NEW 215 MW\textsubscript{el} CFB POWER UNITS FOR ESTONIAN OIL SHALE

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ABSTRACT
Estonian basic power supply is over 90% covered by oil shale fired thermal power plants. Total installed thermal capacity of the boilers is 10.7 GW\textsubscript{th} and every year about 11 millions tons of oil shale is fired.

Two different combustion technologies, the old pulverized oil shale firing and the new CFB technology are used at the moment.

The new CFB units totaling 430 MW\textsubscript{el} delivered by Foster Wheeler Energia started operation in 2003-2004.

The very first operational experience of CFB units are very promising and all basic problems of oil shale pulverized firing like high air emissions (SO\textsubscript{2} – 820-1360 mg/MJ; NO\textsubscript{x} – 90-110 mg/MJ), fouling and corrosion of heating surfaces, low efficiency and low operational reliability seemed to be solved.

Oil shale CFB firing at much lower temperatures (~800°C) than pulverized firing (~1400°C) results only partial decomposition of oil shale contained carbonates, meaning lower specific fuel consumption values and decreased CO\textsubscript{2} emissions.

Also fly ash composition and properties has been changed, which results in different new perspectives of ash utilization possibilities, but also some additional ash land filling problems.

The paper analyses the first data of Estonian oil shale industrial CFB firing in the light of almost 40 year experience of Estonian oil shale use in power production.

Keywords: Estonian oil shale, pulverized firing, circulating fluidized bed, emissions, fouling

ESTONIAN OIL SHALE SHORT CHARACTERIZATION AND OIL SHALE POWER PRODUCTION HISTORY REVIEW IN ESTONIA

Estonian oil shale deposit is the largest in Baltic basin, which accounts for about 2/3 of its industrial part. To the same area belongs the Tapa deposit. Part of the basin is located in Russia.

The oil shale bed is not homogenous and has a complicated structure consisting of oil shale layers of different quality alternating with limestone interlayers. The total thickness of the payable bed in the Estonian field is 2.5-3.2 m, of which oil shale layers account for 1.8–2.6 m and limestone layers 0.6–0.7 m. The heating value of oil shale layers lies in range from 5-10 up to 16-20 MJ/kg. Also limestone interlayers with heating value 0.6-2.9 MJ/kg contain some organic matter. Estonian oil shale is the fuel of low heating value and high ash content. The technical properties of the fuel transported to power plant depend to a great extent on mining and enrichment conditions.

During last years oil shale used in Estonian power plants may characterized by the lower heating value up to 8.6 MJ/kg, ash content up to 46%, moisture up to 14% and CO\textsubscript{2} content up to 20%.

“Estonian Oil Shale” or “Kukersite” was discovered in the North of Estonia more than 200 years ago. This mineral was described in a report in 1798 as “a brownish laminated argillaceous or marly bituminous earth; it burns with flame, without giving an unpleasant odour. Shepherds burn this earth in piles.” Chemical investigations carried out by Prof. C. Schmidt at Tartu (Dorpat) University proved the shale to be very rich in organic matter.
The test mining of the shale started in 1916. At the beginning oil shale was mainly used in railway, cement industry and in households. Also the tests to produce raw oil were started. The Estonian Government started the actual exploitation of oil shale in 1919. Investigations of oil shale for energetic use started at Tallinn University of Technology (TUT) in the beginning of the 1920’s.

Characterization of the main qualities of Estonian oil shale and design of burning devices and boilers for this fuel were the main objects of these investigations. Also the commercial use of oil shale ash as a binding material was investigated. An important milestone in history of oil shale industry was introduction of oil shale firing in Tallinn Thermal Power Plant in 1924.

Before the World War II some small power plants burning oil shale were built in Estonia. In 1940 about 40% of produced 1.87 million tons of oil shale was used as fuel and other part to produce oil. At the beginning of the World War II total capacity of power plants that used oil shale was 32.5 MW.

After World War II oil shale industry in Estonia developed very quickly. Kohtla-Järve and Ahtme power plants were equipped with pulverized firing (PF) boilers. The next stage in development of oil shale power sector started in 1959. In 1959-1966 the high pressure 100 and 200 MW PF energy blocks were started in Balti Power Plant with total installed capacity of 1624 MW. In 1969-1973 the Eesti Power Plant of installed capacity 1610 MW with 200 MW energy blocks started operation. For both power plants the special PF oil shale boilers were designed and built by the greatest boiler factory of Soviet Union in Taganrog. Total capacity of power plants in Estonia was raised up to 3000 MWel. More than 50% of produced electricity has been used in Soviet Union.

After the recovery of independence in Estonia in 1991 a drop of annual oil shale production from 25-30 million tons in the 1980s to 11-13 million tons in the last years was caused by an abrupt fall in electricity consumption due to the bankruptcy of big industrial enterprises and a sharp decrease in electricity export to Russia.

The dynamics of energy balance of Estonia in last four decades described in Fig. 1.

![Energy Balance of Estonia 1960-2002](image)

**Figure 1. Energy balance of Estonia 1960-2002 [1].**

**CFB TECHNOLOGY FOR ESTONIAN OIL SHALE – FROM PILOT TESTS TO FULL-SCALE BOILER**

Former experience with oil shale boilers showed that Estonian oil shale belongs to the fuels with very complicated properties. Pulverized firing of oil shale is accompanied by a number of boiler operational problems – intensive fouling of heat transfer surfaces by the hard fly ash deposits and intensive corrosion and wear of super heaters, due to aggressive components in fly ash (mainly KCl).

The main environmental emissions are of fine particles (fly ash) and sulfur dioxide. The exhaust gas of the typical oil shale PF boiler consists of more than 1500 mg/nm³ of SO₂ in spite of the binding of ~80% of fuel sulfur by ash in the PF boiler. The average particulates content in flue gas was about 1500-2000 mg/nm³. Nowadays both power plants are equipped with new electrostatic precipitators and the particulates content in flue gas is under 100 mg/nm³.

Due to need to renovate these power plants, as well as to growing concerns about emissions, there was great interest in replacing the PF technology with more advanced combustion technology. Based on bibliography it was decided to use fluidized bed (FB) technology. As there was no an operating FB boiler, burning Estonian oil shale or similar fuel, it was first decided to perform corresponding tests.

Tests in atmospheric circulating fluidized bed (CFB) test facility in 1994 were performed by Ahlstrom (later Foster Wheeler), Finland. In 1996 testing was done at 1 MWth test facility at Lurgi Lentjes Babcock (LLB), Germany. In the same year tests proceeded at the laboratory test facility at the University of British Columbia, Canada, coordinated and sponsored by ABB Combustion Engineering. The CFB technology was used in all tests, because of high volatiles content of oil shale.
The tests gave quite similar results in all cases and enabled to give recommendations for designing a new CFB boiler for oil shale and predict the operation conditions of that. The main problems in PF technology – intensive fouling of heat transfer surfaces, intensive corrosion and wear of superheaters and high content of SO₂ in flue gas were observed with great interest. The results of tests and laboratory investigations enabled to predict the properties of oil shale ash from the CFB boiler as well as the corrosive activity of fly ash and flue gas and fouling of heat transfer surfaces. At the same time the principal recommendations for designing the new CFB boiler burning Estonian oil shale were worked out:

- The temperature ~850°C was considered as most suitable for burning Estonian oil shale in respect of fouling and high temperature corrosion of heat transfer surfaces, economical and environmental aspects.
- The tests showed very low SO₂ emission levels (<5 ppm), satisfying the emission limits without the need for any additional flue gas desulphurization equipment. Particulate emissions could be handled by installing bag filters or electrostatic precipitators and NOₓ was low thanks to the relatively low combustion temperatures.

**FOSTER WHEELER BOILER CONCEPT**

Foster Wheeler has recently introduced two major improvements to the CFB technology by introducing the new compact design, where the solids separator has become an integrated part of the combustion chamber structure, and the integrated heat exchanger (INTREX). The solids separator, the recirculation system and the furnace are now built as integrated cooled panels: a design, which naturally leads to several advantages such as footprint size reduction and lighter refractory. Furthermore, the development of the INTREX heat exchanger has brought more flexibility in the application of the CFB technology. This heat exchanger is located in the lower part of the combustion chamber, outside the main combustion area but as an integrated part of the furnace (Fig. 2). It’s most pronounced advantage is its location in shelter from the main combustion and produced flue gas, which generally contain the harmful components in the most active form. Applying this heat exchanger as a superheater enables high superheating temperatures due to the protection from any possibly corrosive environment. The INTREX superheater allows effective utilization of fuels with higher chlorine contents: fuels which in conventional designs would cause corrosion of superheater tubes [3].

**INTREX™ Heat Exchanger.** The innovation that enhances the Foster Wheeler CFB boiler design is the Integrated Recycle Heat Exchanger INTREX, which provides the additional solids cooling, needed for larger boilers where the furnace walls are no longer sufficient. The INTREX heat exchanger is a bubbling bed type. It consists of one or more bundles that further cool the solids collected by the separator before they are returned to the furnace.

- Almost full binding of sulfur into ash resulted, that no hardbound ash deposits was expected to form at heat transfer surfaces of a new CFB boiler. The deposits will be soft and can be easily removed by cleaning of heat transfer surfaces using less intensive cleaning technologies.
- High temperature corrosion problem can be eliminated and heat of the recycled ash can be used by supplement of special heat exchanger
- Due to relatively high chlorine content ash deposits at the low temperature heat transfer surfaces will be potentially corrosively active, but it should not be a problem at expected tube temperatures under 450°C.

As a result of produced tests, it was decided to re-power the Estonian oil shale power plants basing on CFB technology. Basing on test results we can notice that operation conditions of heat transfer surfaces replacing PF technology with CFB will considerably better. Also sulfur emission into atmosphere will noticeably decrease [2].

Operation of the new CFB boilers in Eesti Power Plant confirm that the forecasts got from oil shale combustion in test equipments are fulfilled – the content of SO₂ in flue gas is <5 ppm. Also intensive fouling and corrosion of heat transfer surfaces has not found out.

In addition to cooling the externally circulated solids, openings in the furnace rear wall provides access for additional solids to internally circulate through the heat exchanger tube bundles ensuring sufficient hot solids to the INTREX heat exchanger at all loads. Excess solids spill back into the furnace through openings in the furnace rear wall.

![Figure 2. INTREX Heat Exchanger.](image)
The solids flow rate through the tube bundles is controlled by controlling the amount of aeration air added to the lift legs, which return the solids to the lower furnace. By controlling the solids flow rate through the INTREX heat exchanger, the heat absorption can be varied giving operational flexibility to control furnace and/or superheat temperature. Controlling the fluidization velocity, which can vary the heat transfer characteristic to the submerged tube bundles, can also provide rapid heat absorption control. Water-cooled tubing that is integrated with the furnace circuitry forms the enclosure. The integrated configuration allows the heat exchanger to grow downward with the furnace enclosure so that large maintenance prone expansion joints are not required. [4]

As described in the previous chapter, Foster Wheeler carried out in 1994 comprehensive combustion tests with Estonian oil shale. The test rig used was a FB pilot plant, at Foster Wheeler R&D Center, Karhula, Finland. In the tests, the unique properties of the Estonian oil shale fuel were confirmed. The oil shale is a reactive fuel, with a nearly complete carbon burn out efficiency and low CO emissions. The fuel particle size may however not be too coarse, to avoid coke formation inside the bigger shale particles. Thanks to the high lime content in the ash, the SO₂ emissions are very low. The NOₓ emissions are also low.

The Estonian oil shale has high contents of friable ash, which generates a high rate of soft ash build-up in the convective cage of the boiler. The flue gas are corrosive, due to chlorine and potassium in the fuel, hence inducing a high risk of hot chlorine corrosion of the superheaters.

Based on the test results, Foster Wheeler CFB technology with compact separators and INTREX was selected to offer for oil shale combustion. The specific properties of the fuel, however, required significant modifications to the standard design of a CFB. The most important of these modifications were

- grid design for gentle fluidization, to minimize the fines formation from the friable ash,
- hanging convective superheaters with Foster Wheeler spring hammers for soot blowing, to allow frequent cleaning without excessive steam consumption,
- acoustic soot blowing of the economizers,
- low combustion temperature, <850°C, to decrease ash friability and to reduce calcination of the limestone in ash,
- carefully selected steam temperatures for each phase of superheaters, and
- pneumatic fuel feeding into furnace.

The resulted design is shown in Figure 3.
EXPERIENCE OF FIRST OPERATION PERIOD

Thermal and power production efficiency – comparison with PF

Several boiler tests and improvements are going on, operation experience of the first power unit started at Eesti PP at the end of 2003 is quite positive. Recently, the two CFB's at Eesti PP received provisional acceptance from the power plants owner Eesti Energia. According to the provided tests and measurements power production efficiency at nominal load (215 MW) was estimated to be in the limits of 35-36%, versus 29-30% at oil shale PF, corresponding with specific fuel consumption in the range of 12.0-11.7 MJ/kWh.

CFB boiler higher thermal and power production efficiency comparing with PF have several reasons:

- Different extent of carbonates decomposition (ECD). At the CFB furnace average temperatures of 750-800°C about 75% of carbonates were estimated to dissociate. At PF oil shale boilers ECD is about 98%.

- Different sulphation rate – from the average 80% at PF to almost 100% at CFB (SO₂ in flue gas below 5 ppm).

The summary effect of ECD and sulphation to oil shale LHV (8.2-8.6MJ/kg) is estimated to be about plus 0.33 MJ/kg or 4% comparing with PF. The effect means significantly lower specific fuel consumption values, less CO₂ (~25%) and SO₂ emissions.

Emissions – CFB & PF

Basic air emissions from oil shale combustion are sulphur and nitrogen oxides, solid particles (fly ash), and hydrogen chloride.

Pulverized combustion

In previous years at old oil shale PF boilers the most problematic have been very high SO₂ (820-1360 mg/MJ) and solid particles emissions (1040-1540 mg/MJ). SO₂ emission remained high despite of significant capture of major part of it (~80%) by free CaO, formed at carbonates decomposition at furnace temperatures up to 1400°C. NOₓ (as NO₂) emission factor remained in the limits of 90-110 mg/MJ and HCl concentration in flue gas was below 80 mg/m³ (6% O₂) [5].

Oil shale mineral part carbonates almost full decomposition at PF results also much higher CO₂ emissions (roughly 1 kg CO₂ per kg oil shale) than most of other fossil fuels.

Renovation of electrostatic precipitators at 8 PF power units during years 1999-2002 resulted significant decrease of solid particle emissions (<100 mg/MJ). Corresponding reduction of trace metal air emissions by solid particles (cut size 3 µm) was remarkable also. Distribution of trace metals between different fractions of oil shale ash shows relative enrichment towards smaller particle fractions (from bottom to fly ash). Despite of enrichment tendency the process trace metals major stream (>90% in average) corresponds to the ash flow through the ash removal system and total trace metal air emissions remain below the level of similar coal firing [6].

CFB combustion

Totally different is the situation at oil shale CFB combustion, when furnace temperatures remain in the limits of 750-800°C and sulphation of ash in gas passes is much more complete due to higher residence time of ash particles and an active opening of new reaction surfaces in the friction process of ash recirculation.

In the new CFB boiler near zero HCl and SO₂ concentrations and almost twice lower NOₓ concentrations (<80 ppm, at 4% O₂) were measured.

Total reduction of CO₂ emission factor (mg/MJ) will be about 12-13% comparing with pulverized firing (Figure 4). Figure 5 illustrates changes in total emissions of Eesti Power Plant in 1990-2004 [7, 8].
**Power rate and operational availability**

Full-scale continuous generation of 215 MW of electricity at Block 8 of the Eesti plant began back in March, 2004. The new boilers and modernized turbine island at the second block being repowered, Block 11, and at the Balti plant were synchronized with the grid in May, 2004. The boilers have performed very closely to specifications, and combustion has proved very stable. Foster Wheeler CFB technology has met the challenge of firing oil shale, which is one of the most difficult-to-burn fuels anywhere. Emissions have also been very low, a fraction of earlier levels.

The original fuel particle size distribution appeared to be too coarse, resulting in gradually worsening fluidization in the furnace, and requiring extra care for the quality control of the bed inventory. Due to this, secondary crushers were installed at Eesti PP below the four fuel silos, in June 2004, resolving the problem.

The Balti turbine was originally installed in the 1960s, which makes it pretty old by now, and there were some operational and excess vibration problems with it.

**Deposit formation and fouling of heating surfaces**

As exploitation experience of PF boilers show, the fouling of clean heat transfer surfaces demands some “run-in” period, which is approx. half a year. The main reason for fouling of heat transfer surfaces of PF boiler is the deposited ash containing free lime reacting with flue gas SO$_2$. Result is hardbound sulphate deposit. The condensing of KCl vapor from flue gas to the heat transfer surfaces on the beginning phase of deposits formation fosters this process. The formation of hard deposits favors wearing and tightening effect of fly ash to the formed deposits.

The conditions in CFB and PF boilers are different. In case of CFB combustion almost all SO$_2$ originated from fuel burning bond in furnace and the content of SO$_2$ in flue gas washing convective heating surfaces is extremely low. As investigations show it is necessary that reaction between CaO and SO$_2$ must take place directly on the heating surface. Settling of previously sulphated ash particles to the heating surfaces does not cause hard deposits. Because of low furnace temperatures the decomposition of fuel minerals and evaporation of potassium are low, and possible KCl vapors in flue gas does not exist. So in CFB boiler there are no presumptions for hardbound deposits and only soft, easily removable deposits can be predicted.

As relatively short exploitation experience of oil shale CFB boilers show so far there are no fouling problems of heating surfaces. The inspections show that heating surfaces are mostly clean, covered by thin easily removable ash layer (see Photos 1 and 2).

Investigation of temperature trends (4000 hours) of both CFB boilers was carried out. Analyze of dynamics of inlet-outlet flue gas temperatures of heat transfer surfaces in convective pass show some decrease of heat absorption in superheater.

The latter indicates about slight fouling of superheater. In economizer the heat absorption was in stable level.
**Corrosion – Cl behavior in ash and deposits**

The superheaters high temperature corrosion caused by KCl is one of the most serious problems in PF boilers. In CFB boiler high temperature stages of superheater and reheater located in fluidized bed heat exchanger, INTREX. In INTREX the heat transfer surfaces flushed by air and circulating ash, the chlorine content of ash is low and fluidized velocity is low too. There should not be erosion and corrosion problems in INTREX. The main problem seems to be possible corrosion of superheaters-reheaters in convective pass of boiler. As analyses show the deposits on heat transfer surfaces contain 0.9-1% of chlorine. The TTU investigations show significant decrease of corrosion intensity by KCl if temperature of heat transfer surface stays below 450°C. It can be expected that there is low risk of convective heat transfer surfaces corrosion.

**Fuel and ash properties**

The granular composition of crushed fuel in Eesti PP is given in Figure 6. It was decided to use that fuel for CFB boilers without additional grinding. In adjustment tests of boiler became evident that the fuel granular composition is too coarse and the fuel needs additional grinding. Installation of fuel crushers after feeders reduced the oversized fuel particles content. In Figure 6 can be also seen difference in granular composition between CFB boiler and PF boiler fuels. The fuel for PF boilers is grind in hammer mills equipped with gravitational separators.

As the CFBC fuel is much coarser than PF fuel, the CFBC bottom ash contains also large particles (>10mm). Data about ashes granular composition from Eesti PP CFBC boilers are presented in Figure 7. The granular composition of PF boiler bottom ash is given also.

There are no differences in overall chemical composition of CFBC and PF oil shale ashes. Because of lower temperatures the ECD in CFB boilers is much lower compare to PF boilers. The CFBC ash, especially coarse fractions, contains more carbonate CO$_2$ than PF ash. The carbonate CO$_2$ content for finer ash particles is in the range 7.3-8.5% and for coarse particles 12.5-19.0% accordingly. Usually the PF ashes contain 10-30% free lime and the content is higher in coarse ash fractions. In CFB boiler ashes the free lime content is lower and there are no significant differences in free lime content between fine and coarse fractions.
Ash removal and landfilling
The most serious problem arisen in connection with new CFB boilers in Eesti and Balti power plants is ash removing. At the moment hydro- ash removal system is used and the basic environmental problem is possible release of highly alkaline (pH=13) ash field water to the nature. In the near future the new technology with dry, wet or ash removal with small contents of water should be found, but obviously during nearest few years the old system will be used.

The problem was arisen in connection with content of coarse-grained (>10 mm) particles in bottom ash of CFB boilers. Despite small amount of such particles in total ash (up to 1%, Figure 6.) they can clog the pulp tubing and stop the ash removal from the boiler at all due to small pulp velocity, especially in places where the pulp tube turn up to the landfill. In addition to tubes clogging conditions for coarse-grained pulps disperse on landfill has been worsened. Obviously additional crushing of bottom ash before giving into hydro removal system is needed to solve the problem.

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