 50 Hz.

Development cooperation Vattenfall-ASEA
The rapidly increasing operating voltages made it difficult for the transformers and in particular the circuit breakers to meet the technical requirements. There was a lack of test resources at the manufacturers to verify product performance. In addition, the power companies sometimes found it difficult to clearly determine what requirements needed to be set. In this situation, Vattenfall and ASEA initiated technical development cooperation, which was to be of great benefit to both parties.

The first 70 kV transformers were designed as single-phase units because technology was not yet mature for three-phase designs. Later, three-phase transformers were established, and the designs changed from shell type to core type. For 130 kV, one of the problems was how the windings were to be designed. It was unclear how the voltage was distributed across the windings in case of steep overvoltages, caused by lightning strokes. The theoretical basis was poor, and due to a lack of laboratory resources, Vattenfall and ASEA jointly carried out model tests in connection with the construction of the first 130 kV line.



Interior from the laboratory in Ludvika. To the left in the foreground test transformer for 1MV, behind this impulse generator for 2.4 MV. In the background equipment for short-circuit tests. Photo: Hitachi Energy

At the beginning of the 20th century, the circuit breakers were of oil tank type, where the contacts were opened/closed in a tank with mineral oil. The oil was effective in extinguishing the arcs that arose during the interruption process and was also a good electric insulation medium. A disadvantage of the design was that unsuccessful interruption could lead to both explosion and fire. During the development work, attempts were made in various ways to reduce the oil volume and increase the breaking capacity. To verify the constructions, series of field tests were carried out at Vattenfall's power stations in Västerås, Älvkarleby and Trollhättan.

New laboratory resources and further development

In 1930, construction began on a new short-circuit and high-voltage laboratory in Ludvika. ASEA, with its ambition to be an internationally competitive industry, thus followed the example of the leading foreign companies. When the laboratory was completed in 1933, it was considered to represent the culmination of what modern technology could accomplish. It had two separate departments, a high-power department where circuit breakers could be tested with high short-circuit currents, and partly a high-voltage department that was used for tests with high voltages. In the high voltage department, transformers, circuit breakers and other devices were tested.

The new laboratory resources were of crucial importance to be able to take the next development step, with 220 kV transmission voltage. This voltage was needed to be able to transfer power south from power stations in the Indalsälven river in central Norrland. The first 220 kV transmission was built by Krångede power company, and extended from Krångede power station in Indalsälven to Horndal and on to Stockholm. It was put into operation in 1936. Then followed a further rapid expansion of 220 kV lines during the war years, driven by the rapidly growing need for power which was partly caused by Sweden's closure from the outside world.

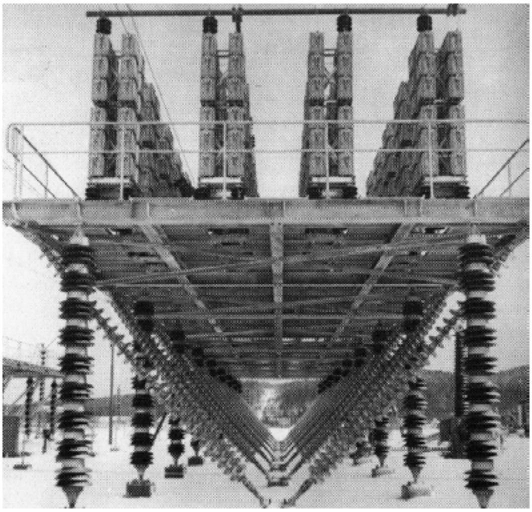
ASEA's work to improve the high-voltage equipment continued, and around 1935 a new oil circuit breaker the so-called contraction breaker, had been developed. This design came to be used on a large scale in the 220 kV network. At the same time, the discussion continued about the risks of oil fires or explosions. As a result, the development of compressed air circuit breakers, which were completely oil-free, was initially started in collaboration with the German company Voigt & Haeffner. Compressed air circuit breakers became dominant when the next development step was to be taken a decade later.

The first 400 kV line Harsprånget-Midskog-Hallsberg. Photo: Hitachi Energy

With the new laboratories, and with the fruitful development collaboration with Vattenfall, ASEA was able to improve both capacity and quality, and during the early 1930s, ASEA's transformers and high voltage equipment were completely on a par with the best foreign companies.

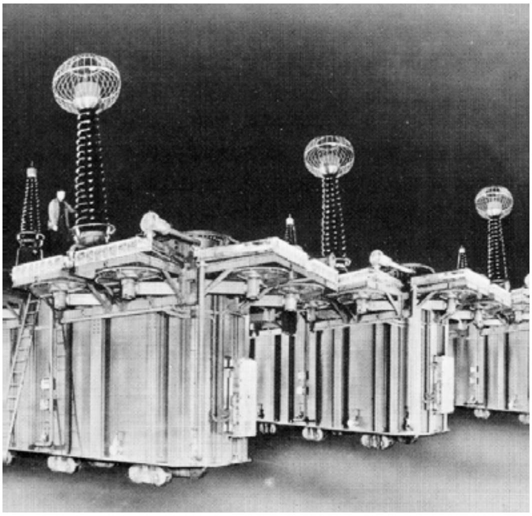
The 400 kV system in Sweden

As a result of the rapidly growing electricity consumption, it became highly interesting to utilize hydropower in northern Norrland, especially in the Lule river, and transfer it to central and southern Sweden. Since the



Part of a series capacitor system. The capacitor batteries are at line potential, and therefore they must have full insulation to earth. Photo: Hitachi Energy

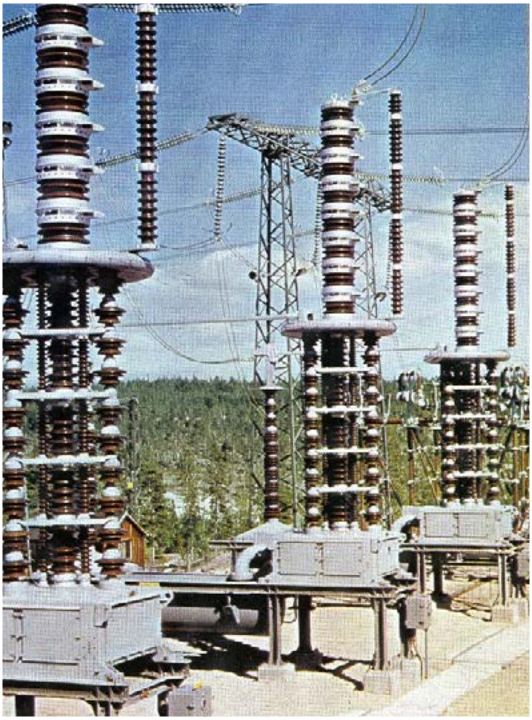
transmission distance was of the order of 1000 km, and it was a question of large amounts of power, it was no longer optimal to use 220 kV transmission voltage. For a number of years, it was discussed whether to use a new higher alternating voltage, or whether to take a radically new path and use DC, direct voltage. DC was a possible alternative as feasible designs were now under way for the high-voltage mercury-arc valves for the rectifiers/inverters that would then be needed. This was a result of the development work that ASEA had been conducting since around 1930 under the leadership of Uno Lamm. The high-volta-



Transformer group consisting of three single-phase units for 1000 MVA, 400/220 kV supplied by ASEA to Vattenfall in 1959. This was the largest transformer group in the world at this time. Photo: Hitachi Energy

ge lines themselves would be simpler and cheaper if you used direct voltage. However, there were many technical uncertainties with the DC technology, and in the end the decision was made to choose 400 kV AC alternating voltage (from the beginning, the voltage was stated to be 380 kV, but 400 kV came to correspond better to the real conditions).
In 1952, the first line was put into operation, stretching from the Harsprånget hydropower station in Lule river, via the Midskog hydropower station in Indalsälven to Hallsberg, where it was connected to the central Swedish power grid. The line passes just east of Ludvika. The towers were designed so that it was possible to convert the line to operate with direct voltage, by replacing the three phase conductors for alternating voltage with four phase conductors (two bipolar arrangements) for direct voltage. This shows how uncertain one was at this time about which technology would be best in the future.

The voltage 400 kV was a new world record, and several difficult technical problems had to be overcome. The transmission capacity of a long AC line is limited by its reactance (”AC resistance”). This reactance can be kept low by using phase conductors with several individual conductors, and it was chosen to use so-called duplex conductors, with two conductors per phase. Another effective method of limiting the reactance is to connect capacitors in series with the phase conductors. After some experiments in the 220 kV network, it was decided to introduce such series compensation of the long lines in the new 400 kV network. The first installation was delivered by ASEA and arrived on site in 1954 at Djurmo close to Dalälven, just ten months after the original line had been put into operation.
The new 400 kV technology quickly became dominant. Already 10 years later, several other countries in Europe had also started building 400 kV systems.



ASEA’s 400 kV air-blast circuit breaker in the substation at Harsprånget. Photo: Hitachi Energy

ASEA's High-Power Laboratory, inaugurated in 1958. Foto: Hitachi Energy

Equipment for 400 kV; transformers, reactors, circuit breakers etc

When the 400 kV lines were to be built, it was very important to control the magnitude of the voltage surges which could occur, as this determined which electrical insulation was needed. To limit the surges, overvoltage protection was used. Such so-called surge arresters had been developed by ASEA in the late 1930s, and consisted of a number of self-extinguishing spark gaps, series connected with silicon carbide resistance blocks. The resistance blocks were strongly non-linear and conducted a very rapidly increasing current with increasing voltage (and when the spark gaps had ignited). This became a successful product for ASEA. In the mid-1970s, zinc oxide resistance blocks with various additives began to be used. The spark gaps could then be removed, as the resistance blocks were extremely non-linear, and conducted practically no current at all at normal operating voltage.

For the 400 kV lines, the demands on the circuit breakers increased. Of course, they had to interrupt the short-circuit currents that could occur, but they were also required to have shorter break-time than was previously needed. The reason was that the networks connected at the line ends could fall out of phase with each other, and the line completely lose its transmission capacity, if it took too long to break a short-circuit current. ASEA's contraction circuit breakers had difficulties meeting the requirements, and Vattenfall wanted to use air-blast circuit breakers, which were also recommended by foreign manufacturers. There was no oil in the air-blast circuit breakers, and the arcs between the circuit breaker contacts were extinguished instead by a blast of compressed air. After intense development work where among other things field tests were made in Vattenfall's 220 kV network, ASEA arrived at a feasible design. This circuit breaker was then used for the first 400 kV installations.

To make it possible to develop better circuit breaker designs, a completely new high-power laboratory was built in Ludvika, which was inaugurated in 1958. The new laboratory had more than three times as much power as the old laboratory, and was also equipped with a large capacitor bank. The capacitor bank made it possible to simulate switching of no-load lines. With the new equipment, the laboratory was completely on a par with the best in the world.

Further development of the air-blast circuit breakers continued. They met the technical requirements, but were complicated and relatively maintenance-intensive. They never became a good deal for ASEA, and eventually the focus turned to much simpler oil-minimum circuit breakers again. New high-strength materials in the extinguishing chambers made the switching capacity fully in level with that of the air-blast circuit breakers. The manufacture of air-blast circuit breakers was discontinued in 1969.

In the transformers, grain-oriented sheet metal was introduced for the cores, which led to reduced power losses. ASEA was not first to introduce this technology, but obtained a license from an American company. The ever larger and heavier transformers required gradual expansion of both workshop and test rooms. The new high-power test room “Mammuthallen” had a test capacity for the highest voltages, including an impulse generator for 4.8 MV. As the transformers became larger, associated tap changers were developed, to permit adjustment of the transformer turn ratio to varying operating situations, and also the bushings required to connect the windings to the environment outside of the transformer.

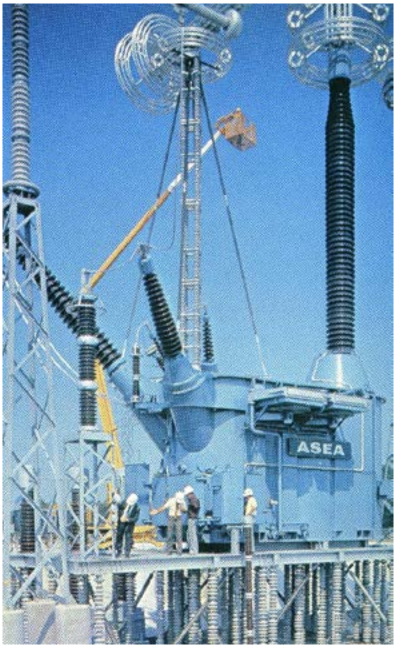
Gear for tap changer, with inventor Uno Olsson. Photo: Hitachi Energy

The tap changers introduced in the 1940s contained a fascinating machine element; gear with non-circular cog-wheels. Many people still remember these strangely spinning wheels from the introduction to the Swedish television program Tekniskt Magasin, which was broadcast for many years at the end of the 20th century. The non-circular cog-wheels gave the tap changer the sequence of contact movements required to switch between more/fewer turns in the transformer windings without changing the load current by leaps.

The bushings were designed with a number of metal layers distributed in the insulation, so that the voltage was evenly distributed (so-called capacitor bushings). Both tap changers and bushings became successful products on their own, and were occasionally sold to competing transformer manufacturers.

To stabilize the voltage in power grids with long high-voltage lines, shunt reactors were used, which were connected between the line and ground. ASEA’s first high-voltage shunt reactors were designed in the early

1960s for the Swedish 400 kV network. A core-type design was developed early on, which meant that windings and insulation systems were of the same type as for



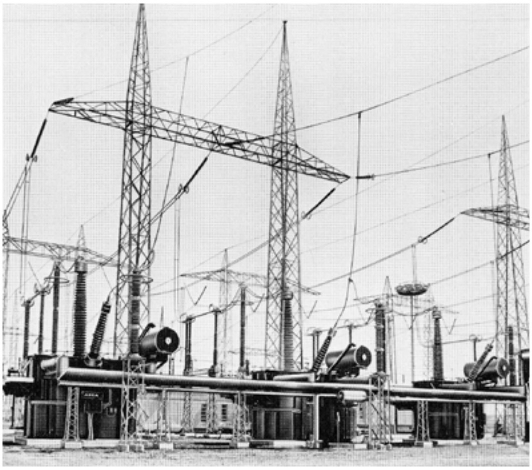
Transformer for ultra-high voltage (UHV) at the AEP-ASEA Test Station in South Bend, Indiana USA. Foto: Hitachi Energy

transformers for the corresponding voltage. The shunt reactor's iron core, on the other hand, had a very special design with a number of air gaps, where ASEA's design was unique, with good properties.

ASEA had consistently consolidated its position as a leading company in the industry. The growing activity with high voltage direct current (HVDC) contributed strongly to this.

Continued development towards higher voltages

Thanks to its laboratory resources in Ludvika and its solid experience of large, high-voltage transformers and devices for 400 kV, ASEA managed to get orders, in the international competition, for a large part of the equipment for the world's first power transmission for 735 kV. The owner



735 kV substation in Hydro Quebec's network, with transformers from ASEA. Photo: Hitachi Energy

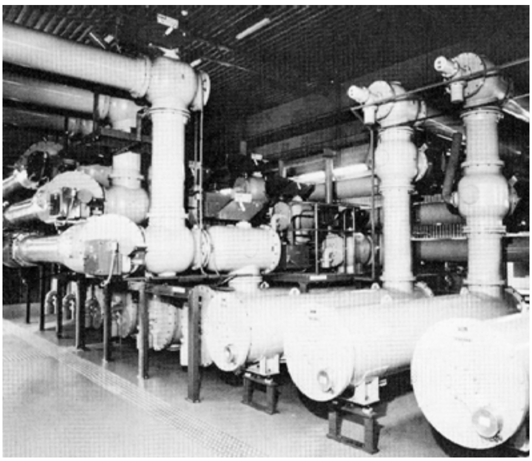
was Hydro-Québec, Canada, and the first link was taken into operation in 1965. ASEA also supplied equipment to the largest private power company in the United States, American Electric Power (AEP) and its 765 kV system. In 1968, these deliveries led to an agreement between AEP and ASEA on ”a comprehensive, joint development work aiming at the new systems and products for ultra-high voltages (UHV) required in the new power grids”. In 1976, AEP and ASEA passed a milestone in their joint project when the test station in South Bend, Indiana, was energized. The single-phase test transformer was designed for the voltage 1,785 kV.

During the 1970s, Vattenfall planned to build a 765 kV network in Sweden, in addition to the 400 kV network. The reason was that the power grid in southern Sweden needed to be strengthened, in order to improve the connection between the new nuclear power plants and the metropolitan regions. The network would also make it possible to export a larger amount of electricity in the future. In 1979, construction began on a line between the Forsmark nuclear power plant, on the coast of Uppland, and Stockholm. Shortly afterwards, however, the plans were stopped by the government, which assumed that the use of electricity would not increase as quickly as previously planned. The decision was also preceded by an intense discussion about the possible danger of the magnetic fields from these lines with very high voltage. The line already started from Forsmark was rebuilt to 400 kV.

Since the turn of the century, China and also Japan have been in forefront of the development towards ultra-high transmission voltages (UHV). Both Japan and China use the transmission voltage 1,100 kV. In China, the expansion of these AC networks takes place in parallel with the expansion of UHV DC transmission systems with voltages of 800 and 1,100 kV.

Gas-insulated switchgear GIS

In the mid-1970s, ASEA began comprehensive development of high-voltage equipment with the gas sulfur hexafluoride (SF_6). This gas is a good electrical insulator and also very suitable in circuit breakers, where it contributes to good interrupting capacity. ASEA developed SF_6 circuit breakers for standard outdoor substations, and also complete gas-insulated switchgear, GIS.



400 kV ASEA GIS substation in Ringhals nuclear power plant. Photo: Hitachi Energy

Such switchgear became very compact, by integrating all switchgear apparatus in SF_6-filled enclosures. As a result of the Swedish 765 kV plans, a prototype of a 765 kV GIS bay was tested as early as 1975. In 1978, the first 400 kV ASEA GIS substation was installed at Ringhals nuclear power plant. A brand-new workshop for GIS equipment was inaugurated in 1982.

On August 10, 1987, it was announced that ASEA would merge with Brown Boveri, formed in 1891 in Switzerland. Like ASEA, Brown Boveri was known as a high-tech company, and the two companies had been strong competitors over the years. However, both companies were relatively small on the large world market, and a main reason for merging was to grow larger in order to improve competitiveness. In addition, the two companies had partly different product ranges, so they complemented each other. The new company was named ABB, and was headquartered in Zurich. After the merger, a number of rationalizations were made, dividing up products between different factories. One result of this was that the GIS production in Ludvika was closed down. In other respects, however, the Ludvika factory maintained its strong position.

Concluding remarks

Finally, we can summarize the reasons why little Ludvika was first in the world with commercial three-phase power transmission, and why it has continued to be a world leader in the field.

- It all started at the end of the 19^{th} century with the existence of a power-consuming and devlopment-oriented industry in Bergslagen. This formed the basis for the first pro jects with electric power transmission. A far-sighted mill owner took the opportunity to start an electrical industry in Ludvika, which eventually came to belong to ASEA.

- Sweden's structure with hydropower in the north and the population in the south drove the development towards long transmission distances and high voltages.
- ASEA became part of a very fruitful development cooperation with the state-owned Vattenfall, and had the opportunity to test its designs in the field. A culmination was when the Swedish 400 kV system began to be built in the early 1950s.
- The Ludvika factory invested early and massively in world-leading laboratories. This was not cheap but came to be of great importance for product development and competitiveness.
- ASEA succeeded in building a strong position in the export market, and thus a strong position also for voltages higher than 400 kV. This was further emphasized when ABB came into being through the merger with Brown Boveri.

Since 2020, ABB's power transmission operations have been divested and are part of the newly formed company Hitachi Energy. The Ludvika factory administers a proud tradition, and continues to be at the forefront of development for high-voltage power transmission with alternating voltage.

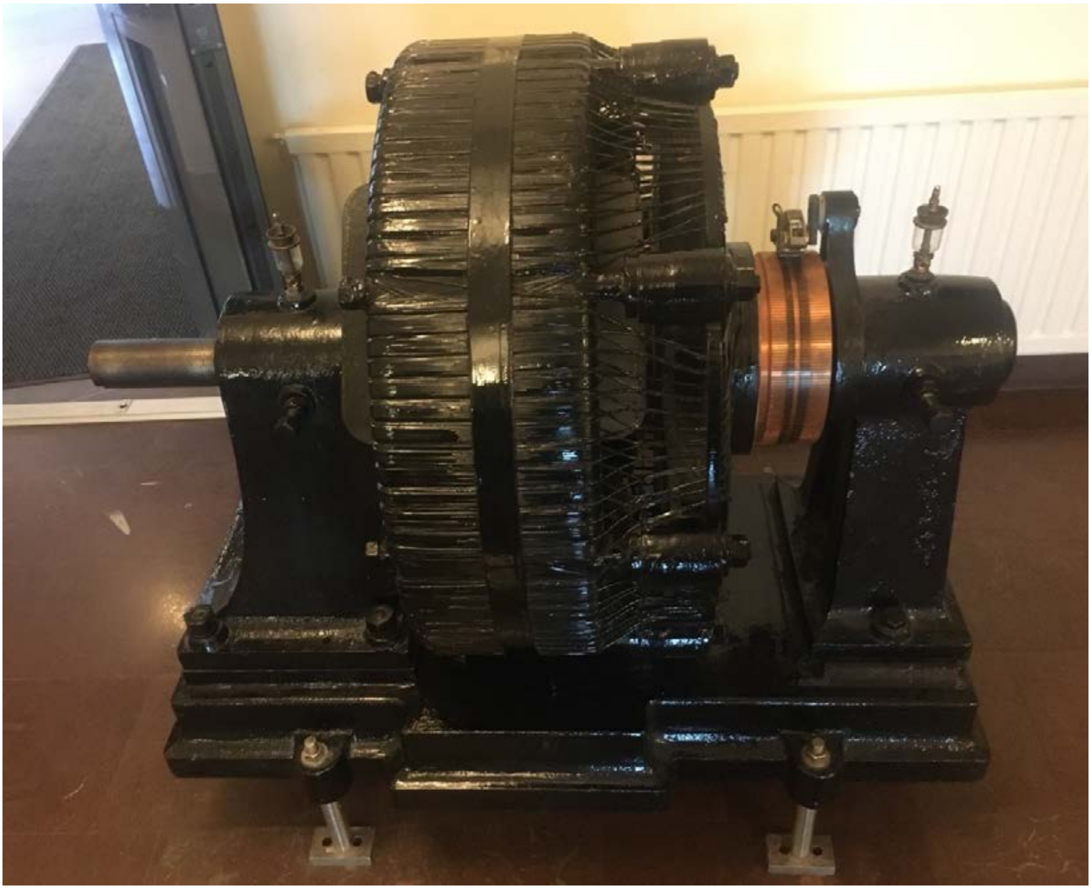
Power transmission with direct current

Tommy Hjort

Low voltage transmissions without converters

The first electric power transmission for motor power in Sweden at all, was carried out in 1889 or 1890 within the area of Nyhammar's mill, about 20 km north of Ludvika, and went from the mill via overhead line to Illmyra mine east of the mill, a distance of 1.3 km. Generator and motor were manufactured at Nyhammar's mill's newly constructed mechanical workshop. The voltage of the transmission has varied with the transmitted power, and at full power (up to 10 kW) and full speed at 600 - 800V. The wire was bare copper on poles with porcelain insulators. The new device meant that the mechanical pumps in the mine could be electrified. At least 14 DC machines according to Darell's design were manufactured at the mill. A direct current machine from the transfer to Illmyra mine was renovated to a working condition in the 1990s and can be found at Hitachi Energy Infocenter, see picture below.

Renovated Darell motor/generator
Foto: Hitachi Energy



High voltage transmissions with converters

Environmental footprint

The driving force for interest into transmissions with high-voltage direct current, HVDC, during the 1950s, was that they wanted to transmit electricity from large hydropower plants in northern Sweden to southern Sweden, where most of the loads were located. It was gradually realized there was not time for the technology to develop fast enough, which is why the technology for 400 kV AC was developed for this purpose. The transmission losses with high-voltage direct current are significantly lower than those for high-voltage alternating current, AC. For DC, only resistive losses occur, while for AC, reactive losses also occur. The difference in transmission losses becomes greater with longer transmission lines. In AC cables, the reactive losses are significantly higher than for overhead lines. Therefore, AC cables longer than 80 km are rare.

Overhead lines for alternating current (AC) give rise to power-frequency magnetic fields, the strength of which decreases with distance from the line. High current in the wire gives stronger magnetic fields than weak current. It has been found that human bodies, which are exposed to strong power-frequency magnetic fields for a long time, can be damaged. Magnetic fields from the overhead line for HVDC have not been found to have a detrimental effect. These magnetic fields are of the same type as the earth magnetic field.

A fairly common size of an HVDC power transmission on land is 3,000 MW. That power can be transmitted at ± 500 kV in whose line right of way is less than half as wide as the equivalent for three AC lines at 400 kV, see Figure 1. Each line at 400 kV AC is capable of transmitting approximately 1,000 MW.

Mercury-Arc Valve Systems LCC

The development of mercury-arc valves for commercial HVDC plants lasted for 25 years, from 1929 to 1954, under the leadership of Uno Lamm. That ASEA's management let it go on for so long was partly due to Uno Lamm's charismatic personality, but also to the fact that in the meantime many low-voltage mercury-arc valves were delivered to mainly tramways as well as to e.g. rolling mills and received money in that way. The mercury-arc valve converters as well as later

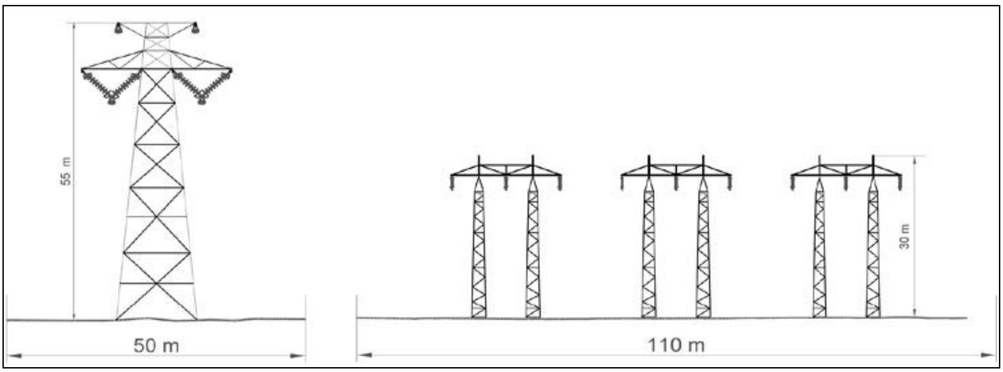


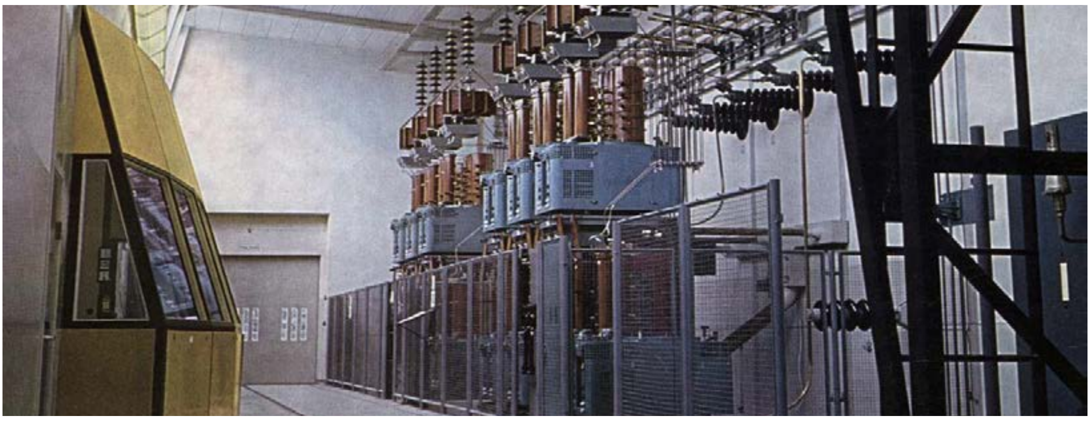
Figure 1: Right of way 3,000 MW @ ±500 kV DC vs 3,000 MW @ 400 kV AC.
Figure: Private

Dr Uno Lamm in Ygne Converter Station, Gotland in 1954
Photo: ASEA, Västmanlands läns museum

thyristor valves were of the type LCC, Line Commutated Converter.

Gotland I was in 1954 the first commercial HVDC transmission in the world, 20 MW @ 100 kV. It ran between the Swedish mainland and Gotland in The Baltic Sea via a cable on the seabed. The return took place through sea water with electrode stations, outside the two shores, which were designed to provide for low field strength.

Sakuma, 300 MW @ 2x125 kV, in Japan was a project around 1965 to connect the parts that had 50 Hz and 60 Hz respectively as grid frequency with a so-called back-to-back station. As it was judged that there was a risk that the technology would be copied,



Mercury-arc valves Gotland I. Foto: Hitachi Energy

Mercury-arc valves Pacific Intertie
Photo: Hitachi Energy

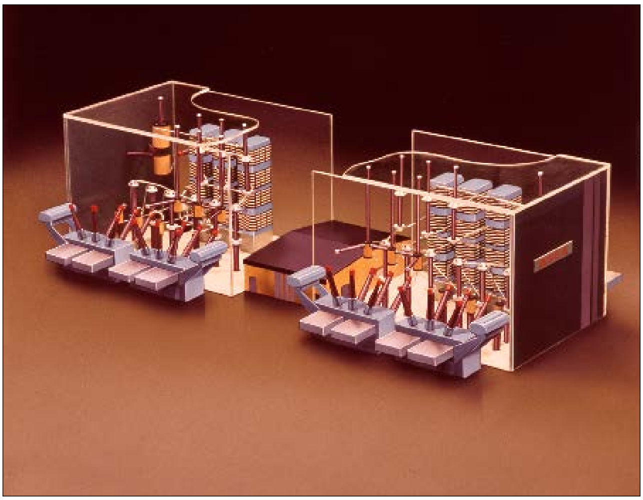
connection with the southern converter station, Sylmar. There, armed people are seen moving around futuristic equipment, which was fenced off. The trained eye perceived it as mercury-arc valves and in one sequence a small red Dala horse could be seen on top of a mercury-arc valve. The stage was the Sylmar station and the mercury-arc valves were those that were taken out of operation for recurring maintenance. After all, Hollywood is only a few kilometers from Sylmar. The investment cost for the link was earned each year for 30 years because there was a big difference in electricity prices between Oregon and California.

ASEA put a very high price in the offer. The order price was slightly lower, but the profit, SEK 60 million, was still enough to pay the development costs for HVDC from 1927 to 1954.

The last mercury-arc valve transmission and at the same time the largest, Pacific Intertie, 1,440 MW @ ± 400 kV, was built in 1971, for the transmission of cheap electric power via overhead line from hydropower plants in Columbia River, Oregon to Los Angeles, CA. Electrically parallel to the HVDC line are AC lines. Because the HVDC transmission control equipment is very fast, the long AC lines can be loaded higher without compromising the stability margin when the HVDC transmission is in operation.
The southern station Sylmar was exposed to an earthquake, magnitude 6.6, on February 9, 1971, which destroyed a lot of equipment. Earthquake-resistant equipment was designed and the station was rebuilt. In the 1980s, at least one so-called action film was shown on American television in

Tyristorventilanläggningar LCC
Even in the last mercury-arc valve systems, phase-phase short-circuits, so-called arcbacks, occurred but rather sparse. The mercury in the valves was a problem for both the external environment and the working environment due to its toxicity. These problems led ASEA to start building test valves with thyristors and test them in existing mercury-arc valve systems in the late 1960s and early 1970s. The commercial 12-pulse valves, which were subsequently developed, were for Skagerrak 1 & 2, 500 MW @ ± 250 kV, Inga Shaba, 560 MW @ ± 500 kV, and CU, 1,000 MW @ ± 400 kV. These were standing valves with forced air cooling. The cooling air was blown into the shaft of the valve stacks and channeled from there out to the thyristor modules at each level. The thyristors were weak. To meet operational

safety requirements, each valve had several additional thyristors installed so that the valves could function even if several thyristors failured. These extra thyristors meant that the total joint voltage drop was higher than optimal and thus resulted in higher than optimal valve losses. The valves had no actual reactors installed to protect the thyristors from current surges. Therefore, in the valve hall there were air-wound reactors in main circuits and the converter transformers were manufactured with otherwise unnecessarily high impedance. This higher impedance resulted in higher than optimal transformer losses. There was electronics in the valves for distribution and amplification of control signals through light guides from earth. That electronics were powered from wind generators at potential. The electronics of each thyristor took their power from the main circuit.
The control device, developed in the early 1970s, which mainly provides an ignition pulse to its thyristor, is able to provide an ignition pulse already on the first flank. This, later moderately modified, control device is still unsurpassed and is used for the largest thyristors.



Air-cooled standing thyristor valves in a bipolar station
Photo: Asea, Västmanlands läns museum

The control and protection equipment included in these 1970s facilities was largely digitized, which resulted in a, for that time, low signal drift. The low signal drift had a direct effect on the maintenance intervals, which could thereby be made relatively attractive.

The Minneapolis Tribune had a theme of industrial design in its Sunday sections in 1978. One Sunday, the valves that ASEA had installed in Station Dickinson of the CU HVDC Project were highlighted as an example of very good industrial design, see the picture above.

When the Itaipu transmission, 6,300 MW @ ± 600 kV, was to be built, ASEA was facing higher voltage and higher current at the same time than ever before. Since no converter transformer had been built before with such a large power and such high simultaneous DC and AC voltages, a prototype transformer was manufactured, that met the requirements. Water cooling of valves was chosen as it is significantly more efficient than air cooling and has been the cooling form for HVDC ever since. To optimize valve hall volumes better, metal-oxide surge arresters were used, which provided better defined air clearances than gap arresters, which was the usual type in the past. The very good cooperation in Ludvika between arrester and HVDC engineers regarding insulation coordination has resulted in relatively smaller valve halls than the competitors' without compromising performance.

In 1984, the Vermont Electric Power Company (Velco) was faced with finding replacement power for its stake in the Vermont Yankee nuclear power

Water-cooled standing valves in 300 kV hall for Itaipu Photo: ASEA, Västmanlands läns museum

plant. Very late, Velco managed to land an attractive power deal with Hydro-Quebec. Since the power grids are not synchronous, an HVDC station was needed. ASEA had one (1) week to tender Highgate Converter Station 200 MW @ 57 kV, with a delivery time of 17 months. ASEA received the order and met the contractual requirements. Neither before nor after has such a station been delivered by anyone in less than 24 months. From quotation to takeover, ASEA's net margin for the project also improved by a few percentage points. Velco, on the other hand, regained the entire investment, including also overhead lines in 8 months. A special feature of Highgate was connection to very weak AC grids, which required binary switching of ten filters/shunt banks on each side featuring ASEA's first 145 kV SF_6 circuit breaker with pre-insertion resistor. The HVDC transformers were ASEA's first of the three-phase/three-winding type. The valves were ASEA's first with large 60 cm^2 thyristors.

ASEA's development of the Mach digital control system in the second half of the 1980s has been said to be the decisive reason why the HVDC business was not moved to Switzerland after the formation of ABB. Mach is a superb system, which is based on having two redundant industrial computers, A and B, to which all kinds of redundant measuring signals from the HVDC station are connected. These signals are then available in the computers and are easily used for many simultaneous functions in control, protection, monitoring, statistics, etc. Both subsystems are "hot" so when the active one falls out for some reason, the other takes over without interruption in the power transmission, but alarms are sent. Of course, the auxiliary power comes from redundant sources.

It was very much thanks to solid marketing efforts with an emphasis on technology by ABB's engineers from Ludvika that China's decision makers realized the excellence of HVDC transmissions. This was followed by orders for several transmissions of 3,000 MW @ ± 500 kV from Three Gorges Dam, several transmissions from various other hydropower plants of 6,400 - 8,000 MW @ ± 800 kV and the transmission Xinjiang – Anhui of 12,000 MW @ ± 1,100 kV, which is the current world record for voltage and power for a power scheme.

IGBT valve systems VSC

VSC, Voltage Source Converter differs from LCC, Line Commutated Converter in such a way that VSC does not need any short-circuit power in connected power grids and thus enables the start of a dead power grid, so-called black start. LCC must have reactive power from connected grids, which VSC can do without. Thus, VSC can operate in all four quadrants of the P/Q diagram in the same way as a synchronous machine while LCC only in quadrants 1 and 2. LCC requires large AC filters to take care of the harmonics formed during commutation in today's 12 pulse valves as in yesterday's 6-pulse valves. Today's VSC valves have a configuration MMC, Modular Multilevel Converter, which means that no harmonics are generated and thus no need for harmonic AC filters. AC filters are however usually installed in VSC systems, but then to take care of harmonics, which are already in the connected network and which emanate from e.g. a large number of smaller industrial converters with insufficient filtration.


Hellsjön Converter Station adjacent to Hellsjön Hydropower Station
Photo: Hitachi Energy

In the next few years after its formation, ABB had an ambition to bring about some development projects, which could be described as bold. One such was to develop HVDC converters of the VSC type. It was important to have a pilot system near Ludvika to simplify testing and possible modifications. In connection with the centennial of the world's first powerful commercial transmission with three-phase alternating current, ABB's project group saw a symbolic value in running direct current with the new technology the same way as three-phase alternating current a century earlier. Gunnar Asplund, Development Manager at ABB HVDC, therefore contacted local utility VB Energi in the spring of 1993. After investigations, it proved possible to take an AC line for 50 kV between Hellsjön Power Station, about 10 km south of Ludvika, and Grängesberg Main Substation out of operation to be used for the pilot system.

In the innovative environment in Ludvika, dedicated knowledgeable engineers backed by competencies at ABB Corporate Research in Västerås and in proactive collaboration with VB Energi were able to carry out the development work of HVDC Light in the short time of 4 years. The work was performed oriented more towards results than procedures. In the spring of 1997, the technology was launched commercially in two seminars in Ludvika, one for the Nordic countries and one for other countries.

During the system tests at the end of 1996, part of the power grid in Grängesberg was run in islanding mode with power supplied from the HVDC link for one hour before phasing in to the regular grid again. During tests of ”black start”, the grid around Hellsjön was made without voltage without notice, a so-called cheat outage, but the HVDC link operation did not start. Two blocking signals were quickly identified due to the cooling equipment lacking power supply. As this was in the period just before Christmas, chores were going on in several kitchens and the outage had to end swiftly. Therefore, two wires were quickly cut off next to the terminal block. The link started immediately and after 6 periods (120 ms) the voltage and frequency were the intended ones.

Another test was to show that the link could be fed from e. g. offshore wind power. Thus, the frequency protection of the hydropower unit, which was solely connected to the link, was deactivated and the unit was run between 48 and 52 Hz. The unit's production was then delivered to Grängesberg at 50 Hz.

Slightly overshadowed by the converters

themselves, the project contained dry plastic cables between the converters and the overhead line. For a long time several concepts for suitable plastic material had been tested for DC cables and the development efforts were now fielded. This resulted in satisfaction. Continued development has lead to HVDC cables for as much as 640 kV are now commercially available. These cables are completely oil-free. Research led by Chalmers Institute of Technology has developed insulating plastic, which seems to enable future HVDC cables for 1 MV.

The magazine Modern Power Systems did not think that Hellsjön HVDC Light was worth writing about, but Transmission & Distribution World Magazine had an article in the September issue of 1997. Let it be said that the data, 3 MW @ ± 10 kV, were very modest, but all functions worked perfectly. At the end of 1999, the first commercial VSC link was put into operation on Gotland with data: 50 MW @ ± 80 kV. At the end of 2020, NordLink came into operation between Norway and Germany with the highest data to date: 1,400 MW @ ± 515 kV. It was the mass-impregnated submarine cables that set the limit for higher data.

Initially, potential customers' interest in VSC technology was weak when only one supplier could offer it. The turning point came when offshore wind farms began to be built. Since around 2015, it is mostly only for very large transmissions that the classic technology, LCC, is chosen.

The first bipolar scheme, where LCC and VSC converters work together, connects Norway and Denmark. One pole is Skagerrak 4, 700 MW @ 500 kV with VSC converter, and the other Skagerrak 3, 440 MW @ 350 kV, with LCC converter. When changing the power direction, the Skagerrak 4 poles in Norway and Denmark need to reverse polarity. That sequence must not take longer than 5 s in order not to jeopardize power grid stability, especially in Jutland. On the DC side, there are therefore high-speed switches for changing the main circuits and discharging the cable for Skagerrak 4. The converter breaker on the AC side is also included in the sequence.

Multi-terminal systems

There are a few multi-terminal systems with LCC converters. VSC converters are much better suited for multi-terminal systems. If these are configured in a meshed HVDC grid, for selective disconnection of faults HVDC circuit breakers (rapid switches + converters + arresters) must be included as well as neutral conductors if unbalanced operation is desired. Such a meshed grid is in operation in China with 4 terminals.

Water-cooled suspended IGBT valves for NordLink
Photo: Hitachi Energy

For radial multi-terminal systems, neutral

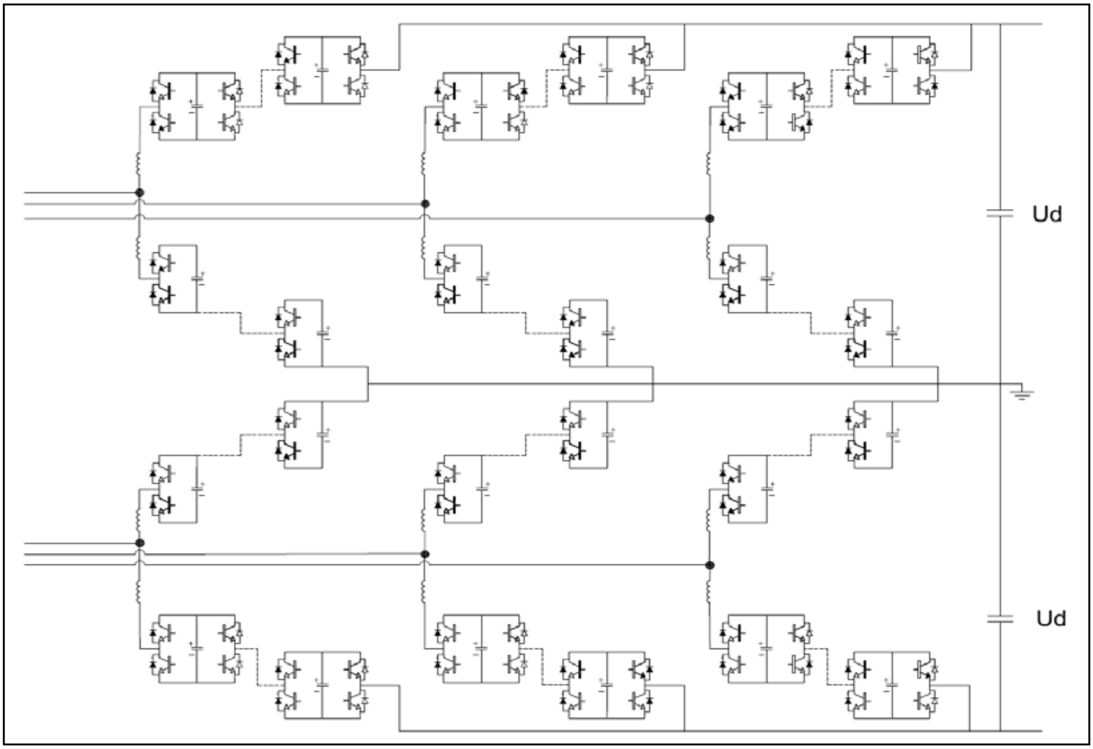


Figure 2: VSC mixed-cell valves
Figure: Private

conductors are not required for balanced operation. Selective disconnection of faults can then be done by blocking fault currents, which is done by using converters in the full-bridge configuration. A study shows that a mixed configuration where the converter half closest to earth is in form of half-bridge can also handle this, see Figure 2.

In all transmission systems, high communication speed between the terminals is desirable. A delay of 20 ms between terminals, as measured between Ertsmyra and Wilster in NordLink, is considered a long time.

In two-terminal systems, the poles of each pole are usually of half-bridge configuration, which results in the lowest valve losses. Valves in full-bridge configuration have almost twice as high losses as valves in configuration half-bridge. Studies have concluded that the combination of full and half bridge, see Figure 2, results in losses approximately in the middle, while such a valve can still block fault currents.

Return current in the sea and in the ground
Salt water is an excellent conductor of electricity. Therefore, early HVDC transmissions, which were often monopolar, used the ocean as return path. For this purpose, electrode stations were made in the sea, but fairly close to each shore. These were designed to achieve low field strengths. Since then, demands for higher power and higher energy availability as well as the precautionary principle applied to the possible impact on nature in the oceans have meant that such transmissions are now usually made bipolar and then no current flows into the sea.

Ground electrodes are now installed for potential bonding of HVDC systems and to conduct current only in the event of a fault and in the event of switching operating modes. Such currents last only for a very short time, which are shorter in time and less in amplitude than currents associated with lightning strikes. During one night in the 1940s, Sweden stood still as not to disturb a full-scale test, which was performed with a ground electrode in Gothenburg and one in Kiruna. Measurements then showed that the current disappeared into the earth's magma already at a short distance from the electrode.

Standing vs suspended valves
HVDC valves have been standing or suspended, but must be able to meet insulation clearances in the valve hall regardless.
The seismic requirements in connection with the Pacific Intertie Upgrading project in 1983 led ASEA to design flexible valves suspended in a frame with springs and dampers. Over the years, such structures have also been used for projects in seismically stable areas.

HVDC market

ASEA/ABB/Hitachi Energy in Sweden has so far had more than 50% of the world market. It is probably the fruit of the fact that Ludvika has been allowed to have an innovative environment, largely founded by the pioneer Uno Lamm. This has meant that Ludvika has been at the absolute forefront of the technology over the years. Siemens Energy in Germany has been the main competitor. Other players today include GE Grid Solutions in France/England, Toshiba in Japan and NR Electric in China. With the so-called electrification to reduce carbon dioxide emissions into the atmosphere, the market will increase significantly.

HVDC development set in perspective

The year 1954 is significant in the world of electric power. The first commercial HVDC transmission, Gotland I, was put into operation in 1954. In the same year, the first nuclear submarine, the USS Nautilus, was put into operation, as was the first commercial nuclear power plant, Obninsk. It seems that significantly more development has taken place since 1954 in the HVDC system than in the nuclear power industry.

In nuclear power, it is still fission technology that applies whether it is a boiling or pressurized water reactor. A lot has happened on safety/security, but almost nothing on the nuclear side. Still only a few percent of the fuel's content is used and the subsequent vapor cycle, Rankine, has a maximum efficiency of less than 40%. During the best year so far, in 2018, Ringhals 4 (8.7 TWh and 1,120 MW) had approximately 7,700 full-load hours, which means that the reactor was out of operation for say 5 - 6 weeks of maintenance that year. It's hardly impressive as such. Then one can add that the reactor in some years is out of operation for a longer period to conduct extensive maintenance of various kinds and that does not improve the picture.

The HVDC industry started with mercury-arc valves, but there the arc-backs and the toxicity of mercury made it look for other solutions. The solution, which saw the light of day in commercial facilities in the mid-1970s, used thyristors, which are not toxic or cause arc-backs. About 20 years later, the step was taken to valves with IGBT transistors. The largest thyristor stations today transmit 12,000 MW @ ± 1,100 kV and the largest IGBT stations can today transmit 4,800 MW @ ± 800 kV if a customer chooses to order. These bipolar plants often have 99.0% energy availability for 100% of rated power and 99.3% energy availability for 50% of rated power. Furthermore, over time, about three (3) forced outages occur per pole and year. Maintenance takes place every two years alternately for each pole with a duration of two working weeks and for the entire bipole every year for less than one working week. Statistics over several decades show clearly better values for availability and reliability for stations where owners, who perform operation and maintenance with their employed staff than those who have contracted staff. The efficiency per station is often better than 99% for two-terminal systems. These above mentioned performances must be considered very impressive. The requirements from HVDC systems have over time also led to equipment for ordinary AC systems being developed into clearly better products.

Tap-changer

Per Krainer

What is a Tap Changer?

Electric power systems consist of different parts with different voltage levels. The factors that affect the voltage levels are above all losses during transport, higher voltage gives lower losses during transmission, in Sweden the corresponding main line has 400,000 V or 400 kV but to be used practically in applications it requires lower voltages which for industry and households are 400/ 230 volts. The connection between the system parts takes place via power transformers, which are simply connected to a high-voltage part and a low-voltage part in an electrical network. Voltage levels depend on the ratio of the transformer, related to the number of winding turns in the primary and secondary windings. To be able to adapt the electrical system to varying operating situations, and to be able to control the power flows, you need to be able to adjust the ratio in the number of winding turns between the high-voltage side and the low-voltage side. This meant that a transformer had to be manufactured with a number of extra winding turns together with a device that can connect or disconnect these control windings, a so-called Tap-changer.

A tap changer can be likened to a gearbox in a car. Its task is to compensate for load variations in the network by changing the ratio between winding turns on the high-respectively low-voltage side. In an electricity network where you feed industries and households, you generally want to ensure that you have as stable voltage level as possible on the low voltage side. If the voltage drops or increases in the power grid, this is compensated by connecting or disconnecting winding turns in the transformer, the transformer ratio changes. This usually takes place mechanically and stepwise between the control windings without the current in the transformer being interrupted and without there being a short circuit between the windings. The tap changer is today a central part of a transmission network. The commercial tap changers used today are available in several different variants but are basically built according to the same principle as just over 100 years ago. Attempts have certainly been made to replace these complicated mechanical machines with power electronics such as IGBTs (Insulated-Gate Bipolar Transistors), thyristors and diodes. These solutions have not yet become commercial products.

Probably the world's first tap changer.

The world's first commercial three-phase AC transmission was put into operation in Sweden in 1893 between Hällsjön and Grängesberg, and the use of electric power then grew rapidly. Until 1910, there were transformers with a specific number of winding turns in the primary and secondary winding and it was possible to do minor regulation of the voltage from the source, the generator. The need for more local regulation came from the three pioneers Otto Stålhane, Assar Grönvall and Axel Lindblad who were driving the development of the world's probably first tap changer, developed in Ludvika. These three pioneers had ended their employment at Förenade Elektriska Aktiebolaget in Ludvika in 1906 and then started the company AB Elektrometall. A collaboration between AB Elektrometall and Förenade Elektriska AB led to a manually regulated tap changer being delivered to Järnkontoret's experimental operations in Trollhättan in 1910. The need was simply to be able to regulate the voltage locally in the transformer and control a melting furnace.

Tap changer development within ASEA and ABB

Tap changers can be divided into different types and each type is divided into different functions. Early in development, it was common to turn off the transformer and then change the winding turns with an of load tap changer (De-energized tap-changer), but as the power grids grew and the energy demand increased, devices were developed that could change voltage during operation, so-called on load tap changers. ASEA became the majority owner of Nya Förenade Elektriska AB in Ludvika in 1916 and thus ASEA is a pioneer in this area. The early tap changers were used for melting furnace transformers. They were equipped with transition resistors to limit the circulating current and avoid short circuits during the time when two taps are connected at the same time. The disconnection of the current took place directly on the taps and the use was limited to small powers. When breaking larger power, the wear on the contacts was considerable due to the arcing.

The continued description is limited to ASEA's and ABB's development work and constructions. The focus is on constructions with separate diverter switch and resistor type selectors

ELEKTROTEKNISK REVY

MEDDELANDEN FRÅN NYA FÖRENADE ELEKTRISKA AKTIEBOLAGET I LUDVIKA.

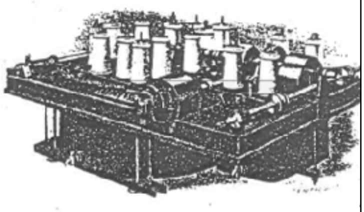
UTGIFVARE: CIVILINGENIÖR R. LITTKE.

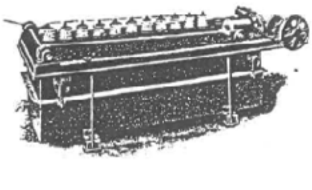
1916 Den 15 April N:R 4

ELEKTRISK UTRUSTNING FÖR SMÄLTUGNAR OCH LIKNANDE.

(Fortsättning från föregående nummer.)

Den vid Järnkontorets försöksverk tillämpade metoden att reglera transformatorernas sekundärström genom omkoppling af högspänningssidans spolar visade sig fungera mycket tillfredsställande och har därför kommit till användning vid alla senare utförda anläggningar. Då det för ugnarnas skötsel är af vikt att spänningen på hvarje elektrodpar afpassas efter de rådande förhållandena utrustas hvarje transformator med sin särskilda regulator. Till sin princip öfverensstämma alla hittills använda apparater med den ofvan beskrifna för försöksverket i Trollhättan, men det konstruktiva utförandet har under senare tid genomlöpt en del utvecklingsstadier. Vid den ursprungliga typen är regulatorn försedd med rund oljelåda fäst vid en gjutjärnsram, hvarå uppmonterats manöveranordning för kontaktarmen, hissanordning för oljelådan och anslutningar för transformatoruttag; sistnämnda äro placerade i cirkel med kontaktarmens axel i centrum. Till uttagen anslutas förbindningarna mellan några af transformatorns mellersta spolar, och är regulatorns anordning sådan, att, då den står i nolläge, de båda mellersta spolarna äro direkt förbundna genom dess kontaktarm. Under dennas rörelse inkopplas i parallell med den ena af ofvannämnda spolar ett lämpligt afpassadt motstånd och därpå träffar kontaktarmen det uttag, som förbinder den af motståndet





Tryckknappsmanövrerad regulator för Söderfors.

kortslutna spolen med den närmast utanför liggande, hvarigenom denna spole sålunda förbikopplas. Vid kontaktarmens fortsatta rörelse brytes motståndets ena förbindning och inkopplas detsamma parallellt med den andra af de mellersta spolarna, hvilken därpå förbikopplas etc. Genom dylik växelvis skeende urkoppling af spolar på ena och andra sidan om midtpunkten varieras spänningen å sekundärsidan vanligen i c:a 8 steg mellan de erforderliga gränserna. I början användes som motstånd vid omkopplingen en drosselspole, men denna har sedermera utbytts mot ett induktionsfritt motstånd, då det visade sig, att spolen alstrade besvärande öfverspänningar. För en under senare tiden färdigställd anläggning (Söderfors Bruk) hafva regulatorerna utförts motordrifna med tryckknappsmanövrering och med brytanordning monterad i särskild oljelåda. Utseendet af denna regulator framgår af kliché härovan. Kontaktarmen påverkas som synes vid denna konstruktion af en elektromotor, hvilken medels en snäckväxel drifver regulatorns långsgående hufvudaxel. Rörelsen hos denna öfverföres dels i likhet med hvad ofvan beskrifvits genom tvänne koniska kugghjul till kontaktarmens drifaxel, dels också genom kamskifvor på ström-

The construction that was developed is described in an early documentation published by MSc Rolf Littke from Ludvika Bruksegare. Littke was already an active board member and secretary of Västerbergslagen Engineering Society in 1922 and came to be active in the society for more than 20 years.

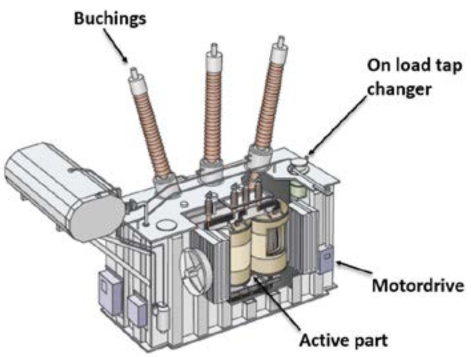
Nomenclature

1. Step voltage: The voltage that is between two taps (regulating windings) in the transformer is normally between about 100 - 5000 volts depending on size, a step between two taps is about ± 0.5 - 2.5% of the transformer ratio. The entire control area is nor - mally between ± 10 - 20% of the trans former ratio.

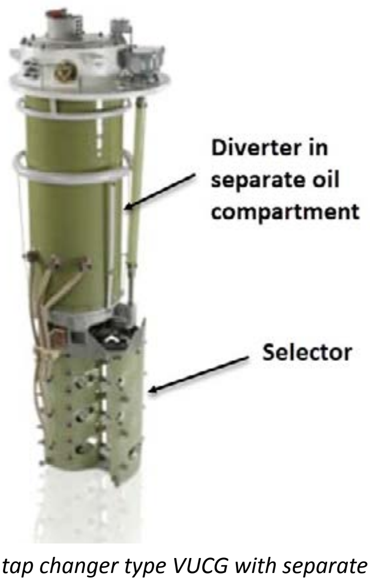
2. OLTC, On-load tap-changer: Tap changer where ratio is changed during load. There are two different types, one where the selection of taps and diverting are separated, and a so-called diverter switch where selection of steps and connection takes place simultaneously and in the same device.
3. De-energized tap-changer: Tap changer where the transformer is turned off before ratio is changed
4. Reactor: A coil with or without an iron core that creates a resistance to alternating current.
5. Resistor: A passive component that creates a resistance to both alternating current and direct current.
6. Preventive auto: Transformer with only one winding (auto) which when connected to two taps prevents short circuit (preventive) in a reactor tap changer.
7. Transformer ratio: The ratio between the number of winding turns on the primary and secondary sides of a transformer.
8. On-tank: Tap changer located on the outside of the transformer tank.
9. In-tank: Tap changer placed inside the transformer tank.
10. Preselector: The mechanism in the tap changer needed for a transformer with function plus / minus and coarse / fine
11. Circulating current: The current that occurs when two adjacent tap windings are connected, it is driven by the step voltage and is limited by switching resistors.

Diverter and selector

The demands for higher power led to the breaking of the current being separated from the selector and a diverter was developed. Due to the degradation of the oil by the arcing, the switching then took place into a separate oil volume which had lower insulation requirements. The diverter was combined with a separate selector which in the de-energized state changed position and then the diverter switched on the new position. The principle can be explained simply by the clutch on a car (diverter) and the gearbox on a car (selector).

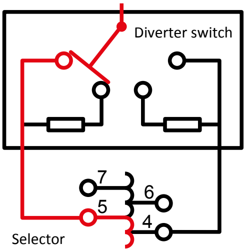


Power transformer with tap changer placed inside the transformer tank. Photo Hitachi Energy

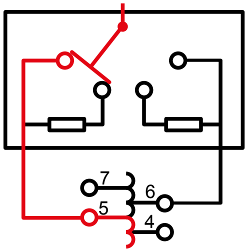


Hitachi tap changer type VUCG with separate diverter and selector, resistor type (in-tank approx. 3 m high and weighing 500-700 kg). Photo Hitachi Energy

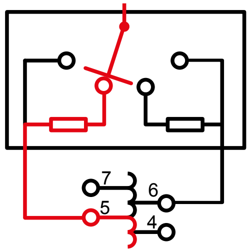
The interaction between diverter and selector is shown in the following figure:



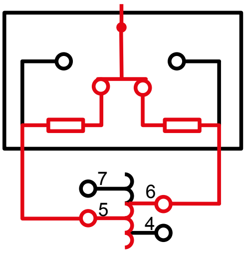
The selector contacted on pos 4 and diverter connected to pos 5.



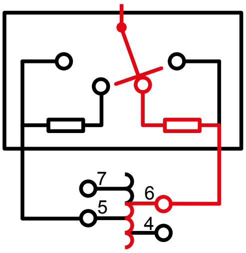
The selector has changed to pos 6 without load.



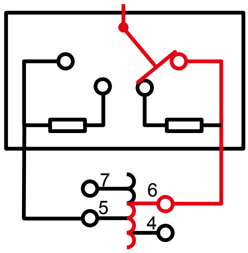
The diverter connects one transition resistor. The resistor is loaded with load current.



The diverter is bridging both resistors and connects pos 6. The load is load current and circulating current.



The diverter disconnects pos 5.



Tap change completed from pos 5 to pos 6.

The sequence when the on-load switch changes sides from picture 2 to picture 6 takes about 0.1 seconds

Reactor tap changer and resistor tap changer

A so-called reactor tap changer was developed early, primarily in the USA, and is largely used only there today. The rest of the tap changers in the world are the so-called ”Jansen” resistor type. The reason is that the resistor tap changer has overall advantages in an electric power grid. The transition from one tap to another takes place digitally and the need not to affect or disturb the network leads to a part of the energy being intermittently relieved via a switching impedance which can be either a resistor or a reactor. The resistor type requires a relatively fast switching while the reactor switch is significantly slower and can also be in the intermediate position without being damaged.

Reactor tap changers are best suited on the low voltage side of the transformer with relatively high currents. The reactor tap changer has some advantages but perhaps the biggest disadvantage is the transient overvoltage’s that occur at higher step voltages when the reactor is switched off, and that it requires peripheral equipment that can be expensive.

Advantages of the reactor tap changer:

- Regulation on the low voltage side gives low step voltages
- High currents, gives high energies in resistances, none at all in a reactor.
- Many steps, default is +/- 16 x0.625%
- Since the reactor tap changer can be in an intermediate position as an operating position, only 8 regulating

windings are needed in the transformer instead of 16 for the resistor type.

Disadvantages of the reactor tap changer:

- Requires a ”preventive auto” on its own core with the effect of 2 steps, costs money
- Not suitable for higher step voltages due to the transient overvoltage’s that occur when disconnecting the reactor.
- Provides continuous circulation currents in the transformer when intermediate positions are used.

Advantages of the resistor tap changer:

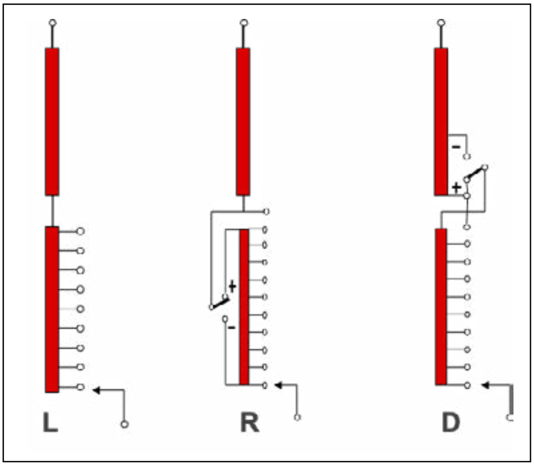
- Gives no transients when switching and can therefore handle high step voltages when operating in oil.
- Can then be placed on the high voltage side which is often the supply side and then gives constant revolution voltage (constant induction).
- Does not require an expensive and space-consuming reactor (preventive auto).
- Circulating current occurs only for parts of a second during switching.

Disadvantages of the resistor coupler:

- Must not stop in the intermediate position and thus need to have stored energy such as a spring for the diverter.

Transformer windings and regulation

The most common types of regulation and thus construction of the transformer are linear, plus / minus and coarse / fine. The choice of regulation is determined based on function and cost. Depending on the type of control, it affects the tap changer. A linear regulation means that the tap changer is ”simpler”, while plus / minus and coarse / fine have more functions.



Different types of transformer windings and regulation

Linear L

- Limited control range approx. 10% of transformer ratio.
- Simpler and thus cheaper design of both the tap-changer and the transformer.
- The type of regulation that has the smallest losses.

Plus / minus R

- Regulating range approx. ± 15% of transformer ratio
- Requires a more advanced tap changer with a preselector.
- The control winding reverse coupling provides more steps but with increased loss.
- May require tie in resistors to be able to controling winding voltage when preselector switching.

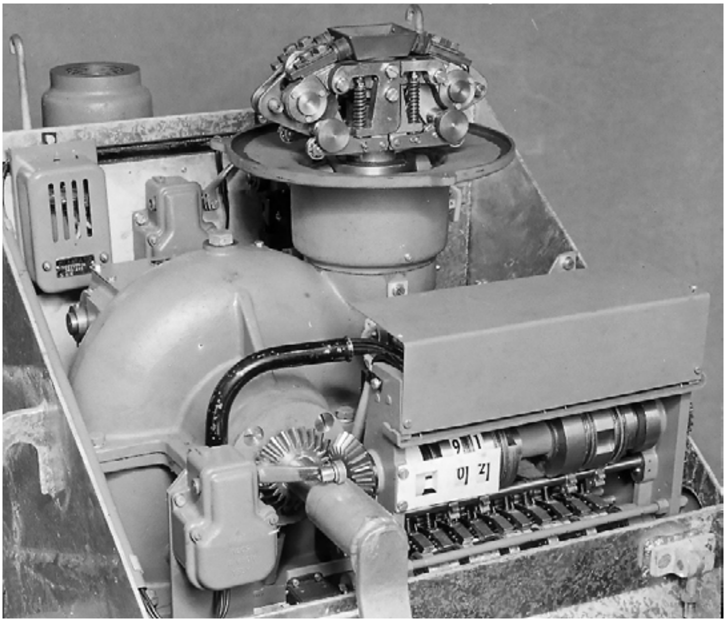
Course / fine D

- Regulating range approx. ± 15% of transformer ratio
- Requires a more advanced tap changer with a preselector.
- Requires an extra “course” winding in the transformer
- Less losses than plus / minus regulation

- Provides more insulation distances and higher values than others and provides higher breaking stresses in the middle position due to inductance between coarse and fine winding.
- May require tie in resistors to be able to controling winding voltage when preselector switching.

Motor drive and function

Before 1927, slow-moving tap changers were delivered, which were manually



Early motor drive with stored energy in flywheel and centrifugal switch. Photo: Hitachi Energy

operated and could be of a so-called eccentric type. Then high-speed variants were developed. The breaking capacity depends to a large extent on the breaking speed. Tap changers with resistance and spring devices of the type called Jansen after a patent taken in 1926 were developed early by MR (Maschinenfabrik Reinhausen). This type of tap changer was developed within ASEA in the 1950s. The selector was available as wiggle type, slide type and cycloid type. For the selector to be able to change position in the de-energized state, there need to be two mechanically equal selector mechanisms, these are alternated every other time. To achieve an alternating sequence, Uno Olsson developed non-round gears whose function was to satisfy the correct sequence. Electric motor drives deliver a smooth motion with a certain number of turns for the selector to change position and the diverter to release the charged spring energy. The early motor drive had stored energy in a flywheel and then the diverter was operated without a spring and with cam drive.

Early motor drivers

When regulating the type that is most common, the resistor tap changer, there is a need for safety in the event of a power failure. Should the drive stop in the middle of a maneuver, there is a risk of the transition resistors overheating, with risk of explosion in the transformer as a consequence. Before the 1950s, ASEA had, among other things, a diverter that was cam controlled. When the selector in the de-energized state moved to a new position and the Diverter switch connected to the new position, the operation needed to be completed. This was solved with a motor drive unit that stored energy in a flywheel. The electric motor drove the flywheel and a centrifugal pendulum via a worm gear. At a specific speed, centrifugal weights engaged in the output shaft and an initial switching was completed independently of the electric motor. During the 1950s, ASEA developed spring-loaded tap changer where the energy was stored in the tensioned springs. A more modern variant is a servo-driven motor drive that is available on the market but has not made an impact as a general product.

Different types of selectors

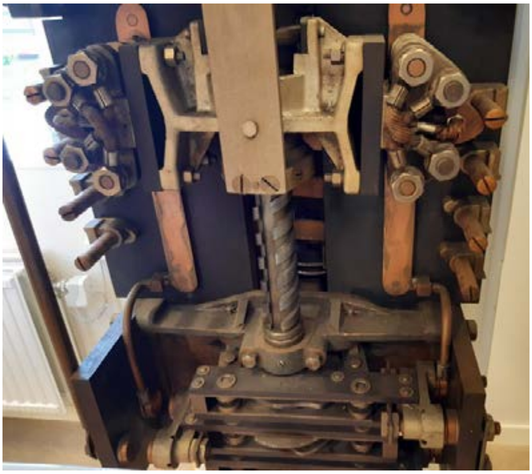
Eccentric selector is an early slow-moving type where the brake of the current was directly in the selector. It could not be used for large power and maintenance was probably frequent. The resistors seen in the picture were for not short-circuiting

A model of an eccentric selector / diverter can be viewed in the office at Hitachi Energy, Components

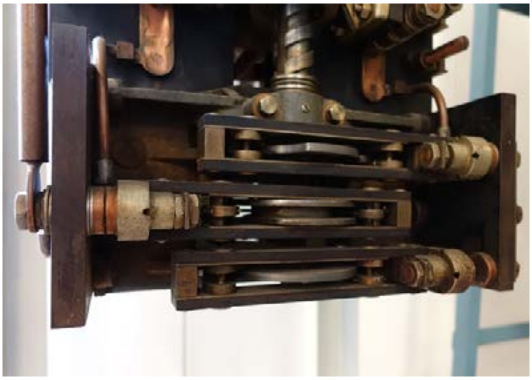
between two windings during switching. There was probably a crackling sound from the transformer when the switching took place due to arcs.

The wiggle type is a linear selector with wiggly movable contact. The associated diverter is cam operated. The construction was available as a standard tap changer in 1927 - 1936.

Cycloid selector, which in ASEA language was called HD, had a cam-controlled diverter. It was manufactured from the mid-1930s to the end of the 1950s. The HD type

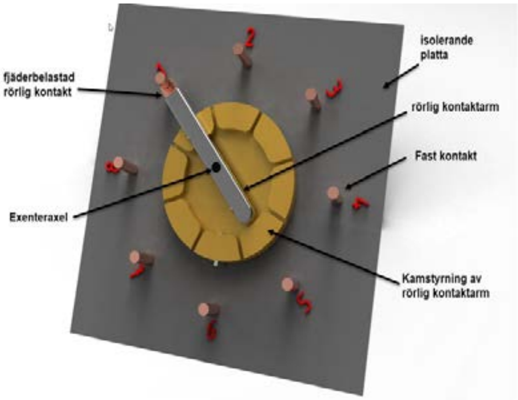


Wiggle-type Selector. Photo: Hitachi Energy



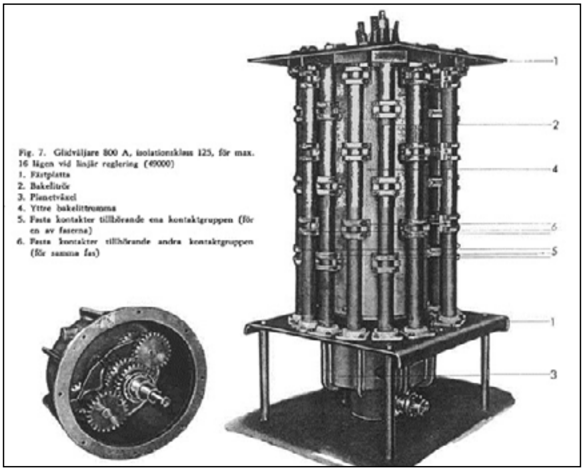
Cam driven diverter for the wiggle-type selector. Photo: Hitachi Energy.

was available in different sizes and had Uno Ohlsson's famous non-round gears. The figure shows the operating principle of a cycloid selector. The fixed contacts 1-8 are connected to the transformer and mounted on an insulating plate. The current flows through the movable contact arm to the diverter. When the input shaft located in the middle rotates one revolution, the movable contact arm performs a cycloid movement thanks to an eccentric mounting of the drive shaft to the contact arm and a cam control of the contact arm.



The operating principle of a cycloid selector.
Photo: Hitachi Energy

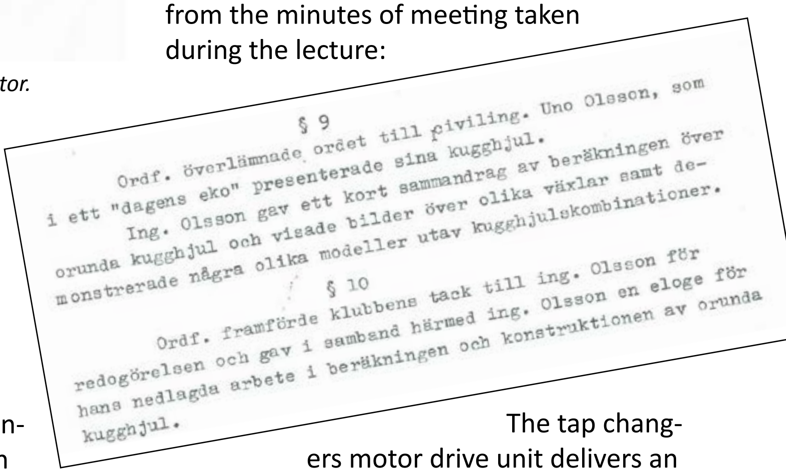
The slide selector is an ASEA product from the 1950s and is suitable for higher voltages and has better short-circuit strength than the cycloid selector. It is located under the diverter and is basically the same basic principle used today. The slider selector contacts are designed to provide high short-circuit strength. When a large current flows over a simple contact point, a force can be created which counteracts the spring force of the contact. In the slide selector, this is avoided by using two parallel-connected, adjacent movable contacts on each side of the fixed contact. In this



Sliding selector with sequential control gearbox.
Photo: Hitachi Energy

arrangement, at high currents, a magnetic attraction is created between the contacts which increases the short-circuit strength.

Uno Ohlsson's non-round gears
On March 25, 1954, ASEA engineer Uno Olsson gave a lecture to members of VBIK, where he described his pioneering non-round gears that were used in the tap changer transmission. Below is an excerpt from the minutes of meeting taken during the lecture:


§ 9

Ordf. överlämnade ordet till civiling. Uno Olsson, som i ett "dagens eko" presenterade sina kugghjul.

Ing. Olsson gav ett kort sammandrag av beräkningen över orunda kugghjul och visade bilder över olika växlar samt demonstrerade några olika modeller utav kugghjulskombinationer.

§ 10

Ordf. framförde klubbens tack till ing. Olsson för redogörelsen och gav i samband härmed ing. Olsson en eloge för hans nedlagda arbete i beräkningen och konstruktionen av orunda kugghjul.

The tap changers motor drive unit delivers an even number of revolutions during operation, while the selector needs a stepwise positioning. To achieve a sequential movement, Uno Olsson created non-round gears that achieve a varying gear ratio and thus different speeds on the output shaft. Today, these non-round gears are replaced by geneva drives that perform the same function but take up less space and are easier to manufacture.

There was also an earlier variant of gear that performed a sequential function. The segment gear was replaced in the 1940s with Uno Olsson's non-round gears. Probably the construction with sequence gears had a relatively large wear and risked getting stuck.

Geneva driven selectors and tap changer
Geneva drives operation is still the most common solution to sequential operation today. ASEA introduced geneva drive in 1963, one of these was the so-called UC

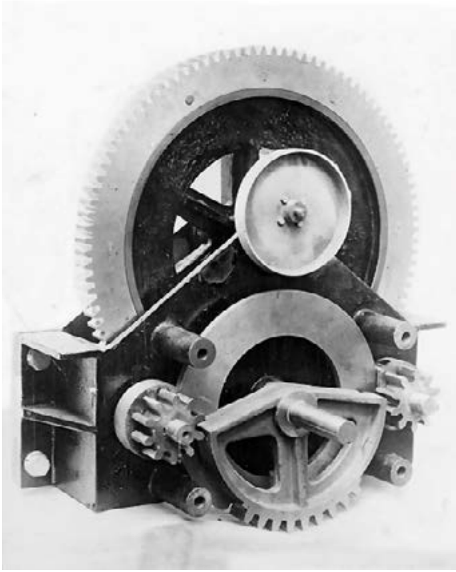
Gearbox with non-round gears for operation of selector and pre-selector. Photo: Hitachi Energy

which was a spring-operated diverter with cylindrical slide selector and geneva drive. Delivered as a standard tap changer and is still available today. Geneva driven operation has the advantage that it is relatively

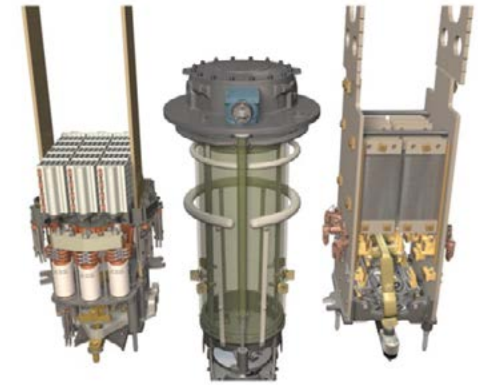
Geneva drive that can sequentially position 36, 72 and / or 54 degrees. Two drive pins on the geneva gear and with different geometric grooves in the geneva wheel create flexibility. Developed as a test prototype by ABB

easy to manufacture. It can be manufactured in several variants and enables great flexibility in terms of angles and positions. In addition, this type of drive has relatively small installation dimensions.

Modern tap changers with vacuum switch

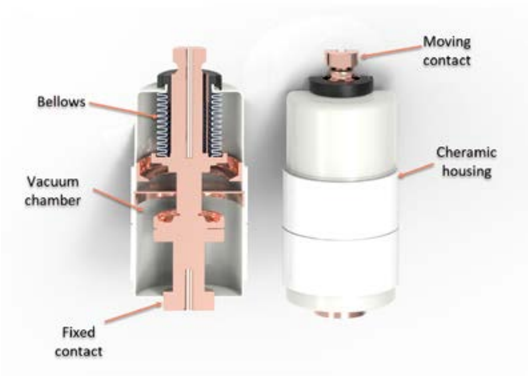


Gearbox with segment gears.
Photo: Hitachi Energy



Vacuum diverter on the left and former conventional load coupler on the right fit in the same housing (in-tank). Image from Hitachi Energy

technology and geneva drive
Vacuum breakers came to be evaluated during the 1970s by both ASEA and the BBC, as evidenced by early filed patents from both companies. It became a commercial product at ABB as resistive tap changers in the 2000s. All previous diverters had broken the current directly in the oil and the result was that the oil was degraded. The need for less maintenance affected the development of tap changers with vacuum interrupters.



Vacuum bottle for diverter in tap changer. Length about 15 cm

A vacuum bottle is a closed bottle with extremely low pressure, almost complete vacuum, which provides very high breaking capacity and low contact wear. It is used both as a switch and shutter. The vacuum breaker has the advantage that it can create a so-called diffuse arc when breaking, even at currents that are normally the case in the tap-changer application. A diffuse arc spreads over the entire contact surface when it breaks the current, in addition, the plasma creates a cloud that condenses evenly over the cathode surface, which can be compared to breaking in oil where particles spread out in the oil. This leads to less electrical erosion. The vacuum interrupter has a longer service life than conventional contacts that breaks in oil.

Final comment

A tap changer is primarily an electrical device that unfortunately needs complicated mechanics. This has activated the brain of many engineers for more than a century. The solutions that have emerged and been implemented are and have been undeniably unique. For a mechanic, it is a challenge to consider invisible electric fields and to force mechanical movements into the transformer's electric insulating oil, which lubricates as well as a barrel of beer. *(Tribological FZG test shows that during some circumstances transformer oil has almost the same lubricating properties as beer).*

It is indeed a product where you are forced to make compromises between different areas of technology to come up with an optimal solution, what is good from a purely mechanical and purely manufacturing perspective can be purely reprehensible from an electrical perspective, everything requires close cooperation and usually called optimization.

Many thanks to Gunnar Andersson Hitachi Energy.

Sweden's first experimental reactor for fusion energy

Åke Classon

On a February day in 1958, the two Uppsala professors Kai Siegbahn and Per Ohlin arrived at ASEA's high voltage laboratory in Ludvika. They wanted help building a plant to experiment with fusion of heavy hydrogen atoms into helium. From the ASEA management in Västerås, they had already received the green light, that ASEA would provide the necessary equipment and personnel. The most appropriate body to handle the case had been found to be the "Group for test equipment", i e myself + assistants. Laboratory director Nils Hylten-Cavallius and the laboratory's best physicist and calculator Hans Witt participated, when the professors began to tell what they wanted. They wanted a plasma of heavy hydrogen, trapped in a magnetic field of "about 10 Tesla" and heated to a temperature of about 100 million degrees.

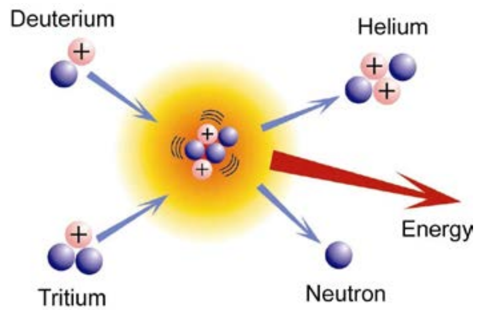


Fig. 1 Fusion of two heavy hydrogen nuclei to helium, releasing energy (Wikipedia) In the fusion reasoning of the time, the term "heavy" hydrogen always applied = hydrogen isotope deuterium with an extra neutron in the atomic nucleus. In nature, it makes up about = 0.1 per thousand of all hydrogen in its many compounds. Even in the human body. The isotope tritium with two extra neutrons is extremely short-lived and does not occur in nature. It was therefore only about 30 years after the Uppsala experiment that attempts were made to split tritium from the metal lithium during the ongoing fusion process.

Then the merger would start by itself. According to available calculations and assessments, it should be possible to achieve the desired temperature if an electric current of about 3 million Amps was driven through a plasma string with a diameter of 5 to 7 mm. The state should be able to be kept constant for at least 1 millisecond to get the fusion to a measurable extent. The Uppsala team wanted to transfer other "details" to ASEA. We agreed that the already known toroidal Tokamak reactor type was most suitable to invest in.

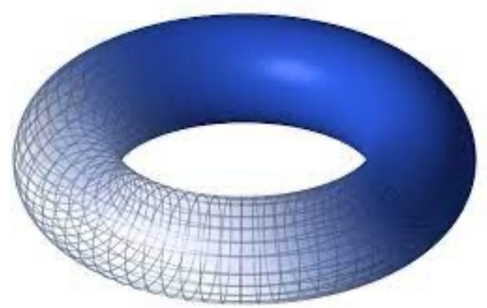


Fig 2 Toroid

In ASEA, we had a hard time imagining any better material for the reactor vessel than steatite (porcelain for high-voltage insulators). It is both mechanically strong, electrically insulating, non-magnetic, vacuum-tight and neutral against neutron radiation, all according to set requirements.

Then came the question of dimensioning. After a lot of discussion, I got a sheet from a so-called Notes pad, which Per Ohlin had in his chest pocket. On it he drew two concentric circles, which thus showed the toroidal reactor vessel, seen from above.

The average diameter was approximately estimated to 2 m after some discussion. The cross-sectional diameter was allowed to be 0.5 m. Other ”details” the professors left to ASEA personnel to design.
In conclusion, an unconditional directive from the Västerås management clarified that the entire future development and construction work with the facility must be kept completely secret from everyone outside the project group. It was important to get ahead of all competitors, who were rumored to be on similar lines. We knew that in the United States they were on the way and possibly also in Russia. As a cover for the entire business, it was decided that we officially worked with bending of coarse Al-pipes with strong magnetic fields.

For several years I myself had a burning interest in all such things, which later came to be called astrophysics. Therefore, this mission came as a godsend from above. But it was now important to recruit more people with interest and knowledge in the same area. The working group eventually grew, mostly with staff from the laboratory. From the Västerås management, we were authorized to place unlimited orders for equipment and processing with priority right throughout ASEA and with external suppliers.

Principle structure
A toroidal reactor vessel of steatite surrounded by concentrated magnetic windings with a maximum number of ampere revolutions within the available space forms a magnetic field which concentrates the plasma to a channel in the center of the toroidal tube. The plasma can then be heated to the required 100 million degrees without coming into contact with and being cooled by the steatite walls. The desired current of 3 million A in the entrapped hydrogen plasma is transformed via another magnetic field along the major axis of the toroid from winding turns on either side of the reactor vessel.

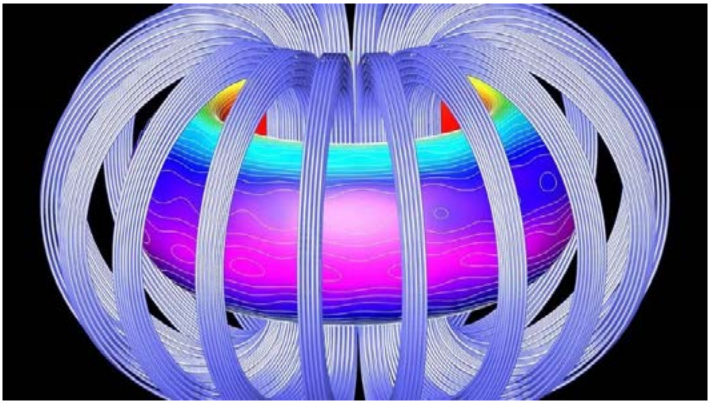


Fig 3 Magnets around the toroid hold the plasma in place. (Wikipedia)

The energy for magnetic fields and plasma heating was intended to be supplied by a very large capacitor. About 1000 of ASEA’s largest mass-produced units, which were used for series capacitors in the 400 kV network, were considered to be able to emit the necessary 3 MA * 1 msec = 3,000 As, if they were charged to a maximum of 35 kV. Disc-wound coils from the transformer workshop were found to provide optimally compact magnetic fields inside the toroid, if they were packed tightly around the outside of the steatite vessel. In order to cope with the very large mutual current forces between the coil disks, it was necessary to fix them symmetrically and evenly distributed around the circumference.

Quartz-filled epoxy (commonly called Araldite) had just begun to be used within ASEA. The material seemed perfect for stabilizing our coils. The spool discs were cast into 80 wedge-shaped ”cake pieces”, which together with an empty extra wedge filled the entire circumference. Uppsala wanted the extra wedge to get into an approximately 4 cm large opening in the steatite toroid side. The dimensions were adjusted so that the coils with carefully planed side surfaces could be packed together completely flawlessly. Calculations and tests showed that this was absolutely necessary to cope with the large currents.

The floor plan for the entire reactor set-up was that the capacitors were divided into 40 surge current generators with 24 capacitors in each. The generators were placed in two concentric circle segments with 20 generators in each. From each generator, a large coaxial conductor was connected to the centrally located reactor toroid with the magnetic coils. There, each generator was connected to 2 series-connected magnetic coils via 2 series-connected winding turns, located above and below the toroid, respectively, and which were intended to transform over the current to the plasma. With these 80 primary revolutions in total, each generator needed to deliver close to 40 kA to induce the desired 3 MA in the secondary plasma revolution.

Each generator circuit was tuned with

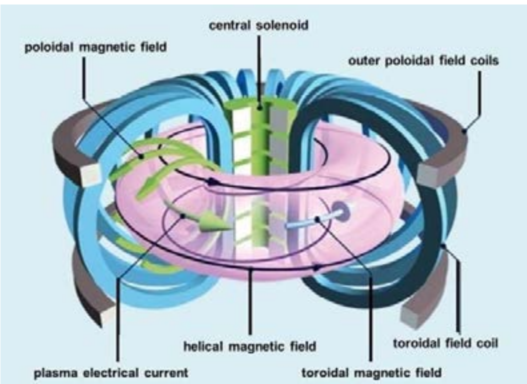


Fig. 4 Current is transformed into the toroid from coils above and below it, outer polodial field coils (Wikipedia)

capacitance, inductance and resistance to provide a damped sine wave with just over 1 msec half-life. After charging to 35 kV, the discharge was started through a spark gap with 2 hemispherical graphite electrodes (”borrowed” from the series capacitors in the 400 kV network). The 40 circuits were not galvanically connected, but the coils were tightly coupled with the mutual inductance through the strong common magnetic field. This gave a welcome good synchronization of all 40 generators and thus a fully acceptable balance for mechanical stresses due to the magnetic forces. That is, if all generators turned on at the same time!
If, on the other hand, one or more circuits were to miss in the ignition, these were blocked by induced counter-EMF in ”their” coils, until the main magnetic field passed through the 0 point and turned direction. The consequence should then be that induced EMF was added to the charging voltage in the missing circuits and forced a discharge in reverse phase to the main field. Thus, strong repulsive magnetic forces could demolish the entire reactor structure. To safeguard against such a catastrophe, two measures were taken:

1. A 90 kV surge voltage generator was inserted to ignite all 40 spark gaps completely synchronously with a fast pulse on an additional ignition electrode between the two graphite electrodes.

2. The reactor vessel with the epoxy-molded magnetic coils and surface-mounted transformer windings must be encapsulated in a mechanically strong, supporting shell of electrically insulating and non-magnetic material. The outer diameter was estimated to be about 3 m and the height close to 1 m. The epoxy technology at the time

could not handle such large units. Concrete must be strongly reinforced to withstand the tensile stresses. After a lot of discussion, we stuck to wood. The problem, of course, was where to find such large pieces of wood. ASEA's model carpentry solved the problem. They happened to have a batch of well-dried timber in their store. They undertook to cut a large number of circular arc-shaped brackets with increasing diameters, which could then be glued together into two identical, compact cylinders. Between these, the reactor with coils and windings could then be encapsulated in carefully adapted cavity. The two housing halves were tightened together with a strong brass bolt in the center + 20 slightly softer bolts distributed around the circumference.

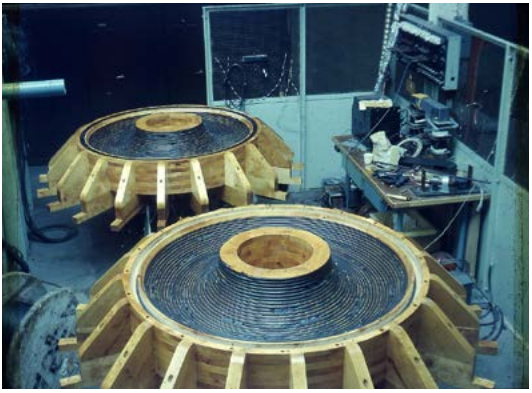


Fig. 5 External two-part wooden construction, "wooden cheese", for encapsulating the reactor vessel. The transformer windings are embedded in the wooden cheeses.

Manufacture of components

I hastily outlined the ideas that emerged on a paper, which was presented to the Uppsala professors together with Witt's calculations. After a brief review, it was decided that the outlined proposal would be processed as soon as possible into finished design documents, so that the necessary orders could be given to the suppliers. To my prompt question about the desired delivery time, the answer came: "Well, preferably no more than a month" !!!!! I tried to explain that the wish was completely unreasonable. My estimate was a minimum of 6 months! It was declared unacceptable. My boss Hylten-Cavallius came to a compromise with, that with continued support from the ASEA management, we would do our very best to deliver our parts within 6 months.

Our ceramics-savvy colleagues at the IFÖ plants in Bromölla became concerned when they received our drawings of 4 segments for a reactor toroid in steatite. The end surfaces of the segments were to be grounded so that they could be fitted together with such a precise fit that they formed a completely tight toroid which, after vacuum pumping, was held together by the external air pressure. The small diameter of the toroidal ring must fit with a few mm clearance against our epoxy cast magnetic coils. In invoking the ASEA management's right of priority, IFÖ started immediately with the first attempts. After a week or so, the IFÖ men were even more worried. The quartz steroids were severely deformed during molding, handling and burning. After two months, they were ready to throw in the towel. The situation was desperate. But already at the first negative signals from IFÖ, we had sent the drawings to NGK in Japan with a cautious request, if they considered themselves able to manufacture the 4 toroidal parts. We heard nothing in 3 months from NGK. IFÖ had then definitely given up. All other production was in full swing. But without reactor vessels with the right dimensions, we were set. Then came a telex from NGK. They only wanted to know how urgent the delivery was. Was sea transport enough, or were we prepared to pay for air freight? The production was not

commented on at all but had apparently led to a fully successful result.
The gluing of the two large ”wooden cheeses” for the reactor enclosure went according to plan. For processing, an ancient wooden lathe with a height of 1.5 m had been excavated from the hiding places at the model workshop. After extensive reconnaissance work, an old pensioner was also found, who could still handle such a machine. After a few weeks, he had managed to turn both ”cheeses” externally cylindrical. Inside they were bowl-shaped hollowed out for the reactor vessel with the magnetic coils and with 40 grooves in each for the cables to the transformer windings.

Final assembly and test drive in Uppsala
As the components were completed, they were transported down for assembly in the hall of 15 times 30 m in the Physics basement of Uppsala University.

Fig. 6 Uppsala University, Department of Physics

To our great relief, NGK’s steatite toroid turned out to fit perfectly inside the magnetic coils. These in turn were softly embedded by the insulation of the transformer windings, when we put the lid on and tightened the two ”wooden cheeses” with all the brass bolts. Thus, we thought we had built the reactor part itself as far as possible secured against explosion and personal danger. Admittedly, no one believed in such a success, that fusion energy could be dangerous. But according to Hans Witt’s calculations, asymmetry in the magnetic fields could be feared to lead to uncontrollable forces, which in the worst case threw heavy explosive fragments at high speeds around the hall. Exterior walls and floors consisted of reinforced concrete, so there was no danger to the surroundings. But the control room was housed in a small scrub behind two thin lightweight concrete walls. For safety, these were reinforced with a total of three layers of stacked sandbags. Inside this shatter protection, we felt completely safe and could control the entire facility from a control table.

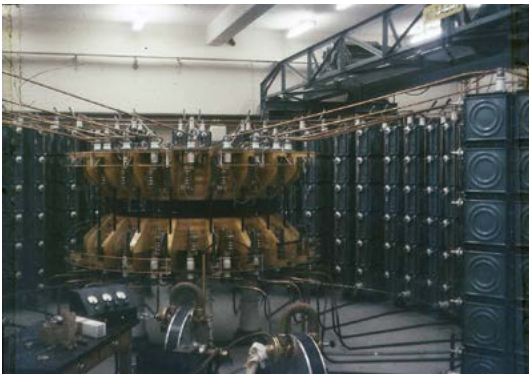


Fig. 7 Generators in the form of shock absorbers and reactor pre-assembled

All 40 graphite spark gaps were fixedly tuned for a controlled ignition at 35 kV charging voltage on the capacitors to avoid the above-feared risks in the event of non-simultaneous ignition in individual gaps.

For safety, we started by charging and discharging a surge generator. After a successful debut, we dared to charge and fire all 40 generators in parallel for a first test with full magnetic fields. The steatite toroid was then provisionally vacuum pumped before, so that its 4 sections were held together by the external air pressure. Everything went according to plan.

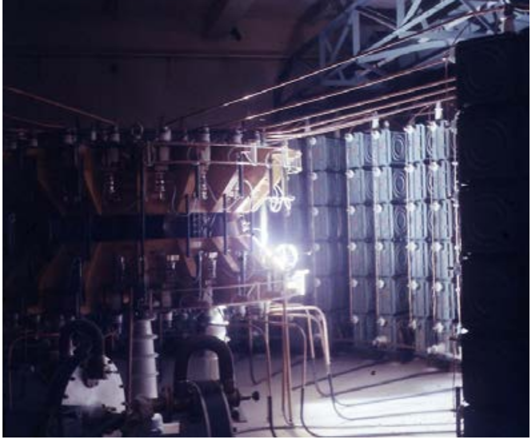


Fig. 8 Discharge of a surge generator

An inevitable condition for successful fusion was that all air and other foreign gases were removed from the reactor vessel before the heavy hydrogen was let in. Rough pumping down to the ordinary workshop vacuum was done with an ordinary mercury pump. But to get the last gas residues out, a workshop on the floor above the reactor hall prepared special molecular pumps. They consisted of a strong plate of special steel with a diameter of about 0.7 m. It was carefully planed and fitted with a super fine fit between the encapsulated steel walls of the enclosure. The disc was pulled with an electric motor up in rotation at about 30,000 rpm. The mercury pump was connected to an opening in the housing at the periphery of the disc. From another opening in the housing near the center of the disc, a coarse tube led in through the recess between the magnetic coils to the 40-mm hole in the steatite vessel. A mass spectrograph, specially purchased from England, was also connected to the same pipe. The idea was that when the mercury pump had removed most of the air from the steatite toroid, the heat movements of the remaining gas molecules would sooner or later randomly slip into the pump tube. At the other end of the tube, each individual molecule hit the rapidly rotating steel plate, which gave it a push into the narrow gap against the steel enclosure. There it was further forced by friction and centrifugal force, until it was caught by the mercury pump. This took its time, before the last gas molecules in this way slipped out of the reactor vessel. Only after 3 days of uninterrupted pumping could we come down to a vacuum acceptable to physicists. Happily enough, we were confirmed in that situation that the Japanese at NGK managed to grind the end surfaces of the toroidal parts so perfectly that the steatite vessel was completely vacuum-tight. But there were worries of a completely different kind. The rapidly rotating steel plate was an extremely stable gyroscope. With heavy storage of the horizontal shaft, the disc could still be forced into the earth rotation at 1 revolution / day, without the disc coming into contact with the enclosure. No one had counted on the street traffic! Heavy trucks occasionally thundered past on a nearby street. They were heard as a faint rumble through the concrete walls of the basement. Of course, the light vibrations could not affect the steel plate with its powerful gyro stabilization. But the enclosure, which was bolted to the concrete floor, was disturbed enough, despite its considerable mass, to bridge the extremely narrow gap against the board. The high rotational energy gave an instantaneous friction welding in the contact surface. Luckily, the workshop on the floor above had two more pumps in progress, and after a couple of days we were able to start pumping again. It did not take many hours before the new pump also broke down. Then followed a few weeks of repeated pump failures, while the workshop worked in three shifts to renovate the demolished pumps. Finally, the problem was solved by hanging the pump housing in vibration-damping material, so that the disturbances could be avoided. And with that, we were finally able to get a stable vacuum, so that a small splash of heavy hydrogen could be let into the reactor vessel, and the big moment for the very first attempts of fusion to helium was on.

Commissioning of the complete facility
The heavy hydrogen gas was first ionized with an electric field. When the entire generator power was then released, the gas was sufficiently electrically conductive to start an induced current through it. Thus, it was transformed into a plasma, which was concentrated by the magnetic field into a narrow strand along the center line of the reactor vessel. The thin plasma strand could also be photographed via the tube to the spectrograph, thus confirming that the entire plant functioned as planned. At least the outer parts of the plasma were hot enough to glow with blue and white light. But then there was only the spectrograph to determine if internal plasma parts had reached the desired temperature of 100 million degrees. Because in that state no visible light was emitted.

But with these results, I and the rest of the ASEA gang had fulfilled our real mission. All that remained was to tune in Fysikum's own staff, so that they could take over the continued operation of the facility. Then also came what we were most worried about. During the attempts to squeeze as much as possible out of the plant, an uncontrolled ignition occurred. In addition to the usual sharp bang from the spark gap and the muffled thumping sound from the setting in the magnetic coils, there was a loud crashing sound. Something had broken! Fortunately, the wooden enclosure had stood upright and captured all the tearing forces. After careful examination, it was clear that only 2 of the 80 magnetic coils had been demolished. It took a few days of work to demolish the entire reactor vessel, change to new spare coils and assemble for control and continued operation with full power. But now we did not dare to push the margins anymore. At least during the time I stayed, unfortunately no long-awaited lines from newly formed helium could be detec-

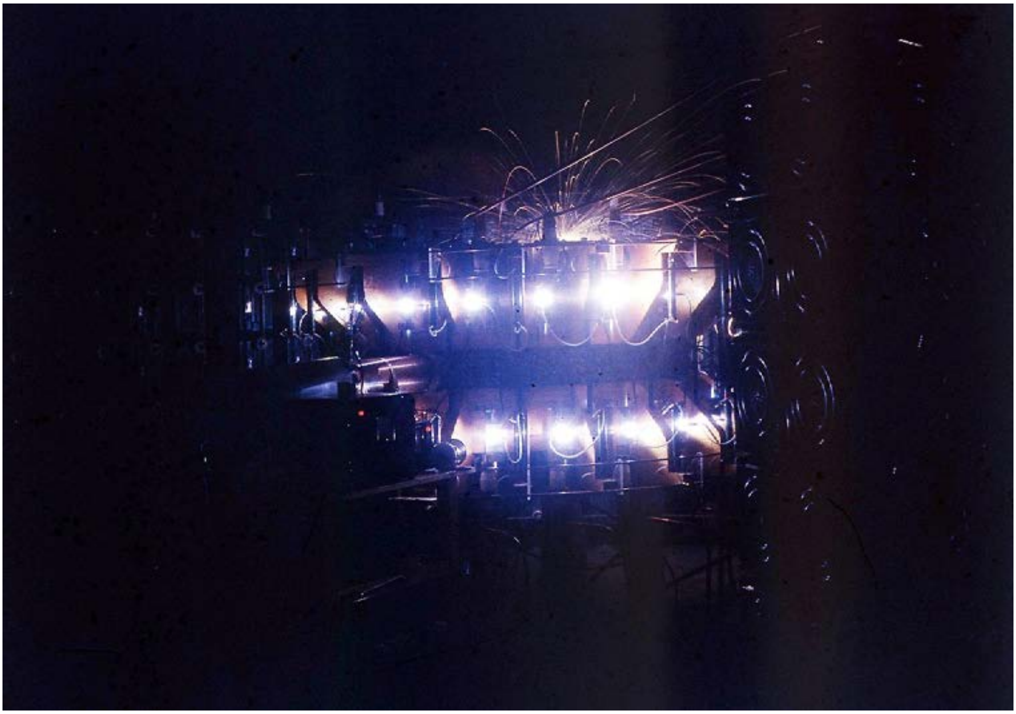


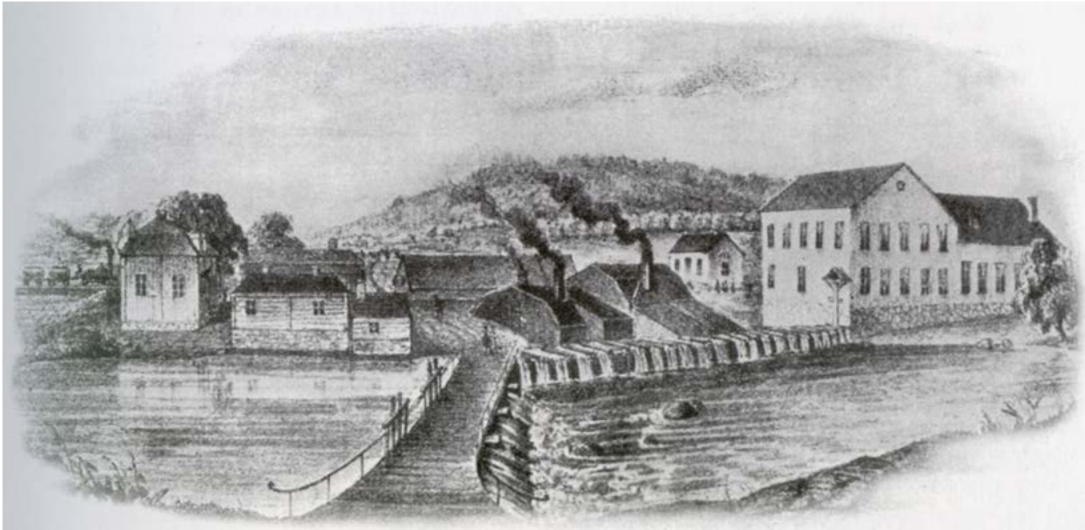
Fig. 9 Ignition of all generators

ted with the spectrograph. And there were no gratifying positive news from the intense runs of the following weeks either. The two Uppsala professors were extremely anxious to reach positive results to be presented before an international conference meeting in Geneva later in the autumn of 1958. There was some consolation at the Geneva meeting, as neither of the other participants, especially the Americans, had succeeded in detecting any fusion in their corresponding experimental facilities. Recent experience indicates that the heavy hydrogen plasma has significantly better conductivity than previously known.
The Swedish researcher Hannes Alfven who was an active opponent of nuclear energy in the form built in Sweden during the 1970s and 1980s, instead recommended the use of nuclear energy in the form of fusion. Today's nuclear power plants are powered by heat that is released when a uranium atom decomposes into plutonium and heat is formed during decay. This process is called fission.

Hannes Alfven received the Nobel Prize in Physics in 1970 for his discoveries of the so-called Alfven wave, which opened up a new field of research, magnetohydrodynamics, some of which is plasma physics. Alfven mapped the magnetohydrodynamic forces that control a plasma that conducts current. An equivalent magnetic moment causes the electric charge to move in a spiral in the magnetic field. Alfven's theory is fundamental to understanding the motion of plasma in a fusion reactor.

An industrial story without a really good ending

Jan-Olov Schröder



Today no one can deny that the description in the title, which is allowed to begin the chapter on Morgårdshammars AB, is in all its simplicity correct. Morgårdshammar has an absolutely fantastic history from a Swedish horizon behind it. The company is still a respected name that is mentioned with the greatest respect around the world.

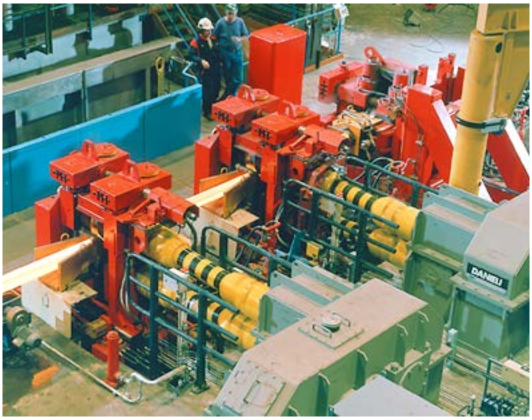
Two products overshadow everything else in the company's current existence in 166 years. Ernst von Zweigbergk's universal rolling mill in the 1870s and Erik Norlindh's two unique world - class patents, the housingless rolling stand and above all the roller guide. These innovations from Morgårdshammar were and are the Rolls Royce of the rolling mill industry.

From the start in 1856 and 120 years onwards, Morgårdshammar has in principle been lined with successes, characterized by visions and determination that have quickly responded not only locally in Sweden but even more globally, far beyond the country's borders.

Then we talk about the time up to around 1975. It was then, when the steel crisis hit all over the world, that the dramatic turn came for Morgårdshammar. Other industries in iron production and related industries were also affected. A little cautious at first, then accelerating. For most, liquidity problems and, of course, declining demand were common.

It was now wise decisions and previous visions were put to the test. We will never get answers to many questions about what happened to Morgårdshammar. What would have happened if the company management had done differently? Was it so wise to sell the company to Anders Wall and his Beijerinvest in 1975? One thing is for sure, that deal was completed in a very high speed.

A disappointment for the people who were close to Morgårdshammar was the fact that an important tradition was broken here. Un-

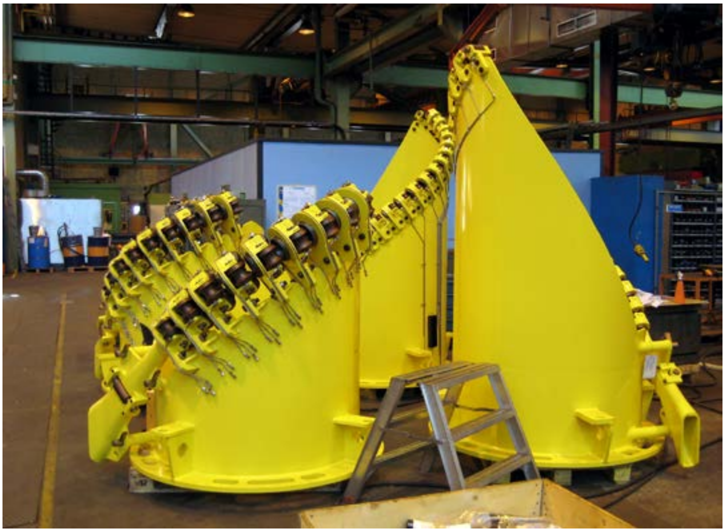


Rolling stand Garrett P-635 continued to be developed. In 1965 the pre stands roughing mill with three rolling stands and new success for MH

til now, the company had been family-owned almost all the time. With Anders Wall, it became a completely new set-up.

It was also negative that everyone in the management did not consist of people with a background from the mining industry and its special skills. Nor did people with a local connection to the area. Both elements were undoubtedly a major contributing factor to Morgårdshammar's success for over a hundred years.
It became even more strange when Volvo and Pehr G. Gyllenhammar in 1983 became the new owners of the traditional Morgårdshammar AB. A significant trend at this time was that large industrial groups were happy to see the business diversified and get more legs to stand on. Volvo was in that type of turn-around. After some strange moves, Morgårdshammar suddenly had owners who sold both cars and food.

Refining was the driving force in 1856
When the company was founded in 1856 as Morgårdshammar's Mechanical Workshop, iron ore and other metals had become Sweden's backbone. Bergslagen quickly became a kind of Klondike, mines with deposits were soon everywhere and iron became gold for the industry.
The blast furnaces received the iron that was delivered to the industry. Many miners who ran the funaces became wealthy. A lot of the iron and steel went to the war industries, but mostly to building societies around the world. But the old mining was in extinction. New technology was required and introduced step by step at an ever-increasing rate.



Garret coilers during ongoing assembly in Morgårdshammar's workshop facing a fast and demanding delivery to Quingtian, China.

The refining of the ore became the driving force for the contractors at that time. The Västerbergslagen area was great attraction with its mines and smelters. The rolling mill in Smedjebacken, now Ovako, was founded in the same year, 1856 with the mining industry as a base, the same as Morgårdshammars.

In the old Norrbärke Parish there was only 21-year-old Axel Westman. He came from a family with ancestors deeply involved in mining. His father Jacob was the one who together with Hagge Bruks Axel Nordlander at the same time started the rolling mill in Smedjebacken. When the then Morgårdshammar's Forge, which was taken over by the English in 1855, suddenly went on sale Axel Westman saw his chance.

Axel Westman, (1835-1898). He was only 21 years old when he founded Morgårdshammar Verkstad and then was active as the largest shareholder during more than thirty years.

For many years, the business was mainly characterized by the manufacture and development of equipment for mechanization of other industries, of course mainly in mining, iron and steel. Morgårdshammar came to be part of the group that was often called the "industry of industries". Larger products that provided good profitability in the very first years were elements such as lancashire forging and rail nails.

Nils Gustaf Héro was the first of the managers to remain in his post for a long time. His path was at first multifold. He came to Smedjebacken as a teenager in a position as a pharmacy student. At the age of 22, he graduated as a veterinarian. In 1856 he became manager of the rolling mill in Smedjebacken and in 1858 also of Morgårdshammar. At the same time, he was a veterinarian for the entire Västerbergslagen for 25 years and diligently active as a municipal councilor. During his 27 years until 1885 as manager, he gave the stability to the company which later came to be classified as "Morgårdsandan", I. e. "the sprit of Morgårdshammar".

A smash hit, the beginning of a true story

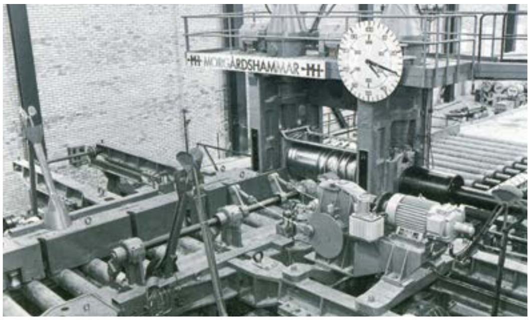
A transformative element in the saga of Morgårdshammar occurred. Ernst von Zweigbergk, (1845-1896), is directly associated with Morgårdshammar's world reputation. He came from Borås. His studies made him particularly interested in hot rolling. He had traveled around Europe and looked at various rolling mills. He went home and invented his own universal rolling mill. No one had seen anything like it before. His ingenious innovation in his patent was based on a work that consisted of horizontal and

Nils Gustaf Héro, pharmacy student, veterinarian, municipal man, but mainly the head of Morgårdshammar in 25 years (1858-1885). Héro provided stability in the business. The years 1856-1874 he was also president for the newly started Smedjebackens Valsverk.

Ernst von Zweigbergk, (1845-1896), inventor of the universal rolling mill 1880 that hit the world with amazement. He lived in Villa Sommarro outside the workshops. He died only 51 years old.

In 1880 Morgårdshammar delivered this 16-universal rolling mill of von Zweigbergk's design to Smedjebackens Valsverk, it was In operation until 1970.

Outside the new MH office is the familiar component of von Zweigbergk's fantastic universal rolling mill from 1880, which brought such a success. The picture is from 2008 and the three are MH representatives from at that time activity in Ukraine.



In 1963, the last complete ingot rolling mill was delivered from MH. Smedjebackens Valsverk was the buyer. It was in operation until 1980 when the rolling mill switched to continuous casting. But the equipment is still in operation, outside Mumbai in India.

vertical pairs of rollers.

The rolling mill in Smedjebacken realized the features of von Zweigbergk's work and ordered one in 1875. The assignment went to Morgårdshammar, and the following year it could be used.
von Zweigbergk's universal rolling mill gave a worldwide response, a smash hit and the beginning of the future saga. The inventor was soon completely tied to Morgårdshammar, who was suddenly in the driver's seat. Until the inventor's death in 1896, he was 51 years old, over 40 of the designer's genius creations had been manufactured in Morgårdshammar, and delivered all over the world. It was at this time that the company became a concept, an industry respec-

Viktor Emanuel Jansson, (1872-1944). President for 27 years, 1912-1939. He had most things modernized with a clear focus on the mining industry.

In 1913, President Jansson staged the first expansion of the old workshop, facing east.

The first wire rod block was already built in Morgårdshammar and got his signature in 1926, called "Ekman's continuous experimental work". Gustaf Ekman, MH president 1900-1912, actually a banker but with a great interest in technology. He developed his unit and was far ahead of his time. 50 years later, MH introduced its modern wire rod block.

Per. G. Ekman, (1901-1986), born in Morgårdshammar and son of Gustaf Ekman became the next president for a long time, for 25 years 1939-1964. His efforts became absolutely crucial for the company's future. Technology development was his hallmark.

ted for rolling mill and mining industries all over the world.

The next manager with many managerial years was Viktor Emanuel Jansson. He continued on the beaten path and remained in the post as long as Héro, for 27 years, 1912-1939. He had most things modernized and created his own electric power station. His focus was to invest even more in machine equipment for the mining industry.

The next long-term manager was Per G. Ekman. He was born in Morgårdshammar in 1901. At that time, his father Gustaf Ekman was the company's manager, in the years 1900-1912. During his 25 years as managing director, 1939-1964, his efforts were absolutely decisive for the company's future. He drew up a long-term strategic plan which, during difficult periods, made the business not only survive but also develop. Technology development was his hallmark and the result was a strong expansion.

In 1944, the mining engineer Erik Norlindh was hired (1909-1969). He soon became one of the world's foremost rolling mill designers with many sovereign patents. His progress cannot be overestimated for Mor-

Mining engineer Erik Norlindh, (1909-1969) soon became one of the world's foremost rolling mill designers with many superb patents. His progress cannot be valued enough for Morgårdshammar

The benefit with Erik Norlindh's roller guides was that they steered the rod material into the tracks of the rollers during rolling. The rotating rollers replaced the previously stationary ones.

This mine hoist system was delivered to Grängesberg in 1900. It was in operation until the mine's closure in 1989-1990. The hoist system is kept in the preserved Machine House.

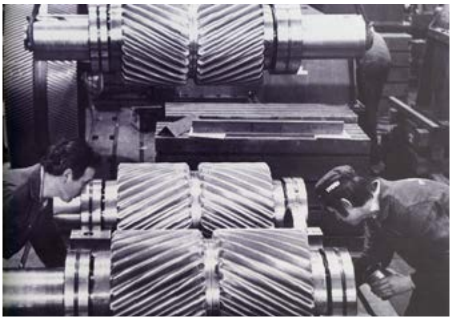
As early as 1870, Morgårdshammar's first crusher of the Blakes Jaw Crusher type was introduced.

gårdshammar's part. He invents rolling mill constructions no one has seen before, of which his roller guide quickly gave himself and Morgårdshammar world fame. The feature was that they guided the rod material into the grooves of the rollers during rolling. The rotating rollers replaced the previous static ones.

Mining did not fit

Morgårdshammar's incomparably largest customers over the years have been the mines and ironworks. In the same way, mining equipment and rolling mills were the incomparably leading product areas. The mines in Grängesberg were among the most diligent customers. Mining equipment was delivered there in a steady stream. An example is an advanced mine hoist system delivered around 1900 and still in operation at the Gränges mine's closure in 1989-1990.

Mining has long been one of Morgårdshammar's largest product groups over the years. As early as 1870, the company's first jaw crusher, called Blake's Jaw Crusher, was introduced. Exactly 100 years later, a new gyratory crusher was developed which received a great response. In this way, Morgårdshammar continued to produce crushers, mills and other mining equipment.



Morgårdshammar's biggest customers over the years have been mines and ironworks. The picture, assembled in the workshop of a gearbox around 1970, before delivery to Boxholm.

Gyratory crusher BS 1350, product group mining equipment, during ongoing assembly in Morgårdshammar. Mining equipment were very profitable for MH.

When Danieli took over Morgårdshammar AB in 1987, the Italians considered that mines did not fit into their range at all. Bit by bit, parts of the mining group were sold out. When the large carousel lathe and giant gear milling machine were sold out, all production of mill parts ceased. The decommissioning of mines took place slowly in the years 1996-2002.

Milking machines and boat engines
From the start, Morgårdshammar specialized throughout the 19th century mainly in solutions and constructions for other industries, depending on drawings, wishes or needs. The contact with consultants and consulting companies was significant. This is the way Morgårdshammar filled in their order book.

Although subcontracting was dominant, at the same time Morgårdshammar had many skilled designers with lots of ideas about their own products or the development of others. Thousands also became a reality. Most, on the other hand, are relatively short-lived as technology advances.
Most famous and talked about own products were something as different as milk separators and smaller boat engines.
In 1895, a contract was signed with the inventor A. Malmros for the manufacture of his patented separator ”Helice”. A special workshop with 25 employees was set up and the business got started quickly. The aim was set at 2000 separators in annual production, both hand- and motor-driven. The forecast did not hold, despite great efforts. An average of 700 a year was not enough. After ten years with substantial deficits, the production of ”Helice” was stopped.

As a replacement product, smaller boat engines were included in the range, both inboard and outboard. The engines quickly became popular, especially the well-designed outboard ”Pilen”. The inboard ”Tellus” was also successful in several models, both single-, two- and four-cylinder. Copies are still left and work great.
After the experiments with what can be cal-

Beautifully shaped letterhead from the 1890s when the production of the milk separator Helice had been included in its own product range, but was discontinued after ten years.

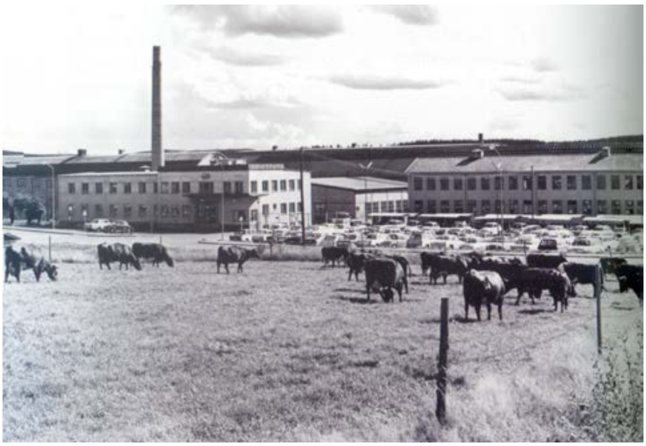
After the milk separators, it was thought that boat motors could become an opportunity. That too was not very successful. Examples of the Brand Pilen and Tellus, on the other hand, still exist and still work today.

led odd products, Morgårdshammar soon returned to concentrating on what they were best at, the mining and rolling mill industry's need for equipment.

Residential construction-agriculture-power station

For a dominant industry in a small community with the size of the municipality Morgårdshammar, the requirement to manage the necessary new recruitment and to retain the workforce was extremely important. A natural feature was therefore to look for and attract skilled workers and getting them to stay.

From the start in the 1850s, Morgårdshammar AB became involved in basic necessities such as housing, dairy and meat products and later on also access to electricity. The company owned both forest and land. In total, some leases over 500 hectares were available. The company participated in various ways to create housing for its employees. Financial benefits of rents and loans against committing to not leaving the company without reason were common conditions.



Agriculture was part of the business when Morgårdshammar Verkstad was founded in 1856, and was not divested until the late 1980s when Beijerinvest became the new owner.

Agriculture was included from the beginning. The barn housed 100 dairy cows and a number of young animals. In some nearby animal stables, another 200 animals were housed. Morgårdshammar was for a long time one of the largest milk suppliers in Dalarna. Agriculture with buildings were sold around the time 1980. When Anders Wall and his Beijerinvest took over in 1975, the old historic mill area immediately began to be peeled off. Forest, land and sawmills went the same way.

In 1913, Morgårdshammar AB ensured that it became largely self-sufficient in electricity and commissioned the construction of its own power station. When it worn out, a new one was built in 1962. The power station was sold in 1987 in connection with the Volvo-Danieli deal the same year. New owners replaced each other in quick succession, Eon, Örebro Energi, Sydkraft and now Kolbäckens Kraft KB, which is part of the German Uniper Group.

500 students were enrolled in Morgårdshammar's Apprenticeship School during the 30 years. It was highly regarded. The graduating class in 1976 was the last before the new high school took over.

Popular apprenticeship school for 30 years

students were enrolled during that time. It was started in 1951. With its well-thought-out syllabus and rules that could not be misinterpreted, the need for skilled employees was secured. The fact that the students were allowed to "walk next to" the elderly out in the workshops contributed to a solid competence. Internships from the second year onwards were attractive. Dropouts were minimal, less than one student per class. New grades were awarded at frequent intervals. Higher grades added to the student salary. In addition, permanent employment was almost guaranteed when the three years were completed.

The school's reputation was attested. ASEA gladly accepted students who went there. On the other hand, countless of them remained at Morgårdshammar throughout their working lives. Of those who later received the veteran tribute for 40 and 50 years of service, the majority have attended the Apprentice school. The apprenticeship school was gradually phased out in the early 1980s. It was not allowed to compete with the biuld-up of the new high school. Companies around the country that had their own vocational schools were probably not completely in agreement with the new arrangement. Of course, a significant cost was passed on to the public school, but many felt that their own industrial schools were well worth the money.

Morgårdsanda-hockey-Mässen

Morgårdshammars IF astounded hockey-Sweden and played a couple of seasons in the highest league. The commitment was huge and the concept of the MH spirit was strengthened.

The fair began as a so-called "food locus". Later a party venue with a high status for representation and staff parties. The MH chefs' Christmas party was tradition.

The arrangements for visiting customers have been almost mandatory over the years. Like here with salmon fishing during a visit from China in 2008.

Morgårdshammar started in 1856 with 30 coworkers. The picture shows the workforce in 1878 with just over 40 workshop workers. In addition, there were about 10 white collar workers. At its peak, when Beijerinvest became the new owner 1975, the company had 750 employees.

The 150th anniversary celebrations in 2006 were extensive and celebrated with customer activities, special theater and festivities, as well as visits by King Carl XVI Gustaf.

Morally and emotionally, the concept of ”Morgårdsandan” has been talked about in countless contexts. There is much to suggest that it existed, was very much alive and special. It was created early. Examples are where father and son joined the work. Up to four to five generations in a row was not uncommon. Veterans hailed over the years have been more numerous than at many other major companies.

There was a certain pride in working at Morgårdshammar. The company also did a lot for its employees' free time. The leisure center in the community, which was inaugurated in 1959, was a gift from the company to the municipality. Morgårdshammars IF, MIF, was formed in 1931 and the participation of the sports venue Hagvallen was significant. In addition to financial support, the non-profit work efforts were dominated by the company's employees.
In this context, it is impossible to circumvent the glory days of ice hockey in the 1960s. MIF stunned hockey Sweden and went sensationally up in the highest league. A new arena was built at record speed. 180 men in the workshop donated 6,000 hours of overtime in money to the construction, the company assisted with the same amount. 1960-1962 MIF played in the elite series against teams like Djurgården, Leksand and Brynäs. Several players had to wear the national team jersey.

The mess as a venue for representation in combination with the staff's party arrangements, was from the beginning a simple serving for the company's bachelors, a so-called ”food locus”. Later, the house was renovated and reasons were given for style and rigor for the company's guests and the own staff's arrangements. The fair was an institution that also contributed to ”Morgårdsandan”.

Staff in numbers, 750 at most
More than 5,000 people have been employed in Morgårdshammar during the 166 years until today. At the beginning of 1856, there were 30 employees. In 1900, 160 in the workshop and 50 white-collar workers. After the Second World War, a staff increase began as never before. From just over 200 workshop workers, the number rose to a maximum of 750 in 1975, the year when Beijerinvest became the new owner.

The overcrowding was reminded early on, and in 1968 the New Office was ready to move in to. In 1950, the distribution was 2.5 workers per official, at the 150th anniversary celebrations in 2006 it was evened out, as many workers as salaried employees. Notable from the 150th anniversary celebrations is an implementation with pomp and circumstance, special theater and a visit by King Carl XVI Gustaf.

At the time of Volvo’s takeover in 1983, the workforce had been declining for a few years. Italian Danieli’s plan when he took over as new owner in 1987 was to keep only 280. Morgårdshammar has since gradually shrunk to today about 50 employees. As recently as June 2022, the latest alarm came. 25 were notified, which ended with 16 people being allowed to leave. The reason for the decline has mainly been explained by increased demands from customers and authorities, but above all fierce competition from manufacturing in low-cost countries.

Today - and a question of the future?
When Volvo realized the unsustainability of running businesses far outside its core area, the worst competitor, Italian Danieli, was early in the picture. The company was founded in 1914 and has always had rolling

Overcrowding made itself felt early on as the company grew. In 1968, the New Office was ready for occupancy.

After Danieli’s takeover, Sund-Birsta’s compactors for rolling mill products were added as a new product group in 1992. Production was moved to Morgårdshammar. The picture, assembling of the binder machine intended for cutting bars.

Each customer contact for a long time included special training in the function and subtleties of roller guides under the concept of Guide Academy. In the spring of 2010, customers from the Czech Republic, Austria, Germany and India.

mills as its main product, something that Morgårds-hammar has already started with more than 40 years earlier. Danieli is based in the smaller municipality of Buttrio southeast of Udine a bit inland where the Adriatic Sea ends in the north. With their acquisition in 1987, the Italians got something they desperately wanted, Morgårdshammar's good world reputation and solid expertise in many special areas for rolling mills.

Solemn moment spring 2011. Morgårdshammar wins one of its largest orders in modern times. The contract relates to a complete wire and rod rolling mill, buyer Mittal Corp LTD in Indore, India. Morgårdshammar's CEO Anders Eriksson signs, Deputy CEO Giacomo Verlini on the far right.

Morgårdshammar AB, it is still called that to this day just like 1856, is a name the Italian owners are very keen to live on. Danieli-Morgårdshammar is now almost entirely focused on rolling mills for long products, especially equipment such as roller guides and roller pairs. One product that has been added is binding machines for rolling mill products. In 1992, Sund-Birsta in Sundsvall was bought and the production of binding machines was moved to Morgårds-hammar.

The revolutionary roll control that was created in Morgårdshammar as early as 1945 is still a world leader. The quality of these control products is recognized for its strength and durability. The major change in recent years is that an increasing propor-tion of production is purchased by subcon-tractors, especially from new EU countries with significantly lower cost levels. Morgårdshammar has, of course, had periods of so-called bad times. They have coincided with the problems of the outside world of various kinds, such as wars and economic crises that have changed the conditions.

Aerial photo from the beginning of 2000, Morgårdshammar's workshops

Today, the cost situation compa-red with the low-cost countries has slowly begun to level out. The question of the future is whether Morgårdshammar gets enough muscle from its owners to main-tain the position as a well-esta-blished company in Smedjebacken municipality, or can even come back and grow on its own?

The mill in Smedjebacken – from Smedjebackens Walsverk to Ovako

Lars-Uno Rystedt

A few glimpses about the development from a rolling mill to a quality steel mill

Here's how it started....
During the reign of Gustav III, in 1788, four years before the fatal shooting at a masquerade ball, a poor 15-year-old boy travelled from his childhood home in Medelpad down to Stockholm and got a job as a store servant. He was a good businessman and after 13 years he applied for and was granted a permit to open a business as a grain seller, retailer and grocer on Brunnsgränd in Gamla Stan. He became a reputable merchant and was appointed city mayor.

In 1845 he bought Hagge Forge. We do not know what made a successful businessman in Stockholm purchase a forge in Bergslagen at the age of 72. Perhaps because he realised that there was a good future for iron and steelmaking, or perhaps to create a business for his eldest son - who worked as a mill student at Ludvika Forge. After his death two years later, his son took over as head of the forge (brukspatron). He ran the forge for a few years, but soon realised that hammer forging would not be a sustainable business in the future. Together with two business friends, he formed a new company that built a rolling mill – Smedjebackens Walsverk (SW) – and they appointed the local veterinarian as a mill manager. After ten years, the company became the largest supplier of steel bars in the country.

The businessman, wholesaler, and Stockholm`s last city mayor was called Eric Nordlander – and as head of Stockholm's Bourgeoisie Northern Battalion was one of the country's richest men. His son, Axel Nordlander took over the mill as "Brukspatron" at the age of 26. At that time, a mill was a conglomerate of businesses – in addition to hammers and hearths in Hagge, interests/parts were included in blast furnaces, mines, mills, sawmills and about 10 agricultural and forest properties. Axel Nordlander later expanded his business empire by obtaining shares in Klenshyttan's, Persbo and Björsjö's huts, in addition to mines such as Höga visan in the Grängesberg field. Ownership of mines to obtain ore, of blast furnaces to gain access to pig iron, of properties to gain access to charcoal, of firewood, timber and arable land, all contributed to a growing business empire. The mill was responsible for ensuring that those who worked there had housing and food on the table.

He also invested in the Wessman-Barken Railway and Norrbärke Sparbank – one of the provincial banks that still remain today.

Axel Nordlander's son, Harald Nordlander, eventually took over the company and as chairman of the board he contributed to SW acquiring its own metallurgy and no longer relied on smelters - substances - from the partners' Lancashire hammers.

The Nordlander family eventually achieved full ownership of the company up to and until 1955 when the investment company Ratos acquired the business.

Building a Rolling Mill
At the hammer in Hagge, smelting pieces were forged into bar iron using the Lancashire method which was the prevalent method of forging at the time. But the rolling technique had begun to spread across the country and Axel Nordlander realised the advantage of rolling out smelting pieces instead of forging them with hammers. A rolling mill is too large an investment for a small mill - the cost of building a rolling mill is high and the raw material base from one mill was not large enough to supply a rolling mill. He searched for business partners and found them in Jacob Westman, co-owner of Westansjö Blast Furnace and By forging plant, and Ludvig Wetterdal, "Brukspatron", owner of Nyhammar and Fredshammar mills.

On January 31, 1854, the three businessmen signed an agreement to form a company for rolling smelting pieces. The site chosen for the work was at the waterfall in Kolbäcksån's outlet on Lake Barken. This site provided the power needed to run the plant and had good transport routes through Strömsholm's canal. The canal – inaugurated in 1787 – was under repair and reconstruction when the rolling mill was built. Transportation to and from the plant was initially handled by sailing boats - canal chases so-called ”schasar” - but in 1861 the company decided to acquire its own steamboat, ”Smedjebackens Walsverk” (later renamed ”Smedjebacken 2”). 10 years later, another steamer was purchased – ”Nils”. There were also plans to build a canal further on from Barken up to Väsman but it never materialised. Instead, a railway was built between Ludvika and Smedjebacken – Wessman – Barken Jernväg – which was inaugurated on 17 August 1860 by Charles XV himself.

Building a new rolling mill in the mid-1800s was not an easy task. The rolling technique was relatively new, and no one was experienced in running such work. Engineer Wilhelm Wennström was hired to design the rolling mill, who at that time was considered the foremost rolling mill builder in the country. For a long time, a person was sought to head up the operation. Eventually the local veterinarian - Doctor N G Hero - was entrusted with this mission and he managed the company successfully until 1874.

The company that was started could be likened to a contract manufacturer – or a cooperative – that received smelting pieces from the partners' parent mill and rolled these out into bar steel. It was then the parent mills that sold and delivered the bar steel to customers.

15 september 1856
Initially, an ingot rolling mill and a medium section rolling mill was built together with two furnaces for heating the smelting pieces. On September 15, 1856, the rolling mills were started, and by the end of the year 361 tons of bar iron had been rolled.

The smelting pieces supplied from the mills had the shape of oblong plates about 6x2.5 dm and one dm thick. Each plate weighed about 90 kg, and up to three plates were put together when rolling into one piece.

The rolling technology was new and customers who had previously received hammered bar steel were sceptical of the smooth, rolled bars. There were competing works hammering the rolled bar in order to sell it and in 1857 a decision was made to build two hammers to hammer the rolled rod. But before the hammers had been ordered, customers had discovered that the rolled bar was as good as the hammered bar, so no hammer was ever built.

Ett rälsvalsverkA rail rolling mill
In 1869, a new rolling mill for rails was started - also this rolling mill was designed by engineer Wilhelm Wennström. It was in operation until 1880 and a total of 27,000 rails were manufactured, about 7,500 tons. It is said that rails rolled in Smedjebacken were in use in SJ's tracks until the 1930s. A piece of rail remains outside the office in Smedjebacken and one outside ”Meken” - the old mechanical workshop that is now an art gallery. In his book ”Bruket vid Barken”, Axel Gjöres tells a story by Carl Sahlin about an incident when rolling rails for Gefle-Dala Jernväg was about to start:
”At the then more than now critical moment, when the first subject was to be inserted into the rolling mill, the designer was present. Everything was carefully prepared with long idling driving, careful rolling of the melting pieces, etc. The first melting piece was brought to the rolling stand and entered with the consequence that a deafening roar occurred and the whole rolling mill was shattered. Wenstrom stood at first petrified in the face of the devastation, but quickly recovered and exclaimed with satisfaction: 'what a great result'! His somewhat astonishing joy was found to persist therein, that not only any part of the rolling mill had been broken, but that almost all of its strained parts had simultaneously collapsed, showing that his calculations had given consistently even-strength (or perhaps we should say even-weak) dimensions to the whole equipment.”

The first engineer
Previously, engineer Wilhelm Wenström had been hired to build the rolling mill and the rail mill, but he was subsequently hired as a consultant and advisor. However, the business developed and became more technically demanding and in 1870 it was decided to hire an engineer – the then 25-year-old Ernst von Zweigbergk. After training at Borås Technical School, he had practised at English and Swedish works. Zweigbergk came to mean a lot for the development of rolling at Smedjebacken and other works. His great achievement was the development of the universal rolling mill. The universal rolling mill is a rolling chair with two or three horizontal rollers followed by two vertical rollers and is intended for rolling flat bars and square bars.

Zweigbergk probably got the idea for the universal work during his travels in Germany and Austria. But there are also other sources. One states that Zweigbergk got the idea from a turner at Nyhammar's mill – Staffas Johan Andersson – who in his youth made a wooden model of a universal mill where he rolled out the gingerbread dough for his mother. Another source indicates a turner Sandberg at Smedjebackens Walsverk who, on a visit to Grangärde, saw a model that resembles a universal work.

Von Zweigbergk designed and developed the universal mill and Morgårdshammar manufactured a plant that could be started in 1876. The results were good and another work was started two years later. Von Zweigbergk also received a patent for the work in 1878. The new design was also a great success for Morgårdshammar's mechanical workshop, which delivered about 50 universal works to various Swedish mills over a 25-year period.

Power supply
Hydropower was the original source to power rolling mills and fans for furnaces. It was also the waterfalls at Kolbäcksån's outlet in Barken that were the reason why the rolling mill was built there. The furnaces were heated by firewood and charcoal. Peat was also tested but to a lesser extent. Imported coal eventually replaced an increasing share of fuel demand.

The foundry hall on the left and the forming hall on the right. In front of them a gatekeeper's cottage where the wages were distributed and where ration cards on food were also handed out during the First World War. Photo taken in 1919.

As production increased and the business expanded, more power was required for operations. But the flow of water in Kolbäcksån varied and it happened on several occasions that the operation had to stop due to low water flow. In 1875, a 50 hp steam engine was installed in the Medium rolling mill, which was used during low-water periods. Around the turn of the century in 1900, another pair of steam engines and a couple of gas engines were procured. In 1906, electrification of operations began through an agreement with Aktiebolaget Ludvika Bruksägare for the supply of electric power via a power line from Flogberget. Oil became available after World War II and in 1947 oil was used in the rolling mill furnaces.

The impoundment of the river had been moved upstream to reduce the risk of flooding. But in 1977, the spring flood was very strong with floods and razed roads in many places in Bergslagen. Kolbäcksån was also affected, and the water rose so high that the water went into the steel plant. The old building for the Medium rolling mill, which was then used as a warehouse for the bar steel, is built over the river, and it was in danger of being raised by the water masses. In order not to break the walls, holes were made in the walls so that the water could run through the building.

A consequence of the flooding and the water running through the bar steel warehouse puzzled a Danish plowmaker. During a visit by the rolling mill's staff, he wondered how the bar steel had been transported from Smedjebacken to Jylland. Between two stacks of steel bars lay a splendid one-kilo bream wedged. He was pleased with the bar steel but considered the bream inedible.

Smedjebackens Walsverk becomes a steel mill.

During the first 50 years of the 1900s, SW

Insertion of scrap in Martin furnace No. 4

changed from a ”subcontracted roller” to an industry with its own steelmaking, rolling and further processing of a significant proportion of the rolled bar steel.

The introduction of its own steelmaking meant a fundamental change in the company. From previously being a ”subcontracted roller” for the owners' hammersmiths, SW now got completely self-made bar steel that the company would market and sell. The old Lancashire hearths could not compete with the modern steel furnaces that smelted scrap and pig iron and at Hagge forge – which had 4 Lancashire hearths, for example – operations were closed in 1910.

Already at the Paris World's Exhibition in 1867, the French metallurgist PE Martin had shown a furnace for smelting scrap and pig iron, which aroused great interest. This method began to gain ground in several parts of Sweden. In 1897, SW built its first Martin furnace with a charge weight of 8 tons. At the same time, the rolling mill was also rebuilt to be able to handle larger ingot weights. In 1911 SW started its second Martin furnace and from 1912 only self-made ingots were rolled.

A third Martin furnace began to be designed in 1916, but the First World War brought unrest in the world economy, and it was postponed until 1925. The fourth Martin furnace was built in 1936 and remained in operation until 1975.

A new century – with a lot of worry

Despite the greatly varying economic cycles from around the turn of the century (1900) until the end of World War II, the business was able to keep going. The war years however meant a shortage of supplies. A shortage of scrap meant the need for more pig iron. The production of pig iron required fuel and difficulties in importing coal and coke meant a greater need for charcoal and firewood. During World War II, the gas-powered motorcar also became a competitor for the fuel. Even the furnaces in the rolling mills used a larger proportion of firewood.

Further processing of the bar steel

TThe tradition of the ancient mills of ”having many strings on one’s lyre” lived on for a long time. In addition to everything connected with steelmaking, there was forestry and agriculture, a sawmill and also housing for the staff. Free accommodation was a benefit in kind until the mid-1940s.

Other businesses were added. Production of reinforcing bars increased in the early 1940s, and in 1945 the manufacture of reinforcing mesh began, and in 1951 the manufacture of reinforcing rings for concrete pipes. A workshop for cutting and bending of prefabricated reinforcement was also started.

Aerial view 1927. In the middle the steel plant. In front of that buildings for the Medium Rolling Mill.

After all, there was some investmentduring this period.

- A Foundry was started in 1899.
- Wire rolling mill 1906.
- New Ingot Rolling Mill 1925.
- Expansion of the Medium section rolling mill in 1932.
- New heavy section rolling mill 1933.
- Cold rolling mills started in the 1940s but closed in 1969
- Chain manufacturing was started in 1927 and operated until 1952.

Production of roof trusses started in 1947 and during a period in the early 1950s, a third of the produced bar steel was further processed within own facilities.

All operations outside the core business have gradually been closed down or sold to other companies.

Welding of roof trusses.

The post-war period – SW becomes a quality steel mill.

Metallurgical process development
To shorten the charge times in the two Martin furnaces that are in operation, a Blaster Cupola furnace was built where you could melt pig iron and charge it in molten form to the Martin furnaces.

In order to replace the old Martin furnaces, a small electric arc furnace with a charge weight of 6-7 tons was built in the mid-1960s. The idea was to gain experience in steelmaking in an electric arc furnace and to prepare to replace one of the Martin furnaces with a larger electric arc furnace. In 1968 they installed an 80 tons electric arc furnace. The last Martin furnace was closed in 1975 and since then the electric arc furnace has been the company's only smelting furnace.

The electric arc furnace is a round furnace body with three electrodes that are lowered towards the scrap. A current is put on the electrodes so that an arc of light is formed between the electrode and the scrap. The arc melts the scrap and heats the molten steel.

That furnace has been rebuilt and modernised several times and is today a modern electric arc furnace. The charge weight has been increased to 125 tons, the original tapping spout where the steel was poured in a ladle has been replaced with a valve at the bottom of the furnace so that it can be bottom tapped. To make melting more efficient, a practice of foaming slag is used: it involves injection of coal powder into the slag to form gas that increases the volume of the slag. The arcs are ”hidden” in the slag which utilises a higher electrical voltage and thus higher power.

The peripherals for the oven have also been modernised. The heavy job of blowing oxygen into the molten steel with a lance to oxidise phosphorus and other undesirable

Tapping the electric arc furnace.

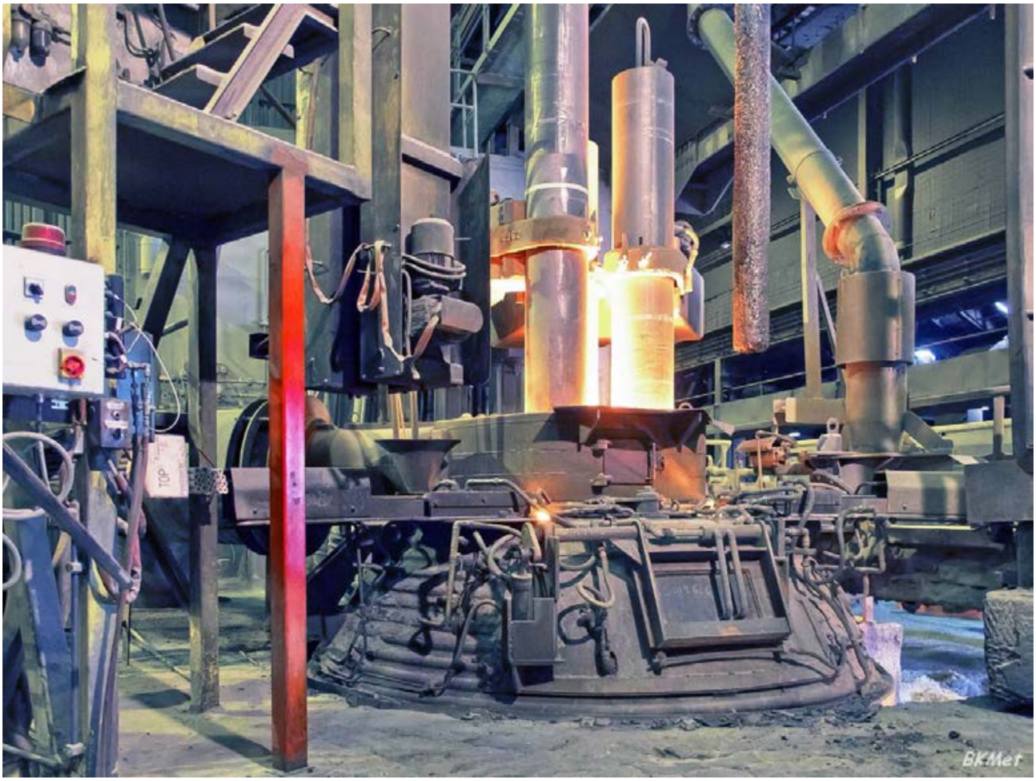
substances is now handled with a robot. The oxygen also helps to heat the molten steel.

Ladle Metallurgy

The quality of steel depends on how many impurities (slag) it contains and the shape of these. The quality also depends on the content of harmful substances in the steel. Examples of these are H (Hydrogen). P (Phosphorus), Cu (Copper). In order to improve the quality of the steel, methods for finishing the liquid steel in ladles (after tapping from the furnace) began to be developed in the mid-1970s. Within a collaboration with Jernkontoret and MEFOS (The Metallurgical Research Station in Luleå), a method was developed to inject inert gas – Argon – with a ceramic lance for stirring and inject a powdered material CaSi (Silicon Calcium) into the steel. Gas injection was aimed at separating slag and equalizing the temperature. The CaSi injection mainly helped to lower the oxygen content and transform the slags into round instead of elongated ones.

Equipment was also developed to be able to feed wire into the steel melt. The wires used were pure aluminium wire or a tube wire containing a powder of Boron, Titanium or Sulphur.

When a continuous casting machine was built in 1980, the requirements for temperature accuracy in casting increased. The requirements for the then existing equipment were met for ten years, before the installation of a ladle furnace in 1991. A ladle furnace is built according to the same principle as an electric arc furnace with three electrodes in a lid over the ladle where you can heat - or keep - the molten steel to the right temperature. In addition to greater temperature accuracy when casting, it also means the advantage of being able to drain steel from the electric arc furnace with a lower temperature. A lower temperature in the electric arc furnace also leads to higher productivity and lower phosphorus levels.



Ladle furnace

The latest step in the development of the ladle metallurgy was taken in 2019 through the construction of a vacuum plant at the ladle furnace. The qualitative advantages of vacuum treatment of liquid steel are that you can lower the content of dissolved gases in the steel. For more alloyed steels, high hydrogen content gives rise to serious internal defects in the finished bar.

Casting

Ingot casting
During ingot casting, the steel was poured in a mould, initially directly from the top - top pouring - but gradually they switched to so-called bottom pouring. Bottom pouring means that the steel is poured down through a vertical pipe which is then transferred to eight horizontal pipes which leads the melt further and drops into the bottom of eight vertical moulds.

Continuous casting
In the 1950s, methods began to be developed to cast the steel directly into billets The advantage, of course, was to avoid the ingot casting plus ingot rolling. In continuous casting, the steel is dropped into a

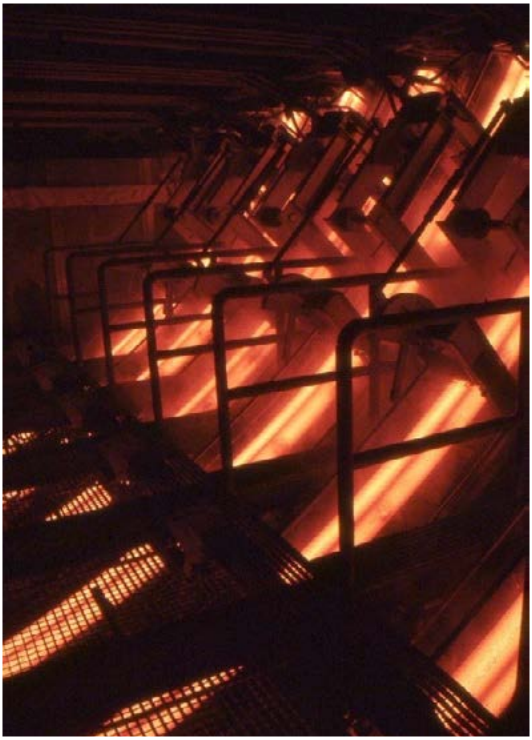
Casting of ingots by bottom pouring

Station for vacuum treatment. The ladled is placed in a container, a lid is put on and air is sucked out while argon is bubbled through the melt. Negative pressure causes gases to escape from the molten steel.

water-cooled copper mould, pulled out of the mould, and cut into finished billets. The first continuous casting plant used in full production in Sweden was built in Halmstad Steelworks in 1962.

In Smedjebacken, continuous casting started in 1980. There, six strands are cast at once. The steel is poured into a tundish and from the tundish the steel flows down into six vertical moulds. The strands go in a curve down to the ground plane where it is cut into ordered lengths.

Since its inception in 1980, the continuous casting plant has undergone several re-constructions and improvements with the aim of improving quality and productivity. A rotary tower has been built to be able to switch ladle during casting and thus be able to cast together several chargers.



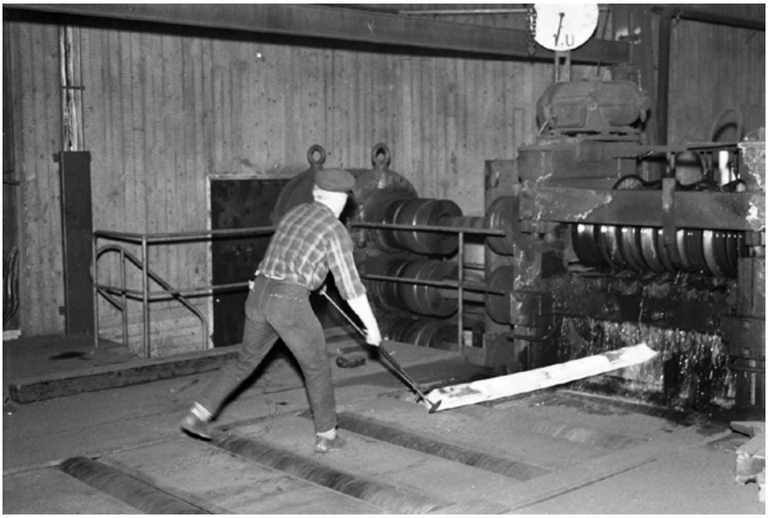
Continuous casting

To protect the steel from oxidation during casting, today casting pipes are used between the tundish and the moulds. Inductive stiring have been installed in the moulds that provide a more homogeneous solidification structure. ABB installed the stirers in the mid-1980s – it was ABB's first supply of electromagnetic stirers in mould.

New ingot rolling mill

In 2014, an extensive reconstruction/modernization of the continuous casting plant from moulds to the cooling bed was carried out. In connection with this, round billet formats were also introduced. The round billet formats are intended for the manufacture of seamless pipes at the facilities in Hofors.

Rolling
A new, more powerful ingot rolling mill – delivered by Morgårdshammars Verkstäder – was installed in 1960 and it allowed the ingot weight to be increased from 1.2 to 3.2 tons. It was replaced by continuous casting in 1980 and closed down, it was the country's most modern ingot rolling mill.


Rolling in Medium section mill in 1957

The rolling mills were supplemented with a new small section rolling mill in 1960 with 21 rolling stands in continuous line-up. Initially, both straight bar and wire were rolled on ring, but ring rolling was discontinued in the 1970s. After merging with Boxholm in 1981 (In Boxholm there is a fine rolling mill and a Medium rolling mill), the production of round bars was moved to Boxholm which left flat bar and reinforcement bars in Smedjebacken. More on the development of reinforcement manufacturing is outlined in special chapter. The small section rolling mill was closed in Smedjebacken in 1999.

The medium section mill had been gradually modernized, but eventually became outdated, as it required a lot of manual labour and involved risky work. It was replaced with a new medium rolling mill in 1973. It was a mill of two reversible rolling stands and a finished line with continuous rolling in 6 stands. The medium section mill has been modernised in stages and in the late 1990s the reversible intermediate stand was replaced by a continuous line with four stands.

Product development – from Commercial Steel to Quality Steel
Until the mid-1900s, SW was a commercial steel mill, but competition increased and the company realised that it needed to manufacture more demanding products in order to increase profitability. The development towards more qualitative steel grades started in the mid-1950s. The development of the production process that had been carried out since then has, of course, been aimed at increasing productivity and reducing costs, but equally at improving the quality of bar steel.

Reinforcement steel
Reinforcing concrete with steel bars began to be developed in the latter part of the 1800s but it was smooth round bar that was used. In the early 1940s, SW, together with researchers at Chalmers, developed a reinforcing steel with ribs to improve the adhesion of the bar in the concrete. SW was the first to introduce the ribbed bars on the Swedish market in 1941 and it became an important and profitable product for the company. The properties of reinforcing steel evolved over the next few decades towards higher strength in combination with increased requirements for weldability. This droves a trend towards micro-alloyed steels. See more about micro- alloyed steels below.

In the mid-1990s, the technology was further developed. When rolling small section bar as reinforcement, the production rate is limited by the speed of the bar out of the last rolling stand. In order to increase production, a method was developed in which, during rolling, the heath was divided into two bars – split – which were rolled parallel through the work. The result was a halving of the final rolling speed which allowed a higher production rate.
Another development was to cool the hot bar immediately after the last rolling stand so that the surface zone hardened. This provided a hard martensitic structure in the surface zone while the core is softer.
This mean that you can use a lower alloy and cheaper steel grade.

The reinforcing steel was an important product for Smedjebacken for several decades. The company developed an extensive further processing of reinforcing products – welding of reinforcing meshes and beams, inlay-ready products by cutting and bending.

But the importance of reinforcing steel diminished as more qualified products were developed. Of the 18 manufacturers of reinforcement that existed in Sweden during the 1960s, Smedjebacken was in the late 1980s the only Swedish manufacturer and in 1999 when the small section rolling mill was closed, it was the end of an era of reinforcement production in Sweden. Nowadays, the only reinforcement manufacturer in Scandinavia is located in Norwegian Mo I Rana owned by the Spanish Celsa Group.

Micro-alloyed steels
Micro-alloyed steels mean steels alloyed with low levels of, for example, Vanadium, Niobium or Boron. Boron alloy steels are considered separately below.

Under the leadership of laboratory manager Åke Letmark, they began to develop micro-alloyed and boron-alloyed steels. By adding small amounts of the nitrogen-fixing alloying substances Vanadium and/or Niobium at concentrations of 0.03 – 0.15%, it was possible to increase the steel's yield strength without significantly impairing the steel's weldability or formability in a cold condition. These steels were introduced to the market both as bar steel and reinforcing steel. SW even received a patent for a micro-alloyed steel.

Boron alloy steels began to be developed at SW in the 1960s. Already during World War II, the lack of alloying substances added to improve the hardenability of steels such as Chromium, Nickel and Molybdenum had driven a development to find alternatives. An element tested in many works was Bor, but the results varied widely and the mechanism behind the effect of the Boron additive on hardenability was not known. With more developed analysis methods and better microscopes, it was possible to establish that it was Boron in dissolved form that provided the hardenability-enhancing effect. But Boron has a high affinity to Nitrogen – uniting with Nitrogen and forming Boron nitride – and they have no effect on hardenability. SW began experimenting with Boron additive and by adding Titanium, which is a stronger nitrogen binder than Boron, was able to develop steel with guaranteed good hardenability. Boron steels quickly became a major product, especially for wear steel.

Boron steels can compete with many conventional toughening steels in that they have a lower price and lower hardness in a hot-rolled condition and therefore easier to shape.

If you see a farmer plowing his field with a red plow, it is probably made by Kverneland in the Norwegian oil metropolis Stavanger and is guaranteed to contain a lot of Boron steel from Smedjebacken.

Other steel types that were developed were spring steels – both Silicon alloy and Chromium alloy, so-called machine steels with an elevated carbon content, and conventional chromium alloy toughening steels.

Environment and Quality

The rolling mill was built on an island in Kolbäcksån's outlet on Lake Barken and when more land was needed to expand the business, slag and residues were dumped into the river and into the lake. Some of the first environmental cases documented are permits for sea exposure of residues – mainly slag. The first judgment of the Water Court dates from 1941 and the dumping ended in 1995 with the construction of a protective embankment against Lake Barken. In total, close to 600,000 m3 of slag were deposited which allowed for a considerable increase in the industrial area.

After the landfill in the work area was completed, a landfill for furnace slag and ladle slag was created at Humboberget south of Smedjebacken. Various projects to reuse slag for other products have been underway since the late 1900s. Through cooperation with other companies, more residual products from the landfill are currently reused than what is produced. Furnace slag is mostly used for road construction and mixing in asphalt provides a quieter and more durable road. Ladle furnace slag is used in the manufacture of insulation. Oxid scales that fall during continuous casting and rolling – chemically an iron oxide – are used in alloy manufacturing. Dust from the furnace filter is reprocessed by Boliden, which extracts zinc and lead, among other things.

Melting scrap in an electric arc furnace generates large amounts of flue gas dust. An electro filter was installed in the 1960s and replaced by a significantly more efficient filter in 1984. Another upgrade was made in 2013 with a filter that can handle 1.3 million m3 of flue gases per hour. The ”smoke” you see today from the plant is mostly water vapor from cooling towers and continuous casting.

Some of the heat present in the processes can be recovered. Heat from water cooling of exhaust gases in steel mills and rolling mills and cooling of the arch furnace vaults are disposed of in the municipality's heating plant and distributed into the community's district heating network. The contribution from the plant's facilities is approximately 29,000 MVh/year. And the much-debated ”hot bath” at Prästabadet in Barken also gets its heat from here.

Carbon dioxide emissions
Steelmaking is completely scrap-based, which means that 97% of the input is recycled material. The electricity used in steel furnaces and rolling mills is fossil-free.

In order to keep the CO_2 load from operations down, a larger proportion of rail transport is sought. About half of the steel mill's production is rolled in Smedjebacken and the rest in the company's rolling mill in Boxholm. Substances from the steel mill are sent every night by rail to Boxholm. A significant proportion of the scrap to Smedjebacken also comes by rail. In Boxholm, there is a collection of scrap for southern Sweden that is sent as return shipping with the subject train to Smedjebacken. A large proportion of the finished bars is also sent by train to the customer.

Through the development of the manufacturing process and other measures, the carbon footprint has decreased by just over 50% since 2015 and is now just under 400 kg of carbon dioxide / ton of steel, about 2,000 kg lower than the global average.

Quality
The ”Japanese miracle”, when Japanese industry after World War II changed the way of working and radically improved the quality of its products, also increased interest in quality technology in the Western world. Work on systematic quality management began in Smedjebacken in the 1970s with certification towards quality standards. The automotive industry has been a leader in the development of standards for quality work and as the production process has developed, the company has met more and more of the requirements. With the latest investment in a vacuum plant, a decisive step has been taken and is today fully approved for deliveries of demanding products to, among others, the automotive industry. Many audits from customers and norm authorities are carried out annually.

Certificates
The company is certified according to environmental management system ISO 14001, energy management system ISO 50001 and quality management systems ISO 9001:2015 and IATF 16949:2016

Collaboration with other companies in Västerbergslagen
Already in the construction of the first rolling mill, Morgårdshammars Mekaniska Verkstad was an important partner and supplier of, among other things, castings. The cooperation between the companies has been important over the years and in addition to larger installations such as the new ingot rolling mill in 1960 and the rebuilding of medium section rolling mill where 4 new roller stands in continuous set-up replaced the manually run reversible middle stand, countless collaborative projects have been of great value to both companies. And the exchange between the companies has not only been about ”hardware” – with two companies operating in the same place, the transfer of know-how through staff changing employers also becomes an important contribution to driving development.

Ever since the rolling mill was electrified in 1906, cooperation with ASEA-ABB-Hitachi has also been valuable. In addition to the delivery of transformers to steel furnaces and rolling mills where proximity to expertise in Ludvika has been important, the development of mercury-arc and later thyristor valves has contributed to higher productivity and reduced disturbances to the electricity grid. Tommy Hjort describes this development as follows:

Thyristor compensator, SVC, in cabinets with cooling fans and heavy-duty busbars. Photo: Harry Frank

<u>Driving rolling mills</u>

In order to be able to deliver the intended quality of the products, not only in terms of the metallurgy, it is required that these are rolled correctly. Therefore, the rollers were controlled by current converters in the form of low-voltage mercury-arc valves from ASEA in Ludvika. In addition to correct speed, these could reverse the rollers quickly and in a controlled way.

With the advent of thyristors in the 1970s, mercury-arc valves were replaced because thyristors did not contain toxic mercury and required significantly less maintenance. From that time, all power semiconductors were manufactured at ASEA in Västerås, as was the supply of industrial converters.

<u>Compensator for arc furnace</u>

An electric arc furnace causes disturbances in the connected electrical network, especially during the process before the contents have turned into molten form. During this process, you can see the 0.6 meter thick and several meter long graphite electrodes stand and jump as a result of the strong arcs that are triggered between the electrodes via pieces of scrap and pig iron in the furnace. Especially for large electric arc furnaces, this causes severe disturbances in the electricity grid. Therefore, in 1974, the second compensator manufactured by ASEA in Västerås with thyristor technology was installed in Smedjebacken's Valsverk. The first one ended up in Domnarvet. As with HVDC, transistors have made their way into this type of compensator. These are able to dampen the disturbances even more. This would mean that the furnace and public loads could be connected to the same busbar in the switchyard of transformer station RT 15 Morgårdshammar. The remaining disturbances on the power grid after the compensator go from the furnace 130 kV busbar through a transformer onto the 400 kV busbar and then through the second transformer to the public 130 kV busbar. The disturbances are thus damped by two transformer impedances. Each arc furnace has its individual signature, so experienced engineers who measure signals on the 400 kV power grid claim that they can see on oscilloscopes which specific arc furnaces are in operation at any given time even if they perform measurements far north in Norrland.

Closing words

Rolling and steelmaking, together with Morgårdshammars Mekaniska Verkstad, have been the hub in the development of Smedjebacken as a community. With wise decisions and successful development, the company has survived for almost 170 years. And with the investments made in recent years, there are good hopes for a continued positive development, now as part of the Ovako Group.

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Ovakos archive

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Mining over time

Markus Karlsson

What exactly is mining? The mine is a place where ore or minerals are mined from the ground. The number of minerals that are mined is large. These are substances that are used in a wide range of industries such as the paper industry, porcelain and glass manufacturing, paint manufacturing, i. e. not only more well-known metals such as iron and copper (Grängesberg, Falun). In addition, there are also stones for use in the construction industry, road construction etc. Mining in various forms has been done since 40,000 years ago, but activities in the current sense go back to about 7,000 years before Christ.

Regardless of which civilization people have started with softer metals, preferably visible on the ground, and then when they learned to expose the rock with fire and immediately afterwards pour cold water, they could loosen pieces, so-called fire-setting, you could also mine iron ore.

Fire was also important because man could use it to process metals and finally also combine different metals to get another harder alloy, such as bronze.

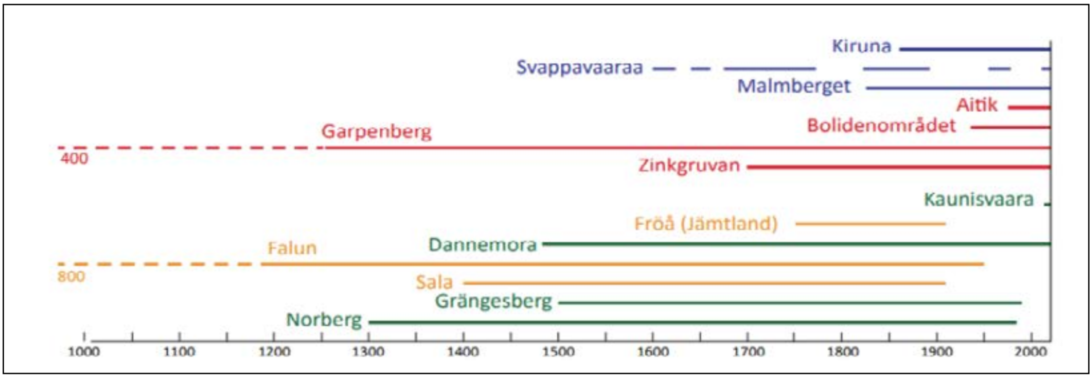
Usually the mining ended when reaching groundwater, they had no water pumps. Everything was done by hand. Mining shafts were narrow and low, older ones max 1.5 m high. Stone that had been cut loose had to be carried out by hand. This required a lot of labor. The air was usually warm and oxygenation was low. Lighting was simple oil lamps or candles. However, candles could also warn if the oxygen level became too low by extinguishing. Shafts and tunnels were reinforced with timber. Winches could be used in some mines to extract ore or water. Archimedes' screw was an invention that enabled mining a little deeper, however, its capacity to lift water was not efficient. Stone and ore were cut by hand or fire-setting was used. This was in use until the explosives began to be manufactured. Although the wheel had been invented, there was no wheelbarrow before the 13th century. Mining was tough and dangerous work.

Bergslagen

Significant mining takes place in Sweden first in area Bergslagen. It touches on several counties; Värmland, Närke, Västmanland, Dalarna, Uppland and Gästrikland. As the name “berg” suggests, it has to do with ”rock” and mining. The ending “-berg” is found in many place names where mining has been conducted, for example Stollberg, Lekomberg, Grängesberg, Fredriksberg, Kopparberg. Bergslagen had the raw material; ferrous rocks, flowing water and large forests. These were the three crucial conditions for developing an iron industry.

It began 2,500 years ago. Iron was then produced from the red earth in the areas around Riddarhyttan. In the 12th century, iron production from iron ore began. Norberg has Sweden's oldest known mines, first mentioned in 1303, but by then the operation had already been running for a long time. Europe's oldest known blast furnace is also located in Norberg. It is Lapphyttan dated to between 1150 and 1225.

From the middle of the 13th century to the 19th century, Sweden was for long periods one of the world's foremost iron producers.



Swedish mines have a long history. The upper part shows mines now in operation and the lower part shows some major historical mines. (blue and green = iron ore, red and yellow = non-ferrous ore mines)
Figure: Bergverksstatistik 2020

At the end of the 13th century, Swedish export goods consisted of hides and furs, tar, iron and agricultural products. Salt, hops, beer, wine and spices and not least clothing were imported. Around 1750, iron accounted for about 70% of Sweden's entire exports. Then it was malleable bar iron of high quality.

Explosives

Around the year 900, the Chinese used black powder. It was not until the 13th century that it came to Europe for use by the military.

The first time black powder was used in a mine in Europe was in 1613 in Germany. The first "drill & blast" is dated to February 8, 1627 in the Schemnitz mine. The first rock blast in Norway was in 1683 in Kongsberg's Silver Mines. In Sweden, fire-setting was a common method of mining rocks, but plenty of firewood was needed. When the silver deposit in Nasafjäll in Lapland began to be mined in 1635, it was a problem to find enough wood up on the bare mountain. German rock blasters were called in to transfer their knowledge with black powder. However, it took a very long time before the black powder became more important in mining. In Sweden, black powder was most often used due to a lack of wood, otherwise it was not until the beginning of the 18th century that it became more common. In the Falun mine, consumption in 1730 was only 42.5 kg, in 1740 it was 4,500 kg and in 1780 15,470 kg.

In the 1830s, William Bickford encapsulated a narrow strand of black powder in a tube of tarred hemp. This way, one got access to a moisture-protected fuse with a relatively accurate burning time, which meant that the rock blaster could light up the shot at the right moment. That way the use of black powder became much safer in the mines.

Nitroglycerin was discovered by the Italian Ascanio Sobrero in 1846. Alfred Nobel heard about nitroglycerin in the early 1850s. The weakness of the nitroglycerin was that it could not be exploded with a fuse and fuse was needed to be able to explode the nitroglycerin in a more controlled way. To solve the problem, Alfred Nobel invented the detonator. Nobel's detonator was a copper capsule with mercuric fulminate, which exploded via a fuse. In 1864 he patented both the detonator and the method of producing nitroglycerin. But the explosive oil, which Alfred called the nitroglycerin when he started selling it, was still dangerous to manufacture and handle. He tried to mix different substances in the nitroglycerin to create a new explosive, and finally found the right combination. When he mixed in a kind of sand called diatomaceous earth in the nitroglycerin, he got a dough-like mass, which was less risky to handle. He called his invention dynamite. It was patented in Sweden in 1867.

Nitroglycerin was in itself a welcome product for the mines, but in terms of safety it was a product that differed significantly from gunpowder. The nitroglycerin came to be used in Swedish rock handling until 1897. The dynamite could not withstand water and Alfred Nobel was not happy with its explosive strength either. He tried to mix nitroglycerin with a small amount of cotton powder (nitrocellulose) instead. This gives a substance that burns easily and explodes if exposed to heavy blows. The new invention was called burst gelatin. The explosive gelatin was stable and as effective as pure nitroglycerin, as the explosive cotton powder did not affect the explosive strength. In addition, explosive gelatin could be used under water. It was patented in 1876.

After this, the explosives have been developed more and more, from frost-free dynamite, to nitroglycerin-free. Nowadays, most explosives that are used, which are so-called emulsion explosives with yoghurt-like consistency. New types of explosives are mixed and become explosive first at the actual blasting site.

Drilling

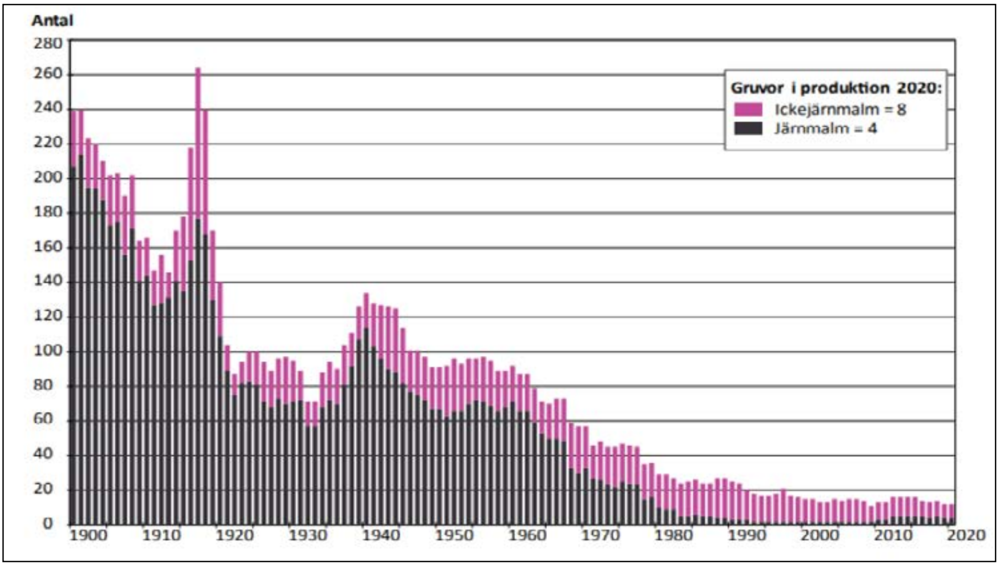
There had not been much progress in drilling since the Roman Empire. Manual force was still needed, and workers, one giving the blow, while the other held skewers which he rotated and held in the correct direction. Drilling driving-depth speed was low and varied according to rock quality. Despite various innovations in explosives, improvement came first with the development of drilling equipment.

In 1857, the first pneumatic drilling machine was launched. Simultaneously with the development of dynamite, the blast holes also needed to be deepened. Now there were also railways and electricity. Development was rapid. The first pneumatic drilling machine came to Sweden to be used in Persbergs Gruv AB. The machine did not work satisfactorily in hard rock and had to be modified on site. Eventually, pneumatic drills replaced percussion and hammers.

New drills also caused problems. They were also called (in the United States) widow-makers because they released a lot of dust, which entered the lungs of the miners and caused a disease called silicosis. The silica dust acted as shards of glass and caused scarring of the lungs. The solution was hollow drill steel, by which one could pump water through to mix with the dust. This created a lot of work to transport the sludge out of the mine, but it extended the lives of the miners. In 1898, Atlas Copco manufactures the first drill that works with compressed air. In 1907, Sandvik began manufacturing hollow steel for rock drilling.

In Stockholm, a rock tunnel was drilled in 1945–1946 through Hägerstensåsen. It was the first use in full operation according to a new way of working that would be called ”The Swedish method” - cemented carbide (tungsten carbide) in the drill steel and the light self-rotating drill with a knee feeder that could be handled by one miner.

Gradually, better drilling platforms or jumbos were developed that made it easy to move the hand-held drilling machines and



Number of mines in operation in Sweden 1900 – 2020 (black = iron ore, magenta = non-ferrous mines)
Figure: SGU

also cover large tunnel areas. In the 1960s, the heavy drilling machines that could only be carried by drilling rigs were launched. Demands for better occupational safety were getting increasingly louder and the new requirements were planned into the construction of new rig models. The hydraulic drill was launched in the early 70's and quickly gained popularity among users. These machines gave about 25% better drilling-depth speed compared to air machines. The development on the drill steel side also took a real step forward with the introduction of pin drill bits. Sandvik was starting to use roller drill bits for ore mining in open-cast mines.

At the end of the 20th century, digitalisation of drilling rigs came and made it possible to measure while drilling. These measured values provide information about the rock material along the borehole.

A long time has passed since the first mines came into operation in Sweden, the number of mines has decreased, but efficiency has improved. The mines will probably be an important industry in Sweden also in the future. Sweden will also be one of the world's leading players in mining machinery.

Sustainability projects in the mining industry

Carbon dioxide-free iron production
SSAB, LKAB and Vattenfall, all national government-owned companies, have started HYBRIT (Hydrogen Breakthrough Ironmaking Technology) with financial support from the Swedish Energy Agency, to jointly develop a fossil-free value chain from mine to steel with fossil-free electricity and hydrogen and thus minimize carbon dioxide emissions throughout the value chain. The technology replaces the blast furnace process, which uses coal and coke to remove oxygen from

the iron ore, with a direct reduction process using fossil-free hydrogen produced from water. Instead of carbon dioxide, water vapor is formed.

The sponge iron or DRI (Direct Reduced Iron) is the next step in the processing chain after the iron ore pellets. Pellets still contain oxygen and must be further processed before they can be used in steelmaking. The iron sponge, on the other hand, is pure, finished iron. Iron sponge is already produced in many places, but now LKAB will do it itself and with fossil-free energy. At LKAB, the iron sponge will be compressed into briquettes, HBI (Hot Briquetted Iron). After that, the value of products increases and transport also becomes easier. The facilities are intended to be built in Luleå and Gällivare.

H2 Green Steel intends to build a plant in Boden to make iron sponge in the same way. H2GS and HYBRIT will thus compete for green electricity in the same part of Sweden.

The steel industry accounts for approximately 10 percent of Sweden's carbon dioxide emissions and seven percent of global emissions. With carbon dioxide-free iron sponge, global emissions will be reduced by approximately 35 million tons of carbon dioxide annually, corresponding to two thirds of all Sweden's emissions. With carbon dioxide-free iron ore products, opportunities are created to produce carbon dioxide-free iron and so-called green steel. The pilot plant at SSAB in Luleå is planned to become operational in 2025. Zero carbon dioxide emissions from processes and products at LKAB will be reached in 2045.

SUM (Sustainable Underground Mining)
The mine of the future is carbon dioxide-free, digitized and autonomous. LKAB, together with ABB, Epiroc, Combitech and Sandvik, has started development projects for sustainable mining at great mine depths. The project requires a completely new type of collaboration, a digital ecosystem where the parties connect both digital systems and operations, new control systems, new and developed mining equipment, and complex and efficient management systems that meet future demands for a sustainable industry. In a test facility, new technology will be developed and tested in a real mining environment and in a virtual test mine. The goal of the collaboration is to find new methods and smarter solutions for future mining. The best way to build an efficient and autonomous production system, which is carbon dioxide-free and maintains the highest possible safety when people and autonomous machines work side by side, must be investigated. The virtual test mine makes it possible to simulate data flows and scenarios, which cannot be tested in the physical test mine.

ReeMAP
ReeMAP Industrial Park, Rare Earth Elements and MonoAmmonium Phosphate, has the ambition to become a center for the chemical engineering industry in the north - an industrial park with a world-leading standard of clean products, energy efficiency and emissions. LKAB can become a significant producer of critical raw materials that are circular and climate-efficient, such as phosphorus, corresponding to five times Sweden's need about 400,000 tons of apatite concentrate (which is further processed into phosphoric acid and MAP / DAP mineral fertilizer products), rare earth metals (Rare Earth Elements, REE) corresponding to 30% of today's imports of REE to the EU at about 2,000 tons, fluorine products for e.g. the chemical industry and medical applications approx. 16,000 tons and gypsum corresponding to Sweden's entire existing needs approx. 650,000 tons.

The enrichment sand, residual product from Kiruna and Malmberget, contains, among other things, apatite, which must be extracted in the form of apatite concentrate in each locality. The apatite concentrate contains phosphorus, rare earth metals and fluorine which are separated and further processed in Luleå. The further processing takes place with wet chemical processes where the material is dissolved and separated. The use of hydrogen and electrified processes means that fossil-based processes become fossil-free. LKAB also plans production of sulfuric acid with pyrite concentrate from Boliden. Hydrogen is produced via electrolysis and renewable electricity. The hydrogen gas is then used in the production of green ammonia. Green ammonia is used to refine phosphoric acid into ammonium phosphates (for mineral fertilizer products). Ammonia can also be used in the production of ammonium nitrate which can be used in Kiruna for production of explosives.

Green copper

The green copper project is part of Boliden's investment to reduce CO_2 by 40 percent until 2030. Boliden's copper smelter Rönnskär outside Skellefteå has recycled various waste materials since the 1960s. Today, the smelter's annual capacity for recycling electronic materials is about 120,000 ton. The material consists of, among other things, circuit boards from computers and mobile phones purchased mainly from Europe. Materials from used or discarded appliances that contain electrical components are an important secondary material. Boliden's copper smelter is one of the world's largest recyclers of copper and precious metals from electronic materials and zinc is also extracted from various residual materials. Upgraded e-waste is called e-scrap. E-scrap is a source of precious metals such as gold and silver, and base metals such as copper. At modern e-waste recycling facilities, such metals can be recycled and reused safely.

The future

All this sounds very good, but most projects do not become a reality until many years from today. How can mining be more sustainable already now? Whenever you dig ore out of the ground, there are permanent traces of mining. However, effects can be significantly reduced with certain measures. Machines, tools and energy used can be sustainable. The machine park can already use electric power instead of diesel. In the short term it will be more expensive to have underground mining, but the environmental impact is significantly less than in a traditional open pit; no noise, dust or visible wounds in nature. It is possible to make an invisible mine when all work is done underground and the soil surface will then remain usable for other users. A technical solution that makes this possible is backfilling of spaces after blasting and excavation will that prevent rock deformations with so-called cut-and-fill mining. A good example of this is Nordic Iron Ore's planned mines in Blötberget, Väsman and Håksberg, where all waste rock is intended to be deposited underground and even parts of enrichment sand can be deposited underground together with the gangue.

To minimize the transport of raw materials, the value chain shall be as short as possible. In practice, this means that raw ore must be enriched into a finished product as close to the mine as possible. It is common for the ore to be enriched into concentrate which is then sent to the next step in the process, namely smelters, in some cases at long distances. Likewise, all goods transports to and from the mine must be carefully planned, everything must be there when needed, but without large inventories. Mining is a lot of logistics of rocks, goods and machinery.

Good planning of this provides benefits in resource utilization. Machine maintenance is an important part of this, no matter what fuel the machine uses - a well-maintained machine works most optimally.

Already today, there are several companies that sell optimization solutions for mines in different sub-areas; materials logistics, ventilation to underground mines, machine control, electricity consumption etc. Ventilation is a large energy consumer and can easily contain large losses if not carefully planned; ventilation should be used where needed (demand control) and with heat exchangers that utilize the heat energy in the exhaust air, these are some examples of solutions. The indirect benefit of electric vehicles is that they also reduce the need for ventilation. In the mine, which Nordic Iron Ore intends to operate in Blötberget within a year or so, it intends to use battery-powered drilling rigs as well as battery-powered explosives-loading rigs. In addition, there may be electric dumper trucks, which get their electricity from catenary wires in tunnel ceilings like trolley buses in cities. All this electrical machinery is then remotely controlled from ground level with very few people underground. This means that the ventilation power requirements can be significantly reduced. Calculations performed for Nordic Iron Ore show that the effect for heating ventilation air to 2 °C would in that way decrease to 2 MW from 5 MW, which would be economically valuable as the energy is expensive in winter.

There is also a program for sustainable mining that was originally developed by the Mining Association of Canada (MAC) to improve the social and environmental impact of the mining industry. The Toward Sustainable Mining (TSM) initiative means that the mining companies' facilities are evaluated annually in eight areas, where they look at energy use, greenhouse gas emissions, enrichment sand management, consideration for indigenous peoples and the impact on biodiversity. TSM has proven to be a good tool and method for measuring environmental performance. Norwegian Mining Industry and the Finnish Mining Association, FinnMin are members of TSM. In Norway and Finland, the method has been adjusted to suit society and legislation.

Nuclear fusion – useful energy generation or research toy

Gunnar Flisberg

Introduction

Will fusion energy be able to be used by humanity and offer cheap, safe, inexhaustible energy without any emissions? Or is the dream of catching the sun in a donut just a dream? For the past seventy years, scientists have tried in vain to emulate the fusion that takes place on the sun. The message has always been that fusion energy will be able to be utilized for humanity within 30 years. ITER, the huge research facility currently being built in Cadarache, France for 20 billion Euro, is the latest step in finding out if it is possible to tame the forces of nature and convert the energy into a conventional power plant.

Another article in this book “Swedens´s first experimental reactor for fusion energy” describes how early experiments to achieve nuclear fusion were carried out at Uppsala University in 1958 with equipment from ASEA in Ludvika. This aroused our interest in power generation by nuclear fusion and whether this technology will ever be realized. The state of research is examined in this article.

Merging two hydrogen atoms into helium is a form of fusion. During the fusion, neutrons and energy are released in the form of heat that can be used to drive a steam turbine / generator in the same way as today takes place in a coal-fired power plant. In fusion, the long-lived isotopes that require storage for many thousands of years are not formed before the radioactive radiation has been reduced to harmless levels. A fusion power plant is also designed in such a way that the reactor can not experience uncontrolled nuclear fission, which means such high temperatures that the reactor core melts down and radiation is spread uncontrolled in the environment, which took place in Chernobyl and Fukushima. During fusion, the fuel is gradually added in small amounts at a time. The fuel in the form of two (deuterium) and trivalent (tritium) hydrogen atoms is available in the sea, partly deuterium and also lithium, which is used for the production of tritium. Easily available fuel lasts for several million years. The fuel has a higher energy density than any other naturally occurring alternative. 25 grams of fuel is enough for a person’s lifetime consumption of energy. A reactor is safe for mankind. An error causes the process to be interrupted and there is only fuel for a few minutes at a time in the reactor. Thus, the reactor can not give rise to a rampant reaction, which can happen in today’s nuclear reactors when you charge them with fuel for several years. We summarize the research on fusion energy that has been carried out so far and point out the difficulties that remain before the technology is ready for commercial use.

The Swedish researcher Hannes Alfven, who was an active opponent of nuclear energy in the form built in Sweden during the 1970s and 80s, instead recommended the use of nuclear energy in the form of fusion. Today’s nuclear power plants are powered by heat that is released when a uranium atom decays and heat is formed during the decay. This process is called fission. The Swedish Nobel Laurete Hannes Alfven recommended instead of present day nuclear fission technology to use fusion for energy generation. He held a speech at VBIK in 1945 with the title “Extraction of nuclear energy” and also in 1961 with the title “Plasma physics”

Fusion

The fusion that usually occurs in today's experimental reactors uses divalent hydrogen atoms, deuterium as a fuel that is brought together to form helium, releasing energy during the process. Even more released energy is obtained if both divalent and trivalent (tritium) hydrogen are used as fuel, see Fig. 1.

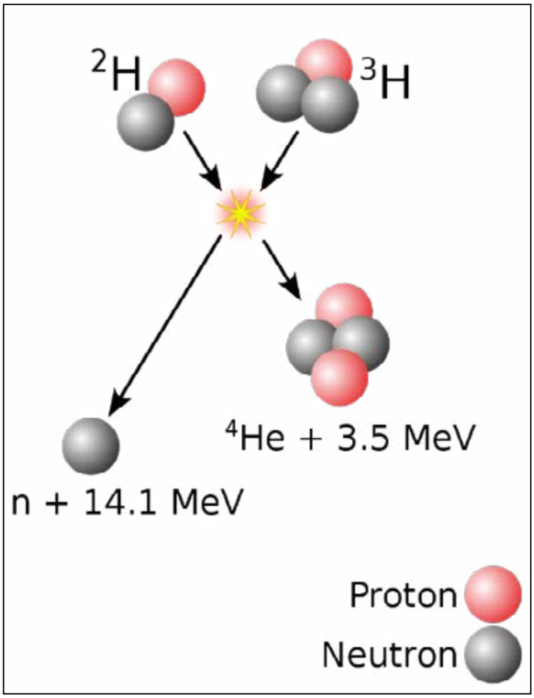


Figure 1 Hydrogen atoms in the form of deuterium and tritium are fused to helium. A neutron and kinetic energy are released in the process (Wikipedia)

Fusion of hydrogen atoms takes place in the sun under high pressure, and high temperature, 15 million degrees. The sun reaches this temperature as it accumulates material and the gravitational pressure increases the temperature in its center. Eventually it gets so hot that the mass of protons and electrons in the form of plasma, inside the sun begins to fuse and create energy. The high pressure in the sun cannot be realized on the earth's surface. Instead, the temperature can be raised to 150 million degrees to make possible the fusion of hydrogen atoms. The fusion takes place in a plasma consisting of ionized hydrogen gas which is achieved by heating to 150 million degrees. The plasma is created in an initially evacuated vessel, in which small amounts of fuel are added and heated. Due to the high temperature, the plasma must be controlled in the reactor vessel so that the walls are not touched as these would melt down immediately from the high temperature. The plasma is formed in the center of a toroid,

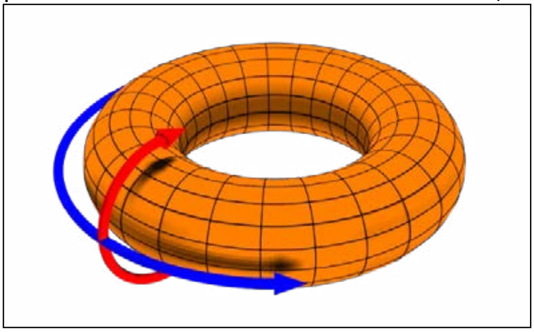


Fig 2. Toroid. Magnets control the plasma current torodially (blue arrow) and polodially (red arrow)

Fig. 2 and is prevented from touching the walls by means of a magnetic field, see Fig. 3. Ionized hydrogen atoms each with a released electron are charged particles and can therefore be enclosed in the center of the toroid by an external magnetic field.

The toroid that contains the plasma is usually called tokamak, which is the Russian word for a magnetic confinement in a toroid. The basic principles for the construction of a tokamak reactor were launched by the Russian physicists Igor Tamm and Andrei Sakharov, inspired by Oleg Lavrentiev. The first experimental tokamak T-1 is attributed to Natan Yevlinsky in 1958. This first experimental reactor was built at the same time as an experimental reactor at Uppsala University by professors Kai Siegbahn and Per Olin, which is described in the chapter "Sweden's first experimental reactor for fusion energy" in this book. Basic research in Sweden was further conducted at an early stage by Nobel Laureate Hannes Alfven and by research groups at the University of Uppsala, KTH and Chalmers University of Technology.

In addition to the coils surrounding the toroid, there is a primary coil located in the center of the toroid. The externally generated current in this coil is transformed over to the plasma to drive a plasma current. This plasma current supplies both a polodial magnetic field and heating of the plasma, Figure 3, but with this method reaches only one third of the temperature required to start a fusion. For further heating, a jet of neutral fuel particles, usually deuterium, is injected. These particles, which are not affected by the magnetic field because they are not electrically charged, collide, after insertion into the plasma, with the plasma particles and thereby transfer their kinetic energy to the plasma and are ionized in this collision. An additional method of heating the plasma is to inject high frequency radio waves, similar to those in a microwave oven.

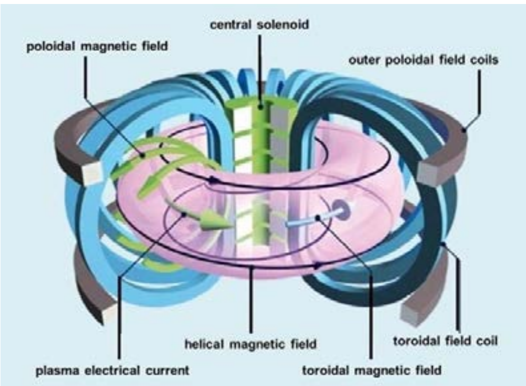


Fig 3. Tokamak, toroid with toroidal and polodial magnets. The task of the polodial coils is to counteract the tendency of the plasma to expand in the direction of the great radius of the toroid, (Wikipedia).

When the plasma has reached the temperature, about 150 million degrees, fusion takes place and the conditions are such that the burning plasma can continue in a self-sustaining process. This occurs when two hydrogen ions receive sufficient kinetic energy to overcome the repulsive forces between the protons in the atomic nucleus. When sufficient temperature to start the fusion is reached, the fusion can continue with the intrinsic energy of the plasma as long as fuel in the form of hydrogen atoms is supplied. The thermal energy generated by the fusion is transferred to plates on the inner surfaces of the toroid. 80% of the energy released during the fusion consists of kinetic energy of the formed neutrons, Fig. 1. Their movement is not controlled by the magnetic field but continues very quickly in the direction they received during the fusion. They are slowed down by the thick walls of the enclosure called ”blankets”, thus hitting the plates on the toroidal walls and transferring their kinetic energy to the plates, which thereby increases their temperature. Cooling loops are connected to the plates and ”blankets”. The water in the pipes boils and steam is formed. The steam drives a turbine in the same way as in a conventional steam power plant.

JET, Joint European Torus, Culham, U K

JET tokamak reactor was built with the hope of reaching break-even with an efficiency Q> 1, i e that the generated energy is higher than the supplied energy to heat the plasma. Operations began in 1983 and in 1991 a controlled merger was reached. In 1997, 16 MW of fusion energy was created, but the supplied energy was at the same time 24 MW, i e an efficiency Q = 0.67, which at that time was a world record. As the first party in the world, they began to use a mixture of an equal amount of deuterium and tritium as fuel.

The reactor has a main diameter of 3 meters and a D-shaped vacuum vessel, 2.5 m wide and 4.2 m high with a total plasma volume of 100 cubic meters. The D-shape reduces the mechanical forces that strive to propel the plasma toward the main axis of the toroid, since the magnetic field contained is strongest on the inside of the toroid. After upgrading, the walls of the vacuum vessel are reinforced with tungsten and beryllium.

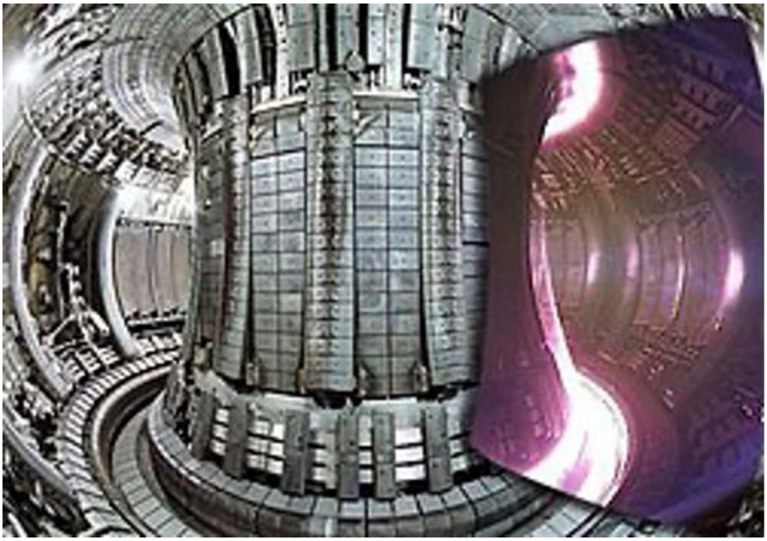


Fig 4 Inside of JET tokamak. An inserted image shows the plasma taken with a video camera showing the visible light of the plasma, (Wired U K).

The vacuum vessel is surrounded by 32 copper-wound magnets, each weighing 24 tons. In total, they induce a current of 51 MA to the plasma for a few tens of seconds. In addition to this magnetic field, there is a toloidal magnetic field (Fig. 3), which encloses the reactor vessel and induces a current in the plasma, which produces a polodial field which means that the plasma has a resulting rotating field / current. The current also helps to heat the plasma. Further heating takes place via two systems, a 25 MW positive neutron particle accelerator which shoots neutral fuel atoms into the plasma which collide with particles in the plasma and are ionized and thus become trapped in the plasma. The second system is a 15 MW ion cyclone resonance heating, equivalent to microwave heating using radio waves. In February 2022, JET announced that it had maintained a plasma for five seconds that with fusion generated 12 MW, I e 60 MJ of fusion energy, which is a world record.

ITER, International Thermonuclear Experimental Reactor

Iter, which means ”the way” in Latin, is under construction in the south of France and is a political cooperation project between the EU, the USA, China, India, South Korea, Russia and Japan. Iters goal is to maintain a fusion for at least 1000 seconds. ITER is about 20 times larger than the JET reactor. Construction began in 2010 and the first plasma is expected to be achieved in 2025.

Iter is located in Cadarache, where there is a strong electrical network with ample access to energy. Originally, the reactor was to be completed in 2016, but the schedule has been exceeded several times. One reason for the delay in construction is the large low-temperature (-269 degrees C) superconducting magnets on 13 Tesla that enclose the reactor. These superconducting magnets are a prerequisite for being able to build the reactor. They are made of niobium tin and niobium titanium. When assembled, the central magnet will be 18 m high and 4.25 m wide.

The fuel for the fusion consists of deuterium and tritium. Tritium is produced in the fusion reactor by cladding the walls with lithium. When neutrons formed during fusion merge the walls, lithium is converted to tritium.

The step after ITER is to build a demonstration reactor, DEMO, which will be able to produce 500 MW for at least 400 seconds. The current world record is held by KSTAR in South Korea, which has managed to keep a fusion going for 100 seconds with an efficiency Q = 0.67, I e more energy is required to supply the reactor than it produces.

Wendelstein 7-X stellarator vid Max Planck Institutet, Greifswald

50 electromagnets enclose the stellar array and consist of a number of turns of finger-thick niobium-titanium alloyed wires enclosed by a casing. Inside the housing together with the wires, helium gas flows at a temperature of -269 degrees C, I e the conductors are low-temperature superconducting. The resistance in the magnetic winding is too high compared to the resistance in the plasma if the magnetic winding were not superconducting.

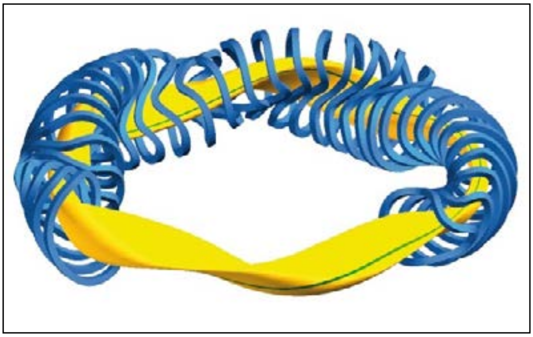


Fig. 5 Wendelstein 7-X Stellarator. The hot plasma (yellow) is held in place by a helical magnetic field (blue) and the reactor vessel in the stellar tower is rotated so that it also becomes helical, (Wikipedia)

The temperature in the plasma is measured with a laser. A high-frequency laser beam that hits the plasma has a frequency change that can be read. With the help of the frequency change, the temperature in the plasma can be determined.

In a stellarator, the fusion can be maintained continuously unlike a tokamak where the fusion can only take place intermittently in a pulsed process. In the stellar array, the stability of the plasma is controlled directly by the magnetic coils. In the tokamak, the plasma current must also be controlled.

ARC (affordable, robust, compact) fusion reactor

ARC is being developed by the Massachusetts Institute of Technology, MIT, and is planned as a Tokamac intended for deuterium and tritium as fuel. The goal for ARC is to achieve an efficiency Q = 3, ie that the reactor should produce three times as much energy compared to the input energy. It is equipped with magnets of superconducting tape of outerium, barium and copper oxide, REBCO. These can achieve high field strength, 23 Tesla and be cooled with liquid hydrogen at a temperature of 20 degrees K, so-called high-temperature superconductors, which is considerably cheaper than low-temperature superconductors, which must be cooled with liquid helium. ARC has a reactor radius of 3.3 m and is planned to generate 27 MWe. A liquid salt, fluorolithium beryllium, FLiBe, surrounds the vacuum vessel as a shell. This casing is in a molten state up to 800 degrees K and thereby serves as neutron moderation, heat dissipation, shielding and tritium generation with a ratio> 1.1, ie for each neutron that hits the casing, 1.1 tritium ion is released, which is added to the plasma as fuel. ARC differs from the ITER reactor in that it uses high-temperature magnets and can therefore be built much smaller and more cost-effectively.

Korea Superconducting Tokamak Advanced Research, KSTAR

KSTAR tokamak is a research reactor in Daejeon, South Korea that was commissioned in 2007 and is still in operation. In May 2021, a new record was set in keeping the plasma higher than 100 million degrees for 100 seconds. The reactor is relatively small with a large diameter of 1.8 m and a small diameter of 0.5 m. It is equipped with 16 niobium-tin superconducting field magnets, 10 niobium-tin polodial field magnets for alternating current and 4 niobium-titanium polodial field magnets for alternating current. Much of the results of the research conducted at KSTAR are experiments that will be used by ITER when this reactor is started up in a few years.

Control system for controlling the plasma in a reactor

The Swedish researcher Hannes Alfven received the Nobel Prize in Physics in 1970 for his discoveries of the so-called Alfven wave, which opened up a new field of research, magnetohydrodynamics, some of which is plasma physics. Alfven mapped the magnetohydrodynamic forces that control a plasma that conducts current. An equivalent magnetic moment causes the electric charge to move in a spiral in the magnetic field. Alfven's theory is fundamental to understanding the motion of plasma in a fusion reactor.

Princeton Plasma Physics Laboratory, PPPL, is a US national laboratory for plasma physics. Its primary mission is research and development of fusion as an energy source. PPPL has computer-simulated the shape and temperature of the plasma both in terms of ion and electron motions. Magnetic sensors detect the position of the plasma in the reactor and a control system commands the magnetic field to change the position of the plasma. Like boiling water, bubbles appear on the plasma surface. These bubbles lower the temperature of the plasma. The simulations aim, among other things, is to eliminate the bubbles on the surface of the walls. It has been found that the core of the plasma and ”walls” behave differently. A high temperature gradient in the layer between the core and walls of the plasma increases the turbulence of the charged particles, which in turn increases the temperature gradient. If the core of the plasma is heated sufficiently, a moment is obtained which causes the core and walls of the plasma to rotate in different directions and at different speeds. This phenomenon is a sheared flow between core and walls. The rotation can be used to improve the stability and performance of the fusion. The different rotational speeds provide a balance between torque and the viscosity of the plasma, which stabilizes the plasma. Under certain circumstances, the plasma can organize itself by forming a shear flow.

Inertial fusion, National Ignition Facility, NIF

The National Ignition Facility, NIF is an inertial reactor at Lawrence Livermore National Laboratory in Livermore, California. Fusion is achieved with the collapse of a small amount of fuel that is exposed to high pressure and temperature by shelling the world's most energy-rich laser. The laser causes the envelope around the fuel to explode and the material reaches a speed of 350 km/s, which causes the fuel to fuse. Construction began in 1997 and was completed in 2009. In 2021, fusion reactions in NIF produced 70% of the laser energy, thus breaking the current world record in efficiency.

A project similar to NIF, Laser Megajoule, has been developed in Bordeaux, France, while a commercial project, High Power

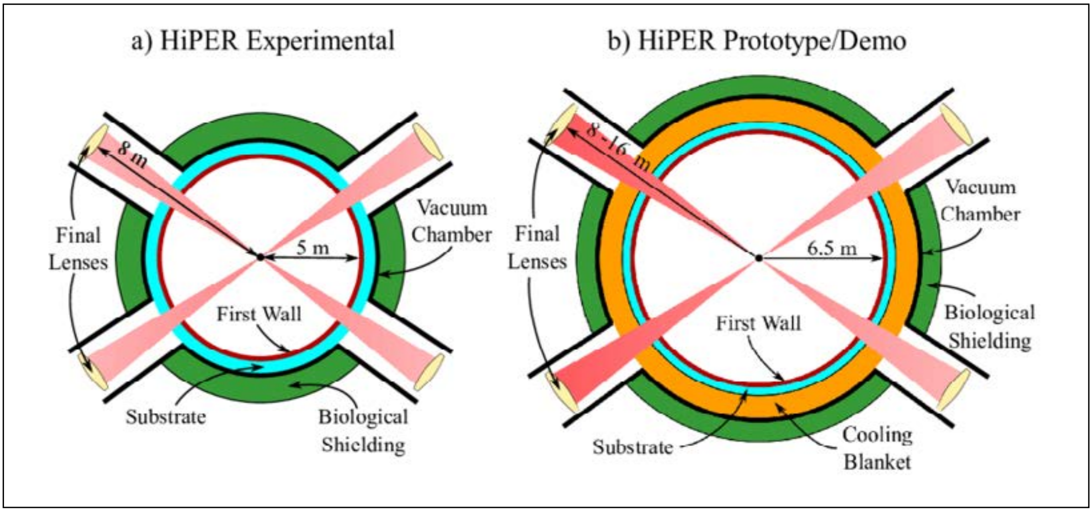


Fig. 8 Inertial fusion (Researchgate)

Laser Energy Research Facility within the EU, is planned.

Research situation today

Harvesting energy by merging light atomic nuclei in a fusion process is extremely enticing: the fuel is almost inexhaustible, the process harmless and the residual products relatively harmless. All this in contrast to the fission in ordinary nuclear reactors, where the energy comes from broken atoms in a reaction that can run away out of control and where life-threatening waste radiates for thousands of years.
The first hydrogen bomb in 1951 exploded in the United States and showed that nuclear fusion works. Controlling the process has proved enormously more difficult than expected in the early 1950s when the hopes of catching the sun in a small box were a very beautiful idea. The problem was that we then did not know how to construct the box.
Around 2035, a prototype reactor, Demo, is planned, which will be able to continuously generate several times more energy than Iter. It is in this that one intends to start producing electricity. Operation of Demo will be able to learn from the experience of JET, which in 2022 produced 12 MW for five seconds. Industrialization and commercialization of the technology is likely to take another decade. It is therefore difficult to believe that we will see a commercial fusion plant in operation before the year 2050. Only when the technology has been clarified will profitability and commercialization come in play. It's really a tough task. We are going to build something that no one has ever done before. It is a huge challenge for engineering. And fun for our generation of engineers to be part of this journey.
There are about forty plants in the world that are working with different methods to keep the hot plasma in control and initiate the reactions. Sweden has a long tradition of fusion research, with research groups - in Stockholm, Gothenburg and Uppsala. Now they focus on Iter alongside their own projects.
The construction of Iter has been criticized by the fusion researchers themselves. Sebastian Balibar, professor at the ENS University of Paris, has in an interview3 questioned the 200 billion SEK Iter costs because it is still basic research. ”I doubt it's worth the money - Iter will not solve the world's energy problems for long, if ever.

There is no material developed for cladding the walls inside the reactor, we have not invented industrial tritium production either, and it is also tricky to gain control of the plasma cloud.“
Bruno Coppi, professor of physics at MIT in the USA and the master of fusion research, has similar objections3 according to an interview. According to him,” Iter is the wrong way at alltogether, rather it misses with Iter the chance to get nuclear fusion as an alternative energy source in the future. To think that you can put the spirit in the bottle, which Iter plans for, is wrong”, he says. ”Instead of solving the problems, as is usually done in research, they invest here on large-scale experiments and risk a flop,” he says. “The plasma behaves differently when the volume increases. It is not a linear process - it will be far too unstable - and we will never have control over it. ”
”Building Iter is a political decision,” says Sebastien Balibar. ”It is a pharaonic project, a symbolic monument in the style of the International Space Station: large and expensive but with a small scientific dividend.”

Indeed, the project was initiated in 1985 by Soviet leader Mikhail Gorbachev and US President Ronald Reagan as a joint venture. Like so many other political projects, the different political wills have moved in different directions, but now, 37 years after the decision, we are here. The profit if you succeed is almost too good to believe in it - unlimited access to energy for all the foreseeable future. Like catching a star in a box.
I personally do not believe that fusion when the process is realized will solve all of the earth’s energy problems. Today’s extremely rapid development of solar and wind power has great advantages in being able to be placed in the form of small units locally close to consumption with reasonable needs for financing. Fusion reactors will require large units with associated high financing costs. Today, the cost of solar and wind power is 0,5 -1,0 SEK/kWh, and the cost is still falling. The fusion power will therefore hardly be able to compete with solar and wind power alone in terms of price per kWh. However, fusion power will play an important role in forming the backbone of electrical networks by supplying base power that Is planable, unlike solar and wind power, which sometimes fail at high pressure when the wind is not blowing and at night when the sun is not shining. In addition, turbines/generators in a fusion power plant can provide short-term stability in the electricity grid when disturbances affect other generation, e g in the event of fault in the electricity grid. These characteristics inherent in the fusion power means that fusion power will complement the stabilizing role that today´s nuclear and hydropower have.

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3. ”Up to evidence of nuclear fusion” Joanna Rose

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– från Smedjebackens Walsverk till Ovako
Lars-Uno Rystedt

Bruket vid Barken, Smedjebackens Valsverk genom hundra år. Axel Gjöres, 1956

Fundia Special Bar AB – en berättelse om två järnbruks sammanslagning och utveckling till en modern stålindustri. Tord Anjou och Per-Olof Ruberth

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Tack för att Ni bidragit med fakta och annan hjälp

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Morgårdshammar,
”En industrisaga utan riktigt gott slut”
Jan-Olov Schröder

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Kärnfusion
– billig säker energi eller ouppnåelig dröm
Gunnar Flisberg

Referenser
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2. *”The bizarre reactor that might save nuclear fusion” Daniel Clery*
3. *”Upp till bevis för kärnfusion” Joanna Rose*

In 2022, Västerbergslagens Ingeniörsklubb VBIK will have been active for one hundred years. During the century that has passed, the association's engineers have been part of, and often been key people in, the very strong technological and industrial development that characterized the area. This anniversary book wants to highlight the very big changes that have taken place through selected stories related to the area's business life.

- Ore mining in Grängesberg's mines
- Electric power transmission with alternating and direct current
- Tap-changers for transformers
- Development work and trends around fusion energy
- Mining and rolling mill equipment from Morgårdshammar
- Steel production and rolling in Smedjebacken
- Mining technology development and future trends