Development of Kraft Recovery Boilers – What have been the Main Development Steps?

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ABSTRACT

Tomlinson-type recovery boiler is celebrating its 85th birthday in 2019. Tomlinson-type recovery boiler has set the basis for modern kraft recovery boilers. Throughout its history, kraft recovery boilers have been widely developed, focusing mainly to increase safety of the operation, boiler availability, firing capacity, power generation, and to decrease emissions to the atmosphere.

All the way, different trends and demands have been guiding the development of kraft recovery boilers. However, three main topics, which have had the biggest influence on kraft recovery boiler development, can be pointed out; 1) economy of scale, 2) power production, and 3) reduction of nitrogen oxide (NO_x) emissions. These have led to increasingly larger furnaces, lower emissions, and higher power generation efficiencies. Today, a modern kraft recovery boiler has features similar to power boilers along with efficient recovery of the cooking chemicals.

This paper will review the development of kraft recovery boilers during the last six decades; how the trends and demands have modified the kraft recovery boiler process, what have been the major steps in the development, and how these changes have affected the layout, structure and process parameters of kraft recovery boilers? This review is based on the data available on units in operation and reference databases.

INTRODUCTION

The kraft process was invented in 1879 and patented in US in 1884 /1/. The first pulp mill using this technology was started in Sweden in 1890 /2/. The invention of the kraft recovery boiler by G. H. Tomlinson in the 1930s was a milestone in the advancement of the kraft process /3/. It enabled the recovery and reuse of the inorganic pulping chemicals in such a way that a kraft mill became a nearly closed-cycle process with respect to inorganic chemicals. For this reason, the kraft process has become the dominant method for producing wood-based pulp.

ANDRITZ (former Ahlström) delivered its first kraft recovery boiler in 1952 to Lohja mill in Finland /4/. The capacity of this boiler was 110 tds/d and steam production 5.0 kg/s (18 tons/h). The steam outlet temperature was 400 °C and steam pressure 45 bar. In 2016 the world's largest kraft recovery boiler at PT. OKI Pulp & Paper mill in Indonesia was started-up /4/. The capacity of the boiler is 12 000 tds/d with a steam production of 582 kg/s (2 095 tons/h). Steam outlet temperature is 515 °C and steam pressure 110 bars.

These two deliveries reflect extremely well the entire development path of kraft recovery boilers during the last 65 years. The capacity and steam production have increased hundredfold. However, the steaming ratio (kg of steam produced per kg of dry solids burnt) of the new OKI boiler is only 7% higher than in the first boiler delivered in 1952. The steam outlet temperature has been increased from 400 °C to 515 °C, which is the highest steam outlet temperature for the present. This is mainly due to alkali-induced high-temperature superheater corrosion /5/.

The development of kraft recovery boilers has always been directed by internal (pulping industry) and external (authorities) demands. Pressures to lower atmospheric emissions from pulp mills, namely sulfur dioxide (SO_2) and nitrogen oxide (NO_x), have strongly affected the furnace dimensioning and air system design. The introduction of high dry solids firing in early 1990s is beneficial in maximizing power production and minimizing SO_2 emissions, but at the same time sets challenges to minimize NO_x emissions /4/.

Modern kraft recovery boilers are able to produce considerably more power than two decades ago /6/. After black liquor was given a green fuel status, the interest to invest on power production from recovery boilers has increased, too. Therefore, modern recovery boilers have features common to power boilers, such as the recovery of heat from the fluegases. Older pulp mills with old recovery boilers have still large deficiencies in energy and they have to buy energy from the grid. In the newest state-of-the-art pulp mills energy self-sufficiency of is even as high as 240% /7/. Subsidies are also paid to the pulp mills in many countries for producing green electricity to the grid.

This paper consists of a review of major development steps in kraft recovery boiler furnace and process during the last 65 years. It is based on personal experiences, units in operation and on reference databases. The main focus is on the effect of global trends on kraft recovery furnace dimensioning and design.

FORMATIVE YEARS OF KRAFT RECOVERY BOILERS

The following is a summary of the most important steps in the development of kraft recovery boiler process and furnace in different decades. Sometimes, the development has proceeded via trial and error, when new innovative steps have been tested in full scale. However, despite the setbacks in the development path, the focus has always been on the future. Sometimes these setbacks have also rendered possible a major leap in the development.

Highlights from Early Years 1950-1970

The first kraft recovery boilers were started-up at the Oulu mill in Finland in 1937, when five Babcock & Wilcox (B&W) boilers were commissioned during the same year. The capacity of the boilers was 120 tds/d, steam outlet temperature was 420 °C and steam pressure 32 bars. Steam production was 4.4 kg/s /8/. Totally 55 new kraft recovery boilers have been built in Finland since 1937. The oldest recovery boiler still in operation in Finland is the 1959 vintage boiler from Combustion Engineering (CE) at the Kotka mills. Currently, Finland has 17 kraft recovery boilers in operation.

In the 1950s all kraft recovery boilers supplied had a capacity below 400 tds/d. They had low steam pressure (< 60 bar) and had a two-drum design with carbon steel tubing. Steam outlet temperature was typically around 400 °C. In the 1960s the design of new pulp lines was based on the following facts:

1. Amount of wood raw material available, wood quality, and wood logistics
2. Produced pulp quality and its markets
3. Available resources (personnel, services, utilities…)
4. Available technology (e.g. recovery boiler)

Typical capacity of a pulp line in the 1960s was at that time 100 000 ADt/a corresponding to around 250-300 ADt of daily production. The main technical factor limiting the pulp mill size was recovery boiler capacity. Recovery boiler markets in the 1960s were governed by B&W and CE, while Ahlström and Tampella were just entering the markets.

The first high-pressure (pressure > 65 bars) recovery boiler in Finland with carbon steel wall tubes was supplied already in 1959 by CE to Kotka mill. The second high-pressure boiler was started-up in 1961 at the Äänekoski mill. The capacity of the boiler was 480 tds/d with steam temperature and pressure of 480 °C and 82 bars. Several other high-pressure boilers with carbon steel tubing were delivered during 1960s. After a short period of operation, all these boilers started to suffer from rapid carbon steel wall tube thinning. In Finland, a national research project was initiated in 1964 to find out the root cause for the rapid wall tube degradation. All Finnish pulp producers and boiler suppliers were involved in the project. This project also led to the establishment of the Finnish Recovery Boiler Committee (FRBC) in 1964 /8/.

According to the study, the root cause for rapid tube thinning was sulfidation by reduced gaseous sulfur compounds /9/. It was also concluded that the only way to prevent this type of corrosion is to use high-chromium materials. However, due to the risk of stress corrosion cracking (SCC) in case of poor water quality, high-Cr steels could not be used as solid tubes. This dilemma was solved by introducing a new type of tubing called the composite tube /10/. A composite tube consists of a pressure bearing carbon steel inner tube with a stainless steel cladding on the carbon steel to minimize issues due to corrosion. The first composite tubes consisted of carbon steel inner tube and a sulfidation resistant austenitic AISI 304L cladding. First commercial installation using composite tubing with AISI 304L cladding was started up in 1972 in Sweden /10/. Good experiences of 304L composite tubing in furnace walls encouraged the suppliers and boiler users to replace carbon steel floor tubes with composite tubing, too.

In older recovery boilers, economizers were of cross-flow type (horizontal) and equipped with finned tubes. These were extremely sensitive for fouling and plugging and had to be located after the precipitators. However, those had to be cleaned after 1-4 weeks operation. Either water or falling shots were used for cleaning the economizers. The falling shots is a cleaning method in which small steel balls from the upper section of the economizers are dropped down into the lower section to remove deposits from the tube surfaces. The dropped balls are subsequently collected at the dust outlet and pneumatically returned to the upper section to be ready for the next shot. In recovery boiler operation, since the collected dust is recycled back to the recovery cycle, possible inclusion of steel balls in the recycled dust and its impact on recovery equipment made the method impractical /11/. First long-flow type economizers, where water flows upwards and fluegases flow downwards along the tubes, were introduced in 1960s. In the mid-1970s, half of the recovery boilers delivered in Scandinavia were equipped with long-flow economizers /8/.

Highlights from Middle Age 1970-1990

In the 1970s and 1980s recovery boiler capacity was steadily increasing, as well as the dry solids content of virgin black liquor. In the 1970s and 1980s steam temperatures and pressures were kept around 480 °C and 80 bar, respectively. No breakthroughs from different suppliers were introduced in that respect. Virgin liquor dry solids content was steadily increased up to 70-75% level.

One major step in the development was the single-drum approach. In single-drum design the lower drum (mud drum) was removed and the two-drum concept replaced with one steam drum and boiler generating bank (BGB). The first single-drum recovery boiler was supplied already in 1950 to Lohja mill in Finland, but the first modern single-drum recovery boiler was supplied by Götaverken in 1984 /8/. Single-drum design became more common in the 1990s.

During 1970-1990 no major steps were taken to increase the boiler capacity, which were still under 2 000 tds/d. Figure 1 shows the growth of kraft recovery boiler capacity during 1950-1990. As can be seen from Figure 1, both the maximum and average capacities were growing hand in hand. Recovery boiler capacity of 3 000 tds/d was exceeded for the first time in the early 1990s. This capacity was long thought to be the maximum for kraft recovery boilers due to several different reasons. One of the major issues limiting the capacity increase was a general belief that in large furnaces air jet penetration would be insufficient and mixing poor. However, the development of computational fluid dynamics (CFD) simulations in late 1980s superseded these beliefs and encouraged the design of larger recovery boiler furnaces. Nothing, but avoiding too high risks, was then limiting the growth in furnace size.

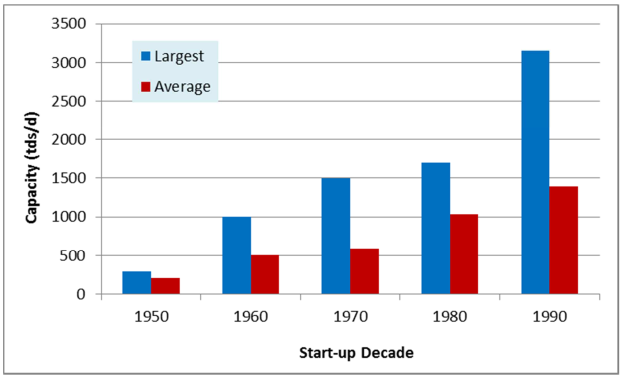

Figure 1: Development of kraft recovery boiler capacity during 1950-1990. Figure shows the maximum and average boiler capacity in each decade.

A few years after AISI 304L composite tubes were adopted for use in recovery boilers, cracking was found in the stainless steel outer layer of tubes that formed smelt spout openings and, subsequently, in composite floor tubes. By 1992, it was apparent that cracking of the AISI 304L layer in composite floor tubes was a widespread problem across the pulp and paper industry. Several studies have since addressed aspects of this problem /12/.

In almost every case, cracks in composite floor tubes were initiated by stress corrosion cracking. Stress corrosion cracking requires that tensile stresses are present on the tube surface at the same time as the tube is exposed to a specific liquid corrosive environment. Under exceptional circumstances, and in very few tubes, thermal fatigue might play a role in initiating cracks. Once a crack has initiated in a tube surface, it may continue to grow by SCC, by thermal fatigue, or by a combination of both /12/.

Extensive studies and research projects were started to find the root cause for observed opening and floor tube cracking. The root cause for crack formation on AISI 304L was the differences in thermal expansion coefficients between carbon steel and AISI 304L cladding. These differences resulted in high tensile stresses leading to crack formation. The nature of the cracks also confirmed that thermal fatigue was not the root cause for the cracking. When the root cause for the floor tube cracking was confirmed, new materials with thermal expansion coefficient closer to carbon steels were developed and introduced.

Alloy 825 type composite tubes have superior resistance to SCC and have now replaced AISI 304L composite tubes in recovery boiler floors. The first complete alloy 825 composite furnace floor was commissioned in 1996 and is still in operation without any issues /10/. Presently, there are two options for floor tubes; 1) carbon steel or 2) composite tubes with alloy 825 cladding. For the present, recovery boiler furnace floor tube cracking issues have been solved.

Highlights form Mature Years 1990-2010

The 1990s can be referred to the era of recovery boiler development. A number of new processes, which dramatically changed the behavior of the boiler, were introduced during 1990s. Extensive fundamental studies were also carried out to better understand black liquor combustion process and dust formation /13-15/. Several companies and research institutes were also studying black liquor gasification /16/.

In the early 1990s high dry solids firing was taken into operation. When 80% dry solids black liquor was introduced into the recovery boiler furnace, an immediate result was a significant reduction in SO_2 emissions /17/. Both the SO_2 and hydrogen sulfide (H_2S) emissions were practically zero when high dry solids firing was in operation. Another positive effect was an increase in the reduction rate and an increase of more than one percentage unit was recorded. Other observed benefits were an increase in steam generation and better controllability of the boiler.

Combustion of non-condensable gases (NCGs) in the recovery boiler was also started in 1990s. Collection of NCGs and combustion in the recovery boiler furnace solved most of the odor issues of the pulp mills. Combustion of biosludge in recovery boiler was commissioned in Finland in 1992 /18/. This process solved some of the issues related to biosludge disposal, but in some mills it generated serious issues in green liquor clarification and filtering. Combustion of biosludge in the recovery boiler recycles some of the chlorides (Cl) in the effluents back to the recovery cycles.

In the beginning of the 1990s, a 3 000 tds/d recovery boiler was considered to be huge in size and it was generally believed that this was the maximum size that a recovery boiler could ever reach. At that time a single line pulp mill was typically dimensioned according to the recovery boiler size. The era of rapid increase in mill capacity and recovery boiler furnace size was seen in the next millennium. The development of CFD simulations enabled the design of larger furnace sizes. Simulations with CFD showed that the penetration of air jets and good mixing was not limited by the furnace dimensions, which was also confirmed with the first boilers operating with capacities higher than 3 000 tds/d. This encouraged the boiler suppliers to increase furnace size and the firing capacity of the recovery boilers. A new recovery boiler was started up in 2004 in Pietarsaari, Finland. At that time it was the world's largest recovery boiler with a capacity of 4 450 tds/d /6/.

Today, the world's largest recovery boiler in operation has a gigantic capacity of 12 000 tds/d. However, even larger furnaces and capacities are on the design board. The next world's largest recovery boiler will be started up in 2021. The capacity of this new kraft recovery boiler will be 13 000 tds/d and only time will show how long this will the world's largest recovery boiler. Figure 2 shows the how the capacity of kraft recovery boilers has developed from 1950 till 2021, when the new world's largest recovery boiler will be started-up. Today, recovery boiler size is not anymore limiting pulp mill capacity and lines with a capacity of 2.5 MADt/a (7 000 ADt/d) has been already realized (Figure 3).

Highlights from Recent Years 2010-2020

Digitalization is progressing in leaps and bounds: the main reasons for this are technical progress, constant further development of the internet, mobile applications and technologies based on artificial intelligence, and increasing globalization. Technology trends emerging as a result of digitalization, such as internet of things (IoT), artificial intelligence (AI), data analytics by means of big data, and augmented reality (AR), not only have a considerable impact on society and the working environment, but also on business operations in industry.

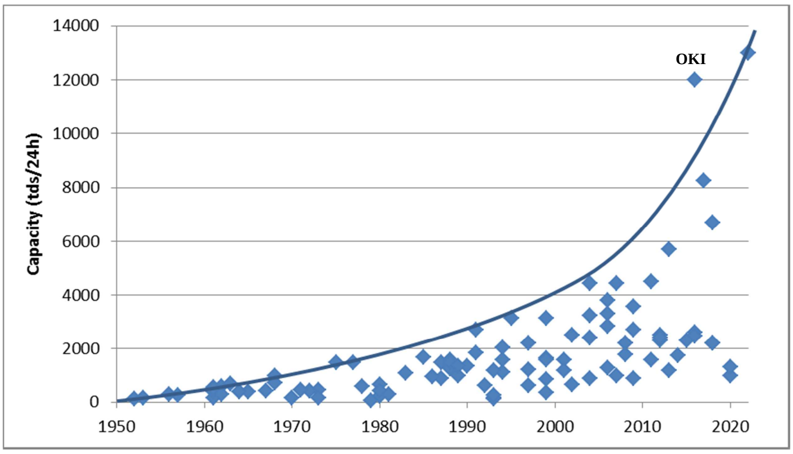

Figure 2: Growth of kraft recovery boiler capacity during 1950-2021.

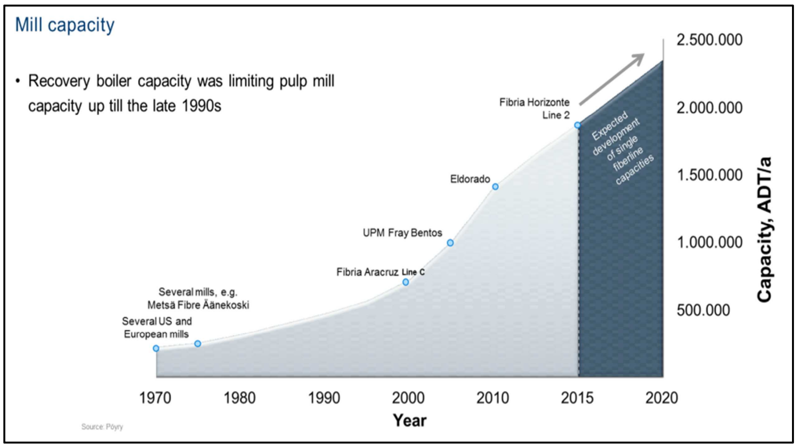

Figure 3: Development of pulp mill capacity during the last 50 decades. Data collected from Pöyry database /19/.

Autonomous refers to acting independently, while automated mill describes what the present situation is; operators are on the driver's seat. Autonomous automobiles use a variety of techniques to gather data about their surroundings and feed this data to advanced systems that interpret the inputs and identify appropriate navigation paths. The development of autonomous pulp mills is using similar path. The entire pulp mill will be digitalized in near future and big data and artificial intelligence will be used for process control and process optimization. The huge amount of data available during the operation of a modern recovery boiler will be utilized in developing an autonomous recovery boiler. Autonomous mill concepts are also based on smart utilization of IoT technology. Digital twin (a digital replica of a living or non-living physical entity) simulations, which are working with artificial intelligence, are already implemented in many production industries /20/.

The first steps towards an autonomous recovery boiler were taken already in early 1970s, when the first trials were made to control recovery boiler combustion /8/. Theoretical mathematical models were developed for liquor spraying, combustion, and steaming. It was soon realized, however, that verification of the theoretical models necessitates development of measurement techniques and procedures. According to the studies in the 1970s it was concluded that a proper control of the combustion phenomenon requires wall-specific control and on-line measurements of the airs and black liquor. The control could be realized, if black liquor dry solids, black liquor temperature, black liquor flow, and black liquor pressure could be measured on-line. The primary air control necessitates the measurement of flow and pressure on each wall. In addition, the knowledge of emissions was believed to help to control the combustion /8/.

With new digital IIoT solutions, the mills are preparing for the growing digital challenges in the industrial environment. They are paving the way for digital predictability. New digital technologies are aimed at digitalizing and networking machines and plants as well as developing new customer-specific solutions. Products are the very latest state-of-the-art and they can be customized to suit individual customer requirements, and they make a substantial contribution towards helping the mills to achieve the best possible productivity and efficiency goals.

ENVIRONMENTAL PERFORMANCE

One of the major developments achieved in kraft pulp mills is in environmental performance. Significant reductions in the levels of effluents and emissions to atmosphere have been achieved. In the late 1970s, Finnish Recovery Boiler Committee carried out emission measurements from recovery boilers to map sulfur dioxide (SO_2), reduced sulfur compounds (TRS), and dust emission levels. According to the studies, SO_2 emissions in dry gases varied 100 - 4000 mg/m^{3}n (1-30 kg/ADt), TRS emissions were 0-1500 mg/m^{3}n (0-12 kg/ADt), and dust emissions varied between 50 and 1500 mg/m^{3}n (0.5-12 kg/ADt). Since nitrogen oxides (NO_x) were not of interest at that time, they were not measured. Due to the large variations in the emissions, average values could not be given.

At that time, Finland did not have any legislation for emission control from the recovery boilers. The legislation for environmental protection, which also set emission limits to recovery boilers, was enacted in Finland 1982 /8/. Since then, the mills have put more focus on measures to reduced emissions, first the sulfur emissions and later also NO_x emissions. Table 1 shows the development of SO_2, TRS, and NO_x emissions from Finnish pulp mills from the 1970s up to 2016. It also shows the present best available technique (BAT) emission limits /21/.

Table 1: Development of environmental performance in Finnish pulp and paper mills /8, 21/.

Emission Component	Emissions late 1970s (kg/ADt)	Emissions 1992 (kg/ADt)	Emissions 2016 (kg/ADt)	BAT-BREF (kg/ADt)
NO_x	NA	1.8	1.3	0.8-1.7
SO_2	1-30	2.0	0.3	0.03-0.17*
TRS	0-12	1.0	0.04	0.03-0.17*
Dust	0.5-12	1.2	0.2	0.02-0.3

*) Sum of SO_2 and TRS.

As can be deduced from Table 1, mills have been able to reduce the emissions significantly. Sulfur emissions have been reduced ca. 85% in 25 years. However, the mills have been able to reduce NO_x emissions only by 29%. The reason for low reduction in NO_x emissions is most probably due to increase in black liquor dry solids content, increased furnace heat loading, and the combustion of non-condensable gases (NCG) in recovery boilers. The dramatic reduction of SO_2 and TRS emissions from the mills is mainly due to the introduction of high dry solids firing in the early 1990s and the development of boiler automation to control the combustion. Reduction in dust emissions is mainly related to the precipitator technology development and due to the better understanding of dust chemistry, properties, and behavior.

POWER GENERATION

The change in the interest to increase power generation from kraft recovery boilers has been quite rapid. In the 1990s, when new mill or new recovery boiler was supplied, energy efficiency was not a topic. However, almost in all new cases energy efficiency is an important topic. Figure 4 shows the development of power generation in pulp mills (i.e. recovery boilers) and the development of internal consumption. To be able to increase the energy efficiency of the pulp mills, efforts to decrease the internal consumption at the mills has to be on the focus, too.

Modern non-integrated pulp mills are nowadays totally self-sufficient in respect to steam and power production, and the idea of producing and selling not only pulp, but also electricity is already a reality at many mills. Even though a mill is self-sufficient in energy, there are normally still many areas where energy could be saved and electricity production could be increased. The markets are globally demanding less pollution per produced megawatts (MW) and better utilization of renewable resources.

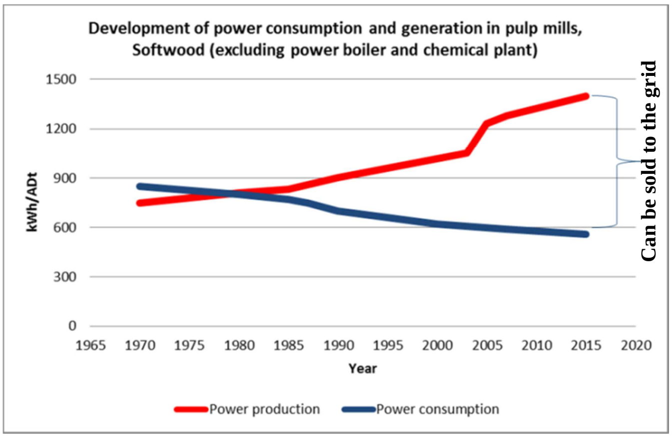

Figure 4: Development of power consumption and generation in pulp mills, excluding the power boiler and chemical plant.

Since the focus has earlier been on the chemical recovery and not on power production, the power generation efficiency (power-to-heat-ratio) has always been rather low in traditional recovery boilers. Today, the main factor limiting the increase of power production from recovery boilers is alkali-induced high-temperature corrosion. Therefore, the development in the steam outlet temperature in kraft recovery boilers has been extremely slow compared to power boilers. Japanese boiler manufacturers have been the pioneers with high-temperature recovery boilers. In order to improve the power generation from the recovery boilers, several technical solutions have been developed and adopted. The first recovery boiler having a steam outlet temperature of 500 °C was started up in Japan in 1983. Recovery boiler with steam outlet temperature of 515 °C was started also in Japan in 1988 /22/.

The first recovery boiler outside Japan with steam outlet temperature over 500 °C was started up in Pietarsaari Finland in 2004. Steam outlet temperature was 505 °C and pressure 102 bars. The first boiler with a steam temperature of 515 °C outside Japan was started up in Östrand, Sweden in 2006 /6/. The highest steam outlet temperature utilized in kraft recovery boilers is still 515 °C, according to the author’s knowledge.

There are several different ways to increase the power production from a kraft recovery boiler. Totally, some 20 MW more power can be generated by different measures. However, some of the measures may include operational risks, such as corrosion, which should be taken into account. The following is not a comprehensive list, but shows the most commonly used measures to increase power generation /6/:

- High dry solids in black liquor
- High steam temperature and pressure
- Sootblowing steam from the turbine
- Preheating of feedwater
- Preheating of combustion air
- Fluegas cooling
- Hot condensate return
- Heat recovery from vent gases
- Interheater
- Reheater

Target to increase recovery boiler energy efficiency has brought several power boiler features to recovery boilers. Increased design pressures, higher steam outlet temperatures, as well as fluegas heat recovery have increased the number, size, and area of heat transfer surfaces, especially the size of economizers. Growing size and high heat fluxes set also special constraints to the mechanical structures. Figure 5 shows the development of steam pressure and steam outlet temperature from 1950 till 2020. Two major steps have been taken in 1960s and in 2006. As can be seen from Figure 5, steam outlet temperature has been ca. 480-485 °C from 1960 till 2000. Steam pressure, however, has been increased in several steps.

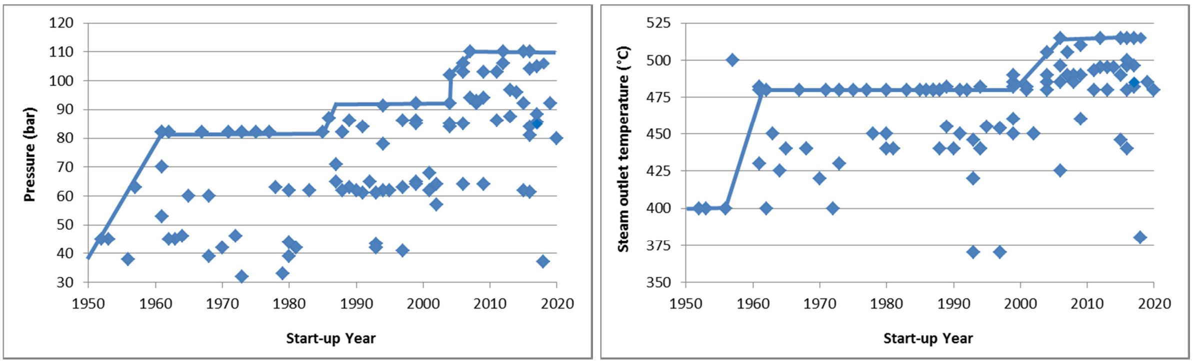

Figure 5: Development of steam pressure (left) and steam outlet temperature (right).

Several countries have a CO_2-free energy policy and subsidies are paid to green electricity producers, including recovery boilers at pulp mills. Therefore, some pulp mills have invested in maximizing power generating from the recovery boiler. Also new concepts have been developed to maximize power generation from the recovery boiler. One of the limiting factors is the pulp mill steam network, where the steam produced from the recovery boiler is directed. In one special case, recovery boiler was disconnected the pulp mill steam net and all the steam produced with the recovery boiler was led to steam turbine for electricity generating. Internal consumption was covered by electricity generated with power boilers in the pulp mill. Recovery boiler pressure level and steam turbine could also be optimized to produce as much electricity as possible.

RECOVERY BOILER SAFETY

Despite the rapid increase in furnace size in recent years, the number of fatal incidents in recovery boilers has decreased significantly during the last 40 years. The last fatal recovery boiler explosion in Finland occurred on September 28, 1965 at Äänekoski mill. The reason for the accident was smelt-water explosion due to a large crack in one furnace screen tube. Due to a too low pH in the boilerwater, magnetite layer inside the tubes came loose. Loose magnetite dregs plugged one screen tube causing overheating and serious thinning of the screen tube and finally resulted in a large burst in the tube. The result of the accident was four casualties and four injured. The operation of the mill was stopped for four months /8/. Figure 6 shows the extent of the explosion one day after the incident.

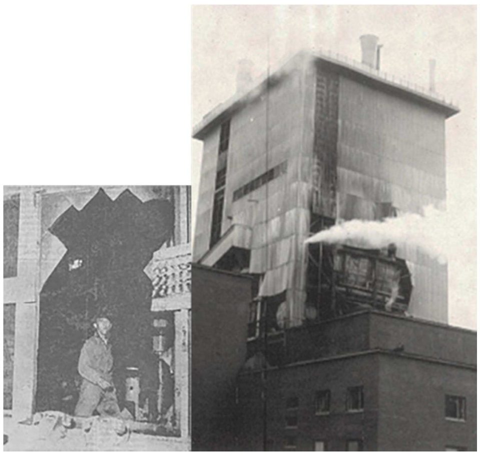

Figure 6: Äänekoski recovery boiler after the explosion /23/.

This incident was a start of the development of recovery boiler safety and safe operation. A big issue was how to stop combustion and melt formation fast enough to prevent smelt-water contact and subsequent gas explosion. The idea of rapid drain was introduced in US in 1966 when a leaking boiler was manually drained. This operation possibly prevented the smelt-water explosion. The idea was soon implemented into BLRBAC recommendations. In Finland, the first recovery boiler safety system guidelines were published in 1974 /8/. At that time they were only recommendations, but the inspection and insurance companies urged the companies to follow the recommendations. The guidelines covered areas such as equipment, operation, inspections and monitoring to assure safe operation of recovery boilers.

Today, safety and safe operation of recovery boilers have been #1 priority in the design for all the suppliers. Kraft recovery boilers are designed according to the recommendations by BLRBAC and recovery boiler committees in Finland and Sweden. Suppliers have also developed operational features increasing the safety of kraft recovery boilers. FRBC has also promoted the safe operation of the recovery boilers by several recommendations and guidelines.

A modern recovery boiler is equipped with an interlocking system (SRS) and with automated emergency shutdown (ESP) and rapid drain procedures. Special attention has been put on steam and condensate systems, as well as in the combustion of NCGs in recovery boilers. Safety system is based on safety and risk assessment (HAZOP), BLRBAC and EN norms and includes main interlocks, purging interlocks, auxiliary fuel interlocks, CNCG burning interlocks, and DNCG burning interlocks. Safety is not depending on the recovery boiler size.

KRAFT RECOVERY BOILER DIMENSIONING

The mechanical construction of kraft recovery boilers has been systematically developed throughout its history. The main goal has been to improve recovery boiler safety and reliability and recently also to decrease investment costs. In addition, energy efficiency and environmental requirements have brought their own features to recovery boiler mechanical design. One of the major factors in mechanical construction development has been the rapid increase in the capacity of recovery boilers. This has increased the physical dimensions of the furnace and heat transfer surfaces. In addition to the physical size, recovery boilers have experienced:

- Increased furnace heat loading
- Increased dry solids loading
- Higher dry solids
- Increased temperatures
- Increased dust loading
- Changing dust properties
- Change in air distribution

Increasing power generation and minimizing NO_x emissions from recovery boilers have induced a significant change in the design of the furnace and in the split between primary, secondary, and tertiary air amounts. As a rule of thumb to achieve low NO_x emissions with primary measures, the last air should be introduced into the furnace on a level where the temperature is as low as possible. On the other hand, to maximize power generation, fluegases should reach the superheaters as hot as possible. From the design point of view, these approaches are somewhat contradictory and the final design is always a compromise between these two targets. Figure 7 shows schematically how these different approaches affect the furnace dimensioning.

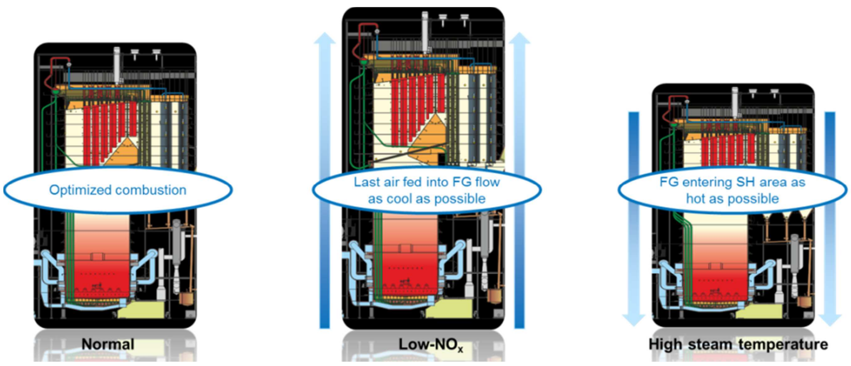

Figure 7: The effect of low-NO_x design and maximized power generating on furnace dimensions (not in scale).

The hearth heat release rate (HHRR) is an indirect measure of the heat flux and gas velocities in the lower furnace. It is defined as the gross heat input from black liquor dry solids fired in the furnace over the furnace cross-section

(W/m^2). The hearth solids loading (HSL) is the black liquor dry solids flow divided by the plan area (kgds/m^{2}s). The term HHRR is used to estimate the capacity of the lower furnace in terms of the ability of the boiler to effectively process the amount of liquor fired in the boiler in relation to the air introduced in the lower furnace. The furnace size, configuration and water wall construction are also determining factors in the recommended HHRR limits.

The nominal furnace loading has increased during the last 20 years and will most probably continue to increase also in the future. Changes in air system design have increased furnace temperatures. This has enabled a significant increase in hearth solids loading with only a modest design increase in hearth heat release rate. The average flue gas flow decreases as less water vapor is present. Thus the vertical flue gas velocities can be reduced even with increasing temperatures in lower furnace /24/. Figure 8 shows the development of HHRR and HSL since the late 1980s. On the average, both HHRR and HSL have increased around 40% in last 30 years. Typically, in larger furnaces the loading is also higher, which partially explains the trends shown in Figure 8.

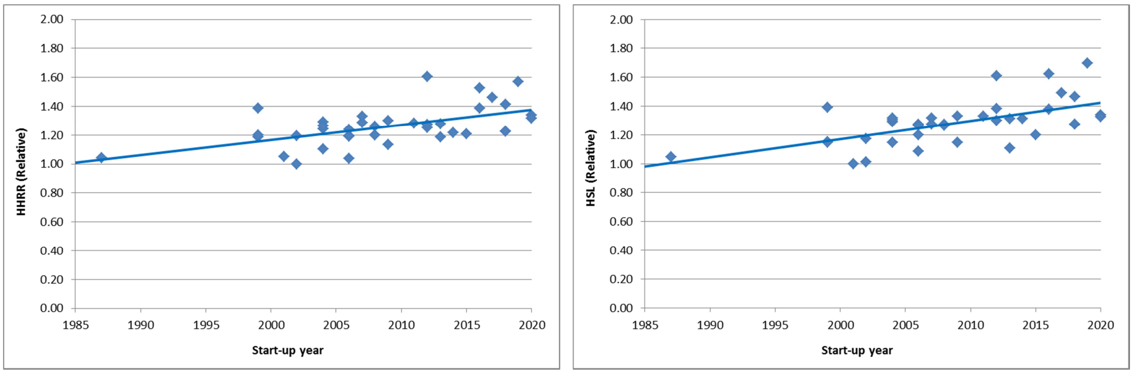

Figure 8: The development of relative HHRR (left) and HSL (right) of kraft recovery boilers.

The main target of all recovery boiler manufacturers is to develop high-quality recovery boilers with high availability. Increase in physical dimensions and heat loading will have an effect on the reliability of the boiler. According to the records, new boilers have less incidents and failures compared to the older ones /25/, despite larger dimensions and higher heat loading.

CONCLUSIONS

Throughout its history, kraft recovery boilers have been under continuous development efforts, focusing mainly to increase the safety of the operation, boiler availability, firing capacity, power generation, and to decrease emissions to the atmosphere. The world's largest recovery boiler in operation has a capacity of 12 000 tds/d, but the development of kraft recovery boilers will unquestionably go on and we have not seen the physical limits of the furnaces, yet. Larger capacities than 12 000 tds/d are already on the design board and the next world's largest recovery boiler with a capacity of 13 000 tds/d is scheduled to start-up in 2021.

The development of kraft recovery boilers has led to several improvements in operation, including:

- Increased safety
- Lower emissions
- Longer operation periods
- Less maintenance
- Higher power production

Modern recovery boilers are able to produce considerably more power than two decades ago and the energy self-sufficiency of modern mills is around 240%. This is a dramatic change, since in the 1980s pulp mills had large energy deficiencies and had to buy electricity from the grid. This has been gained by developing features common in power boilers, such as recovering of heat from the fluegases, using high steam outlet temperatures and pressures.

A lot of things that were only dreams in the 1960s and 1970s are now realized in new recovery boilers, especially safety of operations and emissions to the atmosphere. Modern recovery boilers are safe to operate and can be operated from 12 to 18 months continuously without a shutdown. Sulfur emissions have practically disappeared and modern pulp mills do not have their distinct odor anymore. Mainly due to the collection and combustion of NCGs in the recovery boiler furnace. Reduction of NO_x emissions from recovery furnaces is a more complex issue and only ca. 30% reduction have been realized. However, efforts to minimize NO_x emissions are on the way.

LITERATURE CITED

1. Dahl, C. F., Process of Manufacturing Cellulose from Wood, U.S. Patent 296,935 (1884)
2. Biermann, C. J., Essentials of Pulping and Papermaking, San Diego, Academic Press, Inc., ISBN 0-12-097360-X (1993)
3. Tomlinson, G. H., Waste Sulfite Liquor Recovery, U.S. Patent 2,285, 876 (1938)
4. Salmenoja, Proceedings of the Finnish Recovery Boiler Committee 55th Anniversary Conference, Turku, Finland (2019)
5. Salmenoja, K., Superheater Corrosion in Modern Recovery Boilers, Proceedings of the International Recovery Boiler Conference, Haikko Manor, Porvoo, Finland, pp. 103-113 (2004)
6. Heinola, M. and Salmenoja, K., High Energy Recovery Boilers, Proceedings of the 2014 ICRC Conference, Tampere, Finland (2014)
7. Metsä Fibre, Äänekoski Bioproduct Mill, Metsä Fibre web pages: www.metsafibre.com (2019)
8. Valkeapää, R. and Nieminen, M., Black Liquor – From Black Liquor Challenges to an International Cluster – 50 Years of Recovery Boiler Cooperation (in Finnish), Painotalo Plus Digital Oy, Lahti, Finland, ISBN978-952-68166-3-0 (2017)
9. Platan, M. and Virtanen, P., Industrial Co-operation on Recovery Boiler Plant Problems in Finland (In Finnish), Paperi ja Puu 9, 519-526 (1972)
10. Forsberg, U, Kraft, H., Peltola, T., Philipp, A., Puikkonen, T., Henriksson, M., and J. Wåle, Ten year experience with sustainable composite tubes in SCA high efficiency recovery boiler in Östrand, Sweden, Proceedings of Tappi PEERS Conference, Jacksonville, FL, USA, (2016)
11. Tran, H., and Tandra, D., Recovery Boiler Sootblowers: History and Technological Advances, Tappi Journal 14(1), 51-60 (2015)
12. Keiser, J. R., Sarma, G. B., Hubbard, C. R., Swindeman, R. W., Singbeil, D. L., and Singh, P. M., Why Do Kraft Recovery Boiler Composite Floor Tubes Crack?, Tappi Journal, 84 (8), 48-48 (2001)
13. Tamminen, T., Kiuru, J., Kiuru, R., Janka, K., and Hupa, M., Dust and flue gas chemistry during rapid changes in the operation of black liquor recovery boilers: Part 1—Dust formation, Tappi Journal, 1 (5), 27-32 (2002)
14. Tamminen, T., Laurén, T., Janka, K., and Hupa, M., Dust and flue gas chemistry during rapid changes in the operation of black liquor recovery boilers: Part 2—Dust composition, Tappi Journal, 1 (6), 25-29 (2002)
15. Tamminen, T., Forssén, M., and Hupa, M., Dust and flue gas chemistry during rapid changes in the operation of black liquor recovery boilers: Part 3—Gaseous emissions, Tappi Journal, 1 (7), 25-29 (2002)
16. Whitty, K. J., The changing scope of black liquor gasification, 45th Anniversary International Recovery Boiler Conference, E. Vakkilainen, Ed., Finnish Recovery Boiler Committee (2009)
17. Hyöty, P. A. and Ojala, S. T., Super Combustion of Black Liquor, Proceedings of the 1987 Tappi Engineering Conference, pp. 49 – 53 (1987)
18. Mäntyniemi, J., Isoniemi, M., and Harila, P., Biosludge and NCG Incineration in a Recovery Boiler, 1995 International Chemical Recovery Conference, Toronto (1995)
19. PöyrySmart - Online Information and Analysis Portal, Pöyry Management Consulting Oy, Finland (2019).
20. Saddik, A. El., Digital Twins: The Convergence of Multimedia Technologies, IEEE MultiMedia, 25 (2), 87–92 (2018)
21. Finnish Forest Industries: https://www.forestindustries.fi/statistics/environment/ (2019)
22. Arakawa, Y., Taguchi, Y., Maeda, T., and Baba, Y. Experience with High Pressure and High Temperature Recovery Boilers for two decades, Pulp&Paper Canada 106 (12), 89-92 (2005)
23. Äänekosken Kaupunkisanomat (in Finnish): https://aksa.fi/tragediasta-50-vuotta-soodakattilan-rajahdyksessa-menehtyi-nelja/ (2015)
24. Vakkilainen, E. K., Kraft recovery boilers – Principles and practice, Suomen Soodakattilayhdistys r.y., Valopaino Oy, Helsinki, Finland, 246 p, ISBN 952-91-8603-7 (2005)
25. Salmenoja, K., Most Typical Failures in Kraft Recovery Boilers – A Statistical Approach, Proceedings of the 2018 Tappi PEERS Conference, Portland, OR, October 28-31, (2018)

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Development of kraft recovery boilers

What have been the main development steps

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Outline

- Introduction
- Environmental performance
- Mill capacity
- RB capacity
- RB safety
- Power production
- RB dimensioning
- Digitalization
- Development highlights
- Conclusions

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Introduction

- Tomlinson-type recovery boiler has set the basis for modern kraft recovery boilers
- Throughout its history, kraft recovery boilers have been widely developed
- ANDRITZ (former Ahlström) RB short delivery history
  - First kraft recovery boiler was delivered in 1952
  - The world's largest kraft recovery boiler to PT OKI Pulp & Paper mill in Indonesia was delivered in 2014

	Delivery year	Capacity (tds/d)	Steam production (kg/s)	Steam temperature (°C)	Steam pressure (bar)
Lohja, Finland	1952	110	5	400	45
OKI, Indonesia	2014	12 000	582	515	110

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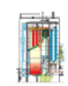
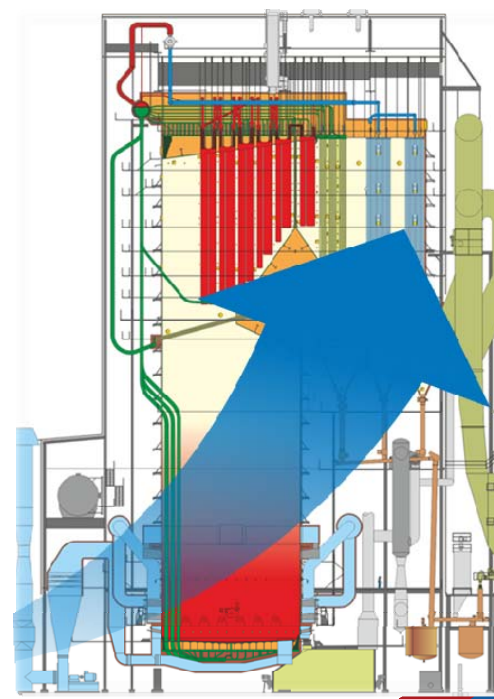
Introduction

- These two deliveries reflect very well the entire development path for kraft recovery boilers during the last 65 years
    - Capacity and steam production are ca. 100 times higher than 65 years ago
    - Steam outlet temperature is only around 30% higher, which is mainly due to the high-temperature corrosion of superheaters
- This summary gives an overview of kraft recovery boiler main development steps during the last 65 years



Lohja



OKI

Environmental performance

- New BAT-BREF document sets guidelines for national environmental regulations and permits
  - Both concentration based (mg/m^3n) and specific (kg/ADt) emission limits
  - Daily and yearly averages
- Progress has been extremely positive with other emissions, but not with NO_x

Measured values in different decades	SO_2 (mg/m^3n)		TRS (mg/m^3n)		Dust (mg/m^3n)	NO_x (mg/m^3n)
1970	100-4000		0-500		50-1500	Not measured
1990	100-800		0-50		10-200	120-260
2010	0-100		0-50		5-190	120-250
BAT-BREF	10-70	5-25	1-10	1-5	10-25	120-200

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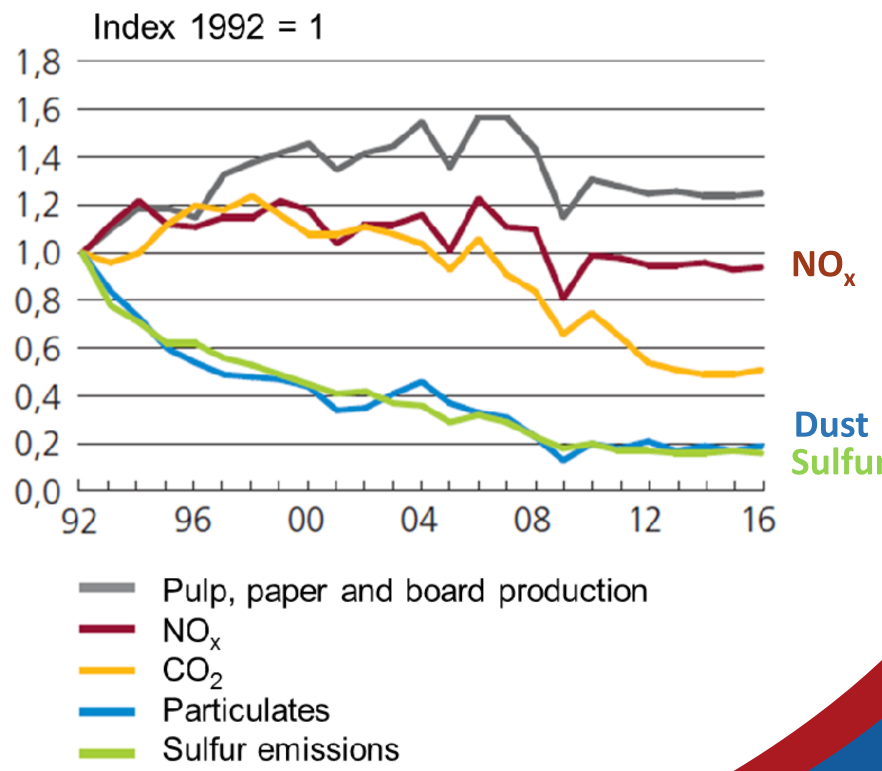
Environmental performance

- Lowering NO_x from present level sets challenges
    - NO_x mainly from fuel nitrogen
    - NO_x increases with increasing dry solids content
- Reduction of sulfur dioxide (SO_2) emissions due to high dry solids firing
- Collection of NCGs and combustion in the recovery boiler furnace solved most of the odor issues of the pulp mills



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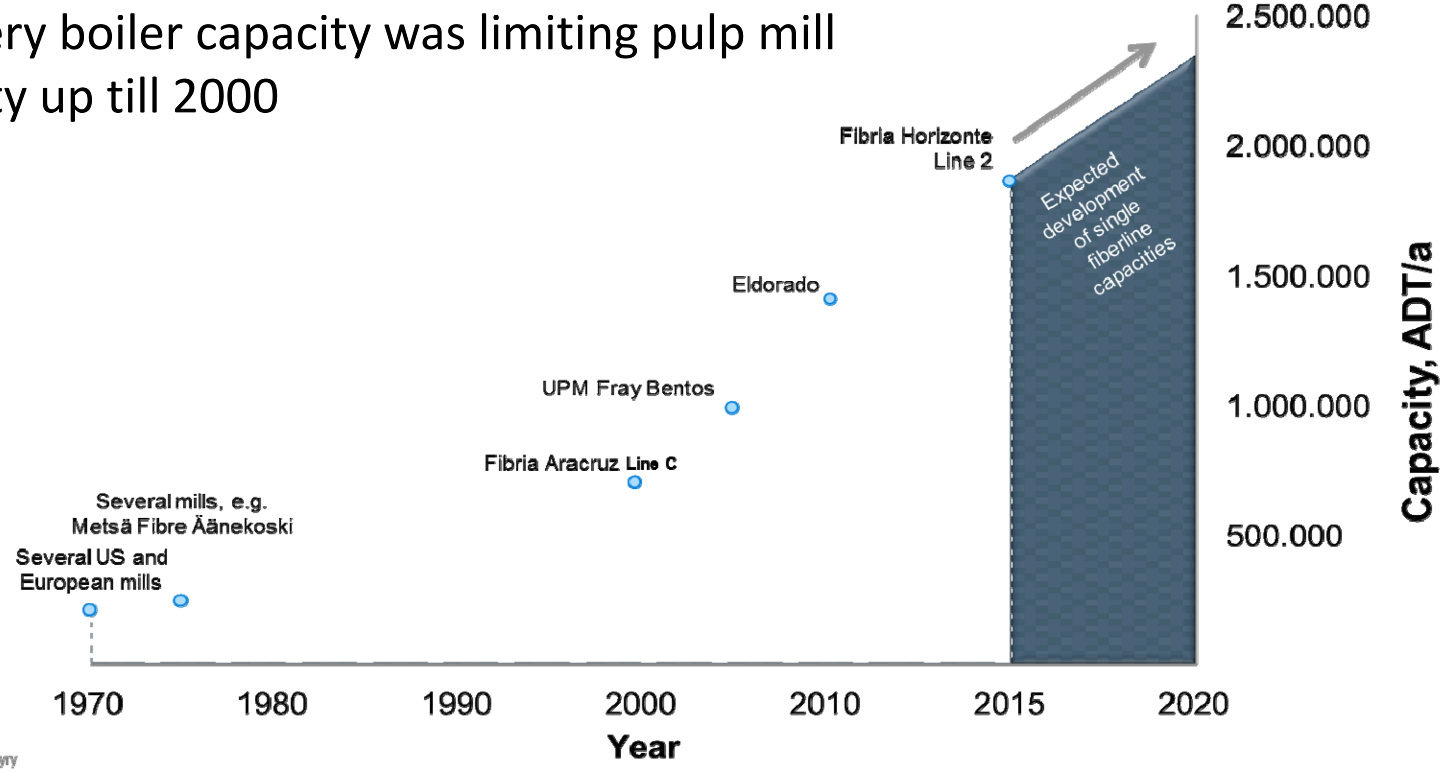
Mill capacity

- Recovery boiler capacity was limiting pulp mill capacity up till 2000



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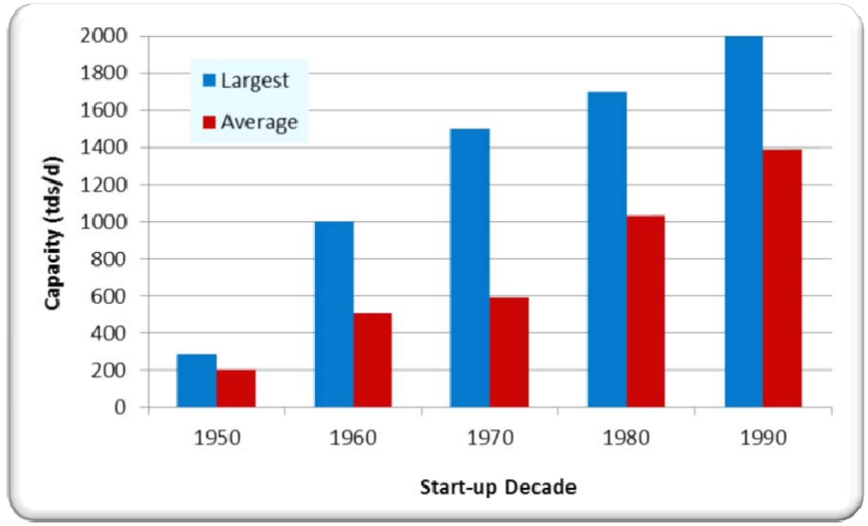
RB capacity

- The development of CFD simulations enabled the design of larger recovery boiler furnaces
  - Penetration of air jets is not limiting the furnace dimensions
- Today, recovery boilers are capable of serving a pulp mill capacity of 2.5 MADt/a (7 000 ADt/d)
- Recovery boiler is not any more limiting the capacity of a single-line pulp mill



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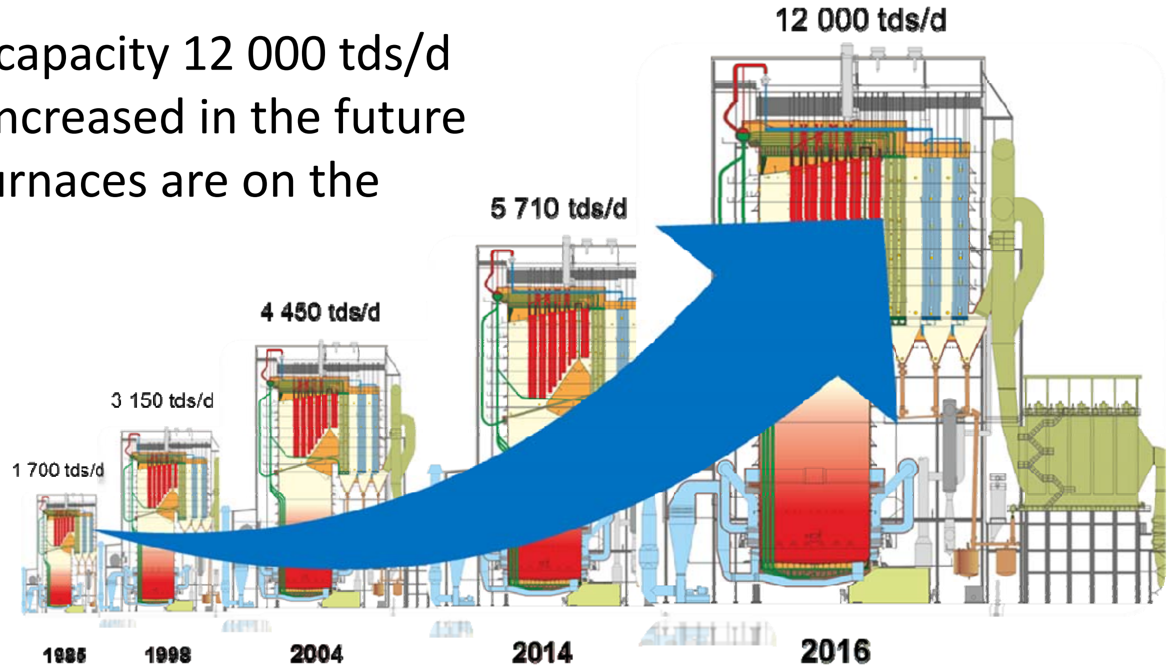
RB capacity

- Close to 10-fold increase in capacity since the 1980s
- Highest BL firing capacity 12 000 tds/d
- Capacity will be increased in the future
    - Even larger furnaces are on the design board

World record
12 760
tds/d



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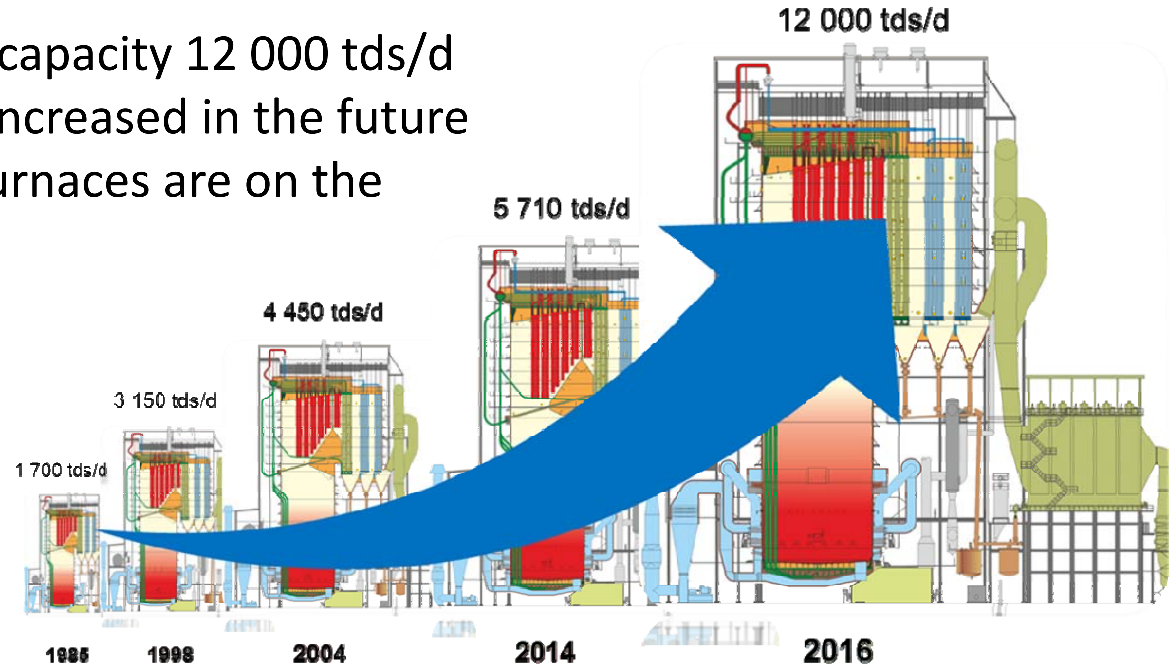
RB capacity

- Close to 10-fold increase in capacity since the 1980s
- Highest BL firing capacity 12 000 tds/d
- Capacity will be increased in the future
  - Even larger furnaces are on the design board

World record
28,130,696
lbds/d



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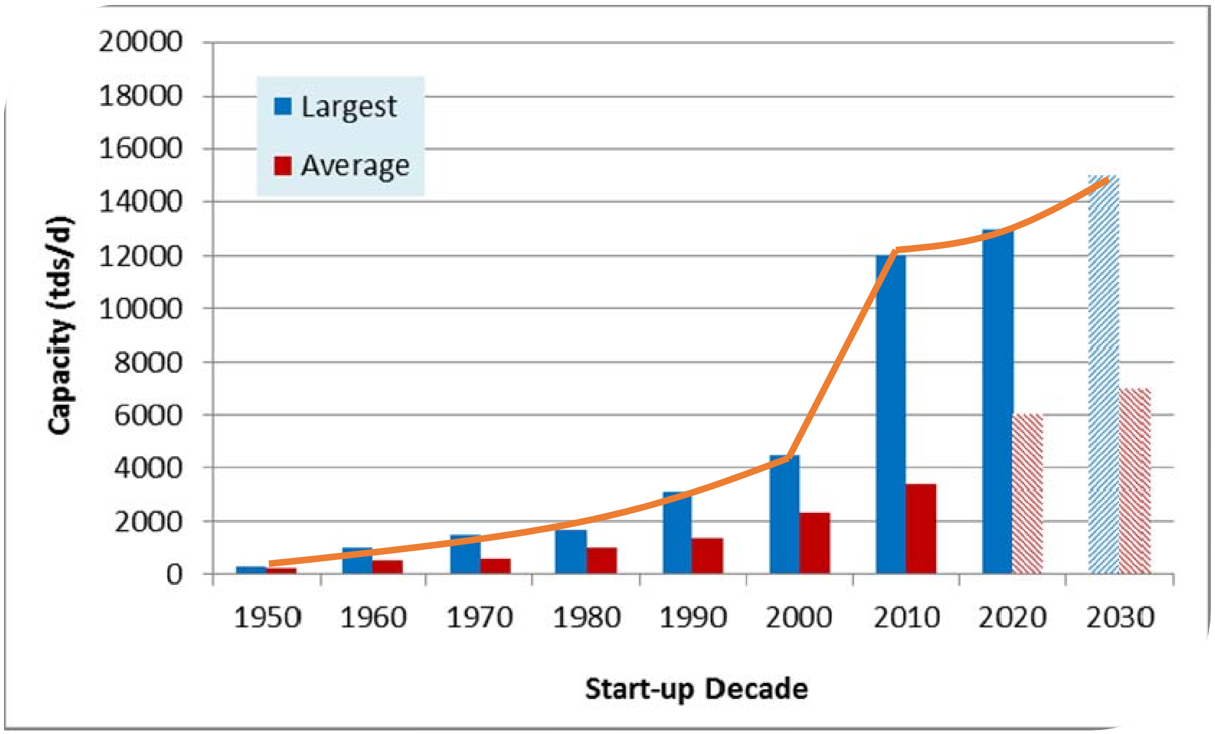
RB capacity



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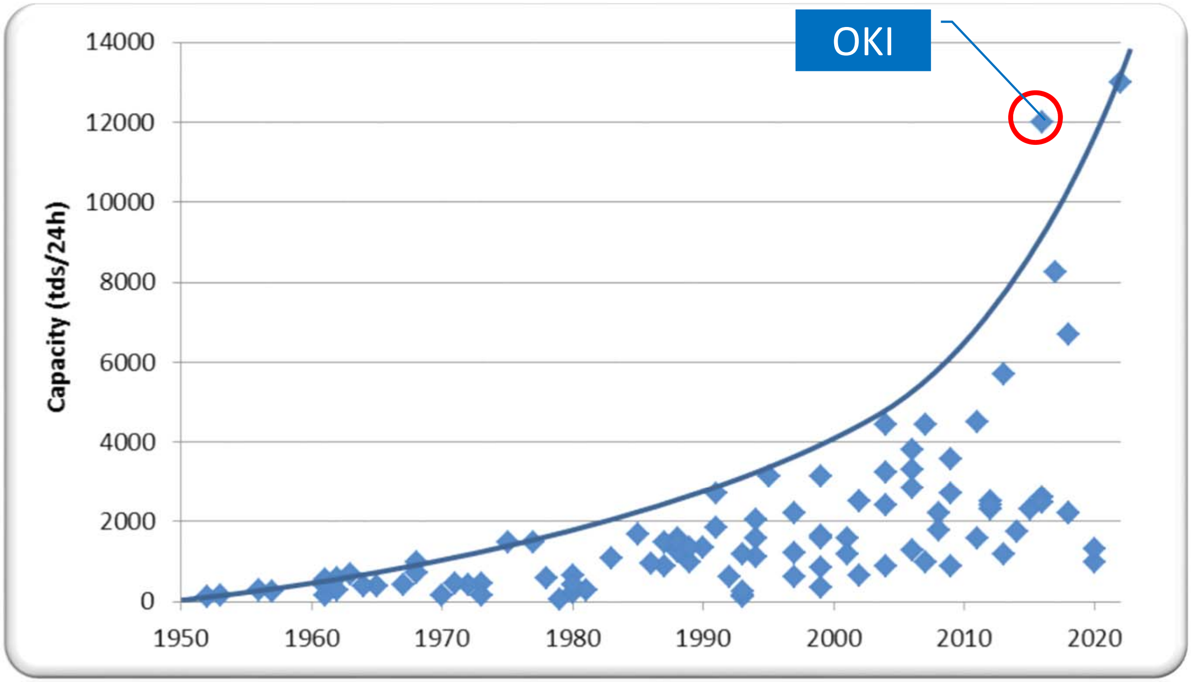
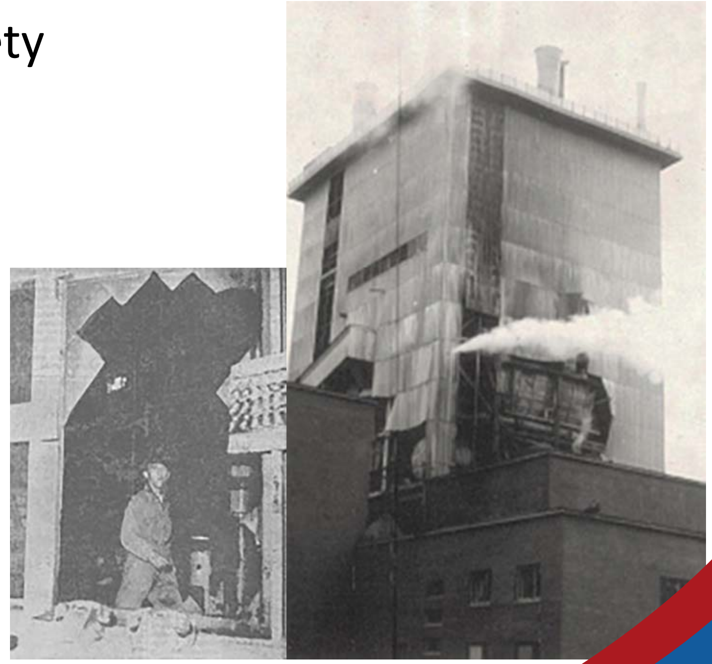
RB capacity



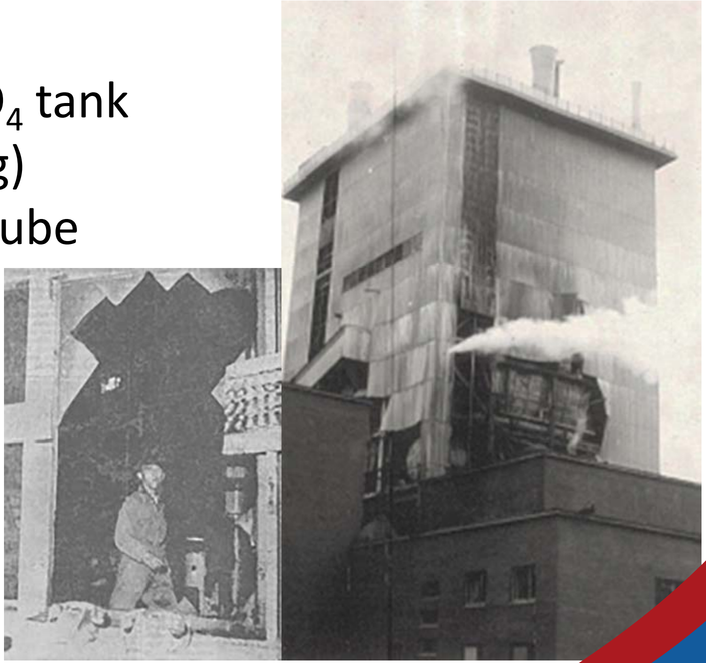
RB safety

- Safety and safe operation of recovery boilers have been #1 priority in the design
    - Development of features increasing the safety
    - Interlocking systems
    - ESP and rapid drain procedures
- Idea of rapid draining came from US
    - Manual draining due to a leak in RB
- Despite the rapid increase in furnace size, the number of incidents has decreased significantly
- In Finland, the last fatal RB explosion occurred in 1965 at Äänekoski mill



RB safety

- Smelt-water explosion* due to a leakage in furnace screen tube
  - Low pH in boilerwater due to a leaking H_2SO_4 tank
  - Loss of magnetite layer (on-line acid cleaning)
  - Loose magnetite flakes plugged one screen tube
  - Overheating and large burst
- Four casualties and four injured
- FRBC has promoted the safe operation of the recovery boilers by several recommendations and guidelines



* 1.0 kg of H_2O ~ 0.5 kg of TNT

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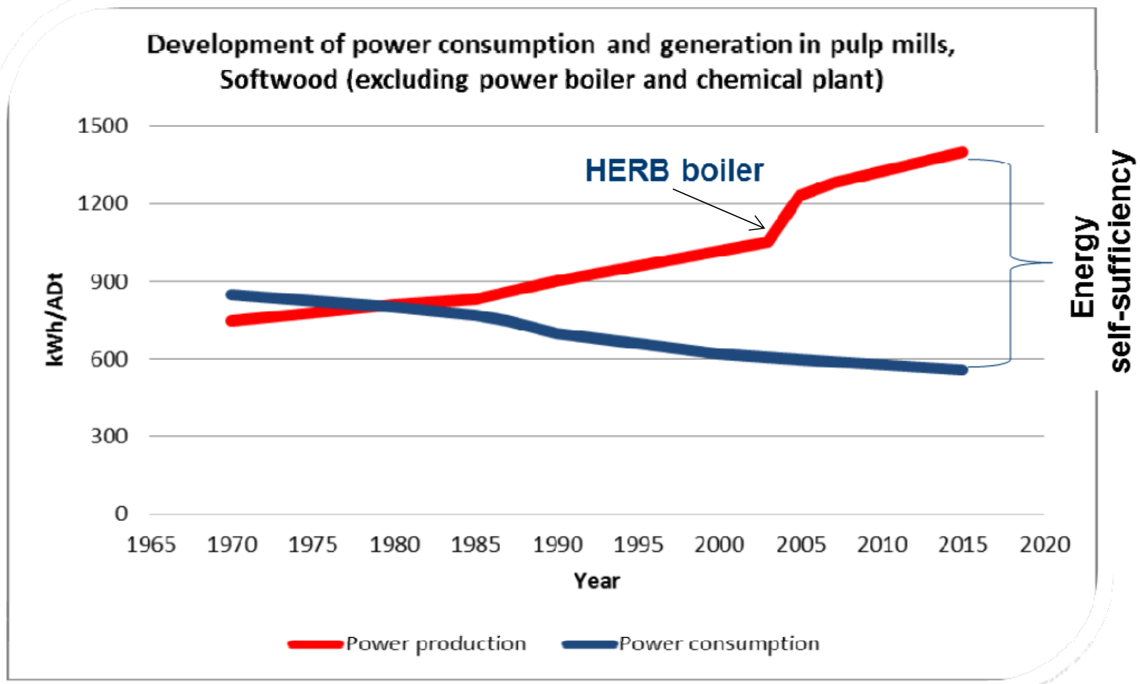
Power production

- Highest mill energy self-sufficiency today up to 250%



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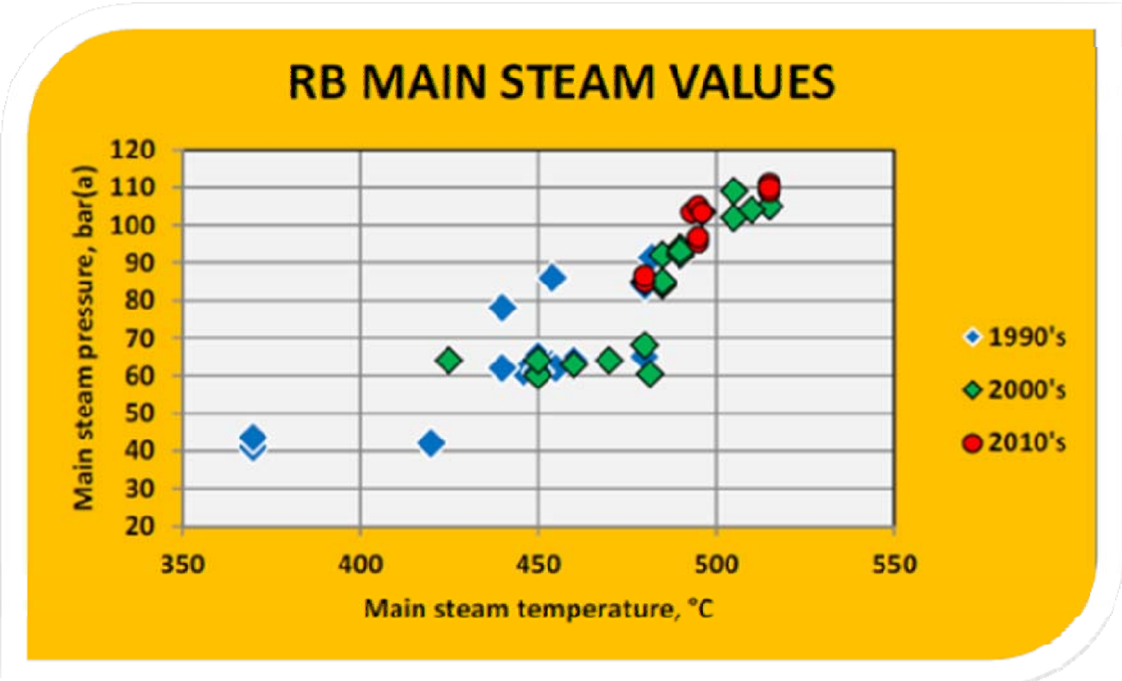
Power production



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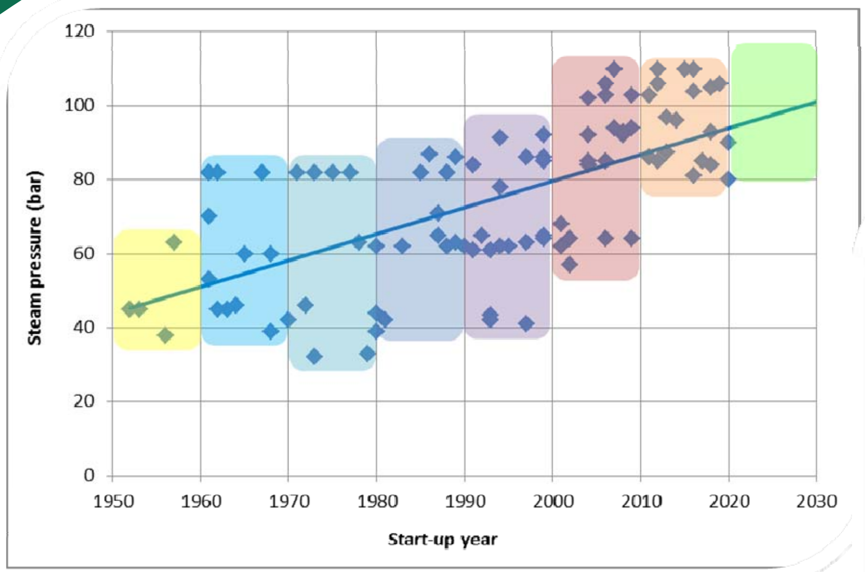
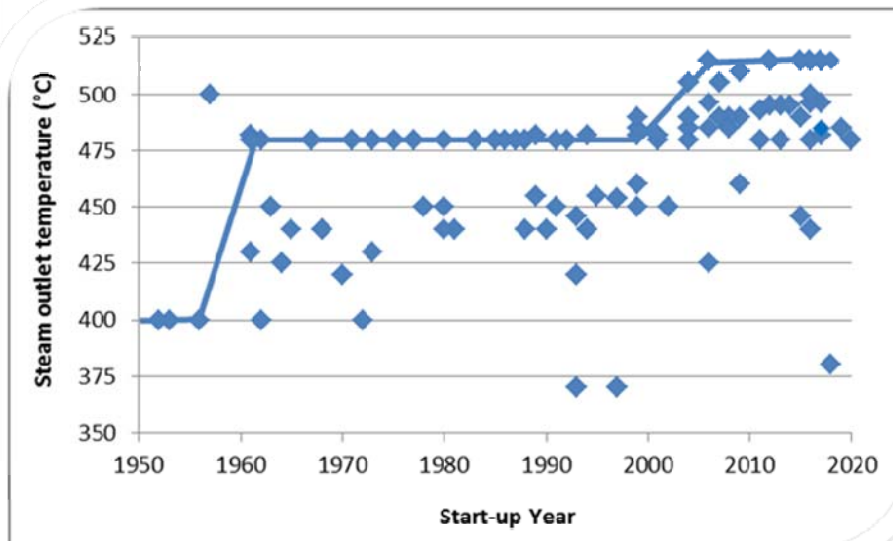
Power production





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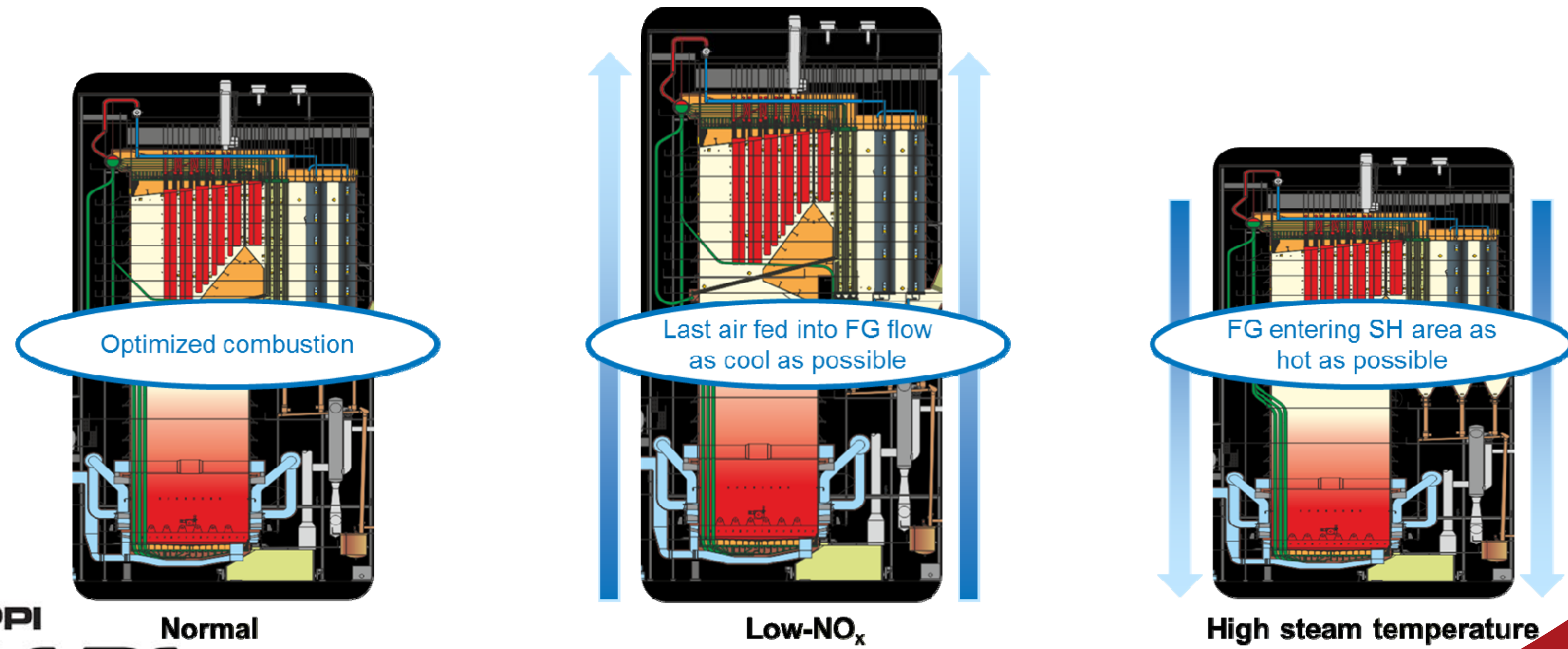
RB dimensioning

- Furnace dimensioning is always a compromise between achieving balanced combustion, minimized emissions, and high efficiency



Digitalization

- The following decade 2020 will be the era of digitalization
- The entire pulp mill is digitalized and big data and artificial intelligence will be used for process control and process optimization
- Mills are preparing for the growing digital challenges in the industrial environment with digital IIoT solutions
    - Paving the way for digital predictability
- New technologies are aimed at digitalizing and networking machines and plants as well as developing new mill-specific solutions
- New technologies make a substantial contribution towards helping the mills to achieve the best possible productivity and efficiency goals

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Development highlights

1. **Introduction of high-pressure recovery boilers in 1960s**
    - Rapid wall carbon steel tube wastage
    - Introduction on composite tubing
    - Establishment of the Finnish Recovery Boiler Committee (FRBC) in 1964
2. **Development of CFD calculations and simulations**
    - Enabled large dimensions in furnace design
    - RB not limiting pulp mill capacity
3. **Introduction of high dry solids firing**
    - Zero SO_2 emissions
4. **Increase of steam outlet temperature > 500 °C (515 °C)**
5. **Development of power production features**

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Conclusions

- Development of kraft recovery boilers has led to:
  - Increased safety
  - Decreased emissions (NO$_x$ reduction challenging)
  - Longer operation periods (24 months in view)
  - Less maintenance
  - Higher power production
- Recovery boilers are not anymore limiting pulp mill capacity
  - Capacity still increasing
- New challenges due to changes in the cooking process
- Digitalization of the recovery process is on-going
  - IIoT, digital twins, big data, etc…