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EXPERIENCE OF OIL SHALE COMBUSTION IN AHLSTROM PYROFLOW CFB-BOILER

X. ХОЛОПАЙНЕН

ОПЫТ СЖИГАНИЯ ГОРЮЧИХ СЛАНЦЕВ В ПСЕВДО-ОЖИЖЕННОМ СЛОЕ В КОТЛЕ ТИПА «ПАЙРОФЛОУ» ФИРМЫ «АЛСТРОМ»

Introduction

Oil shale is defined to be a sedimentary rock containing solid, combustible organic matter in a mineral matrix. The organic matter (called kerogen) decomposes to yield oil, when heated in reducing atmosphere.

Oil shale deposits were formed in lakes and seas some tens of millions years ago. Oil shale consists of indurated mud, composed of mineral particles mostly formed by chemical precipitation. Porosity and permeability of oil shale are very low. By the formation of the solid hydrocarbons (kerogen) of oil shale mineral constituents were also enclosed [1].

The oil shale can be exploited by two main processes: a) extracting the organic part kerogen by pyrolysis in retorts and obtaining an artificial crude oil like liquid, b) direct combustion.

The main interest in the world has been directed to the pyrolysis and retorting of oil shale to obtain artificial crude oil or gas. Direct combustion of oil shale was first studied in conjunction with these retorting projects, to utilize the fixed carbon which remains in retorting products. Today direct combustion alone is also considered as a possibility to generate energy in a large utility power plant.

Oil shales rich in oil can be combusted either by pulverized fuel combustion (PF) or by fluidized bed combustion (AFBC). PF has, however, some disadvantages versus AFBC:

— huge quantities of shale has to be pulverized (due to low calorific value). AFBC needs only crushing to —1/4″-size. In the retort applications the spent shale can be combusted as such in AFBC;

— PF needs additional flue gas desulphurizing scrubbers because high combustion temperatures don't enable to form $CaSO_4$ in the combustion chamber. The lower combustion temperature of AFBC facilitates the $CaSO_4$-formation, so that virtually all sulphur is bound with the fuel ash containing excess of CaO;

— PF leads to hard buildups on heating-surfaces due to high gas temperatures which cause volatilization of alkalies present in the fuel. PF may also cause melting of the ash;

— NO_x emissions are also higher in PF than in AFBC.

Oil shale reserves are quite abundant all over the world. However, the relatively low crude oil prices have not encouraged large scale utilization of it in the western world. In some special places the utilization has been of local importance. Most western projects have been funded by their governments.

Oil Shale Reserves

Known world oil shale reserves run, by estimate, to about 3.4×10^{12} barrels i. e. 20×10^9 TJ.

The world total fuel consumption in 1987 was 269×10^6 TJ [2]. That means that the known oil shale reserves would suffice for a total fuel consumption for 73 years (at 1987 consumption level). Thus the oil shale reserves are abundant, but their utilization has started only in few places, due to the low quality of shales. The economically recoverable resources are very speculative because the oil price has changed quite a bit during the last ten years. There is even one source from 1984, were it is said that USA has no economically remunerative oil shale deposits]6].

There are oil shale deposits in more than 30 countries all the world over (see Table 1 and Fig. 1) [2—5].

Table 1. Oil shale reserves, 10^6 barrels
Таблица 1. Мировые запасы горючих сланцев, 10^6 баррелей

U.S.A.	2 166 200	Germany	2 000
Brazil	802 000	Burma	2 000
USSR	112 600	Yugoslavia	>1 540
Zaire	100 000	Jordan	800
Italy (Sicily)	63 000	Luxembourg	700
Canada	44 030	Belgium	690
Morocco	37 900	Argentina	400
China	28 000	Spain	280
Australia	17 000	New Zealand	250
Italy	10 000	South Africa	130
Madagascar	10 000	Bulgaria	125
France	7 000	Poland	48
Thailand	6 000	Chile	21
Israel	5 000	Turkey	18
United Kingdom	3 500	Austria	8
Sweden	3 160		
S u m			3 424 400

Combustion becomes a serious problem by the very high content of ash in shale. We can list the areas of concern as follows:

Economical problems,

— high ash content of the fuel requires abnormally high investments in fuel preparation (in transportation, fuel preparation, crushing, conveying, storage and feeding to the boiler);

— large ash flows must be efficiently cooled down to obtain high thermal efficiency in the power plant;

— ash removal system also needs high investments due to large flows (conveyors, silos, dust abatement, transportation);

— utilization of ash for some useful purpose (cement manufacturing, building materials, road construction) or to dump it.

Ecological and hygienic problems,

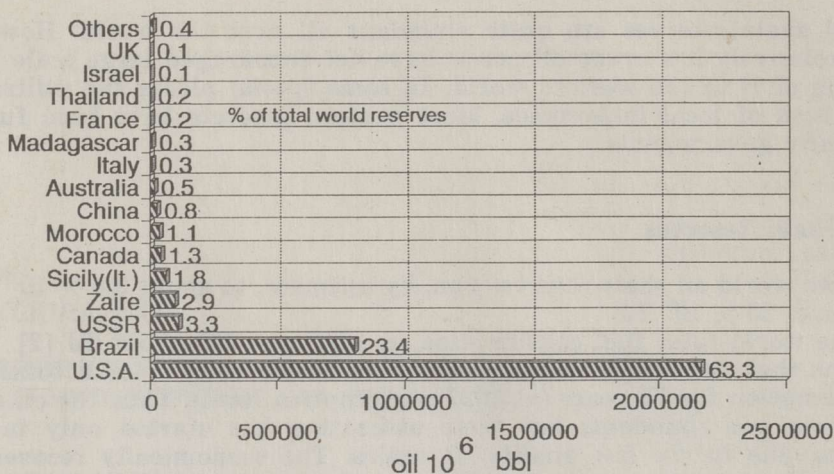— mining may cause problems to the ground water;

	% of total world reserves	
Others	0.4	
UK	0.1	
Israel	0.1	
Thailand	0.2	
France	0.2	
Madagascar	0.3	
Italy	0.3	
Australia	0.5	
China	0.8	
Morocco	1.1	
Canada	1.3	
Sicily(It.)	1.8	
Zaire	2.9	
USSR	3.3	
Brazil	23.4	
U.S.A.	63.3	

oil 10^6 bbl

Fig. 1. Oil shale reserves (total 3424 billion barrels)

Рис. 1. Мировые запасы горючих сланцев (в общей сложности 3424 млрд. баррелей условной нефти)

— SO_2 emission by PF combustion requires scrubbers (by fluid bed combustion it is not a problem);

— dust emissions from solids handling and storage near the plant requires precautions;

— as the ash is very alkaline, ground water has to be protected near dust dumping areas.

If the above-mentioned problems will be solved according to today's standards they may increase the cost of oil shale in energy production in many cases to a level where coal and oil are competitive. Thus their use is mainly feasible only locally.

Large scale utilization is realized in China and in Estonia. Estonia has two power stations; the Baltic Thermal Power Plant near the town Narva consisting of 18 boilers with an installed capacity of 1435 MW$_e$ from 1959—1962 and the Estonian Thermal Power Plant with an installed capacity of 1610 MW$_e$ from 1973. PF combustion is utilized in Estonia. In China Fushun and Maoming retorting plants produce 1.6 million barrels of shale oil yearly (1984). The Chinese have used bubbling bed combustion for a long time and are now evaluating and testing circulating fluid bed technology.

Ahlstrom Experience with Oil Shale

Ahlstrom, as the leading manufacturer of circulating fluid bed boilers, has been involved in the development of various customer projects in the 1980's. The firm has carried out the development and oil shale testing in pilot and demo-plants as well as in full scale plants. Six different kinds of oil shale fuels have been tested, see Table 2.

One of the developments has been elaborated together with PAMA (Energy Resources Development) Ltd of Israel. PAMA started to develop oil shale retorting and direct combustion of shale with the process residues in 1981. In recent years, when the price of crude oil has been 15—20 US$/bbl the direct combustion power plants have attracted the
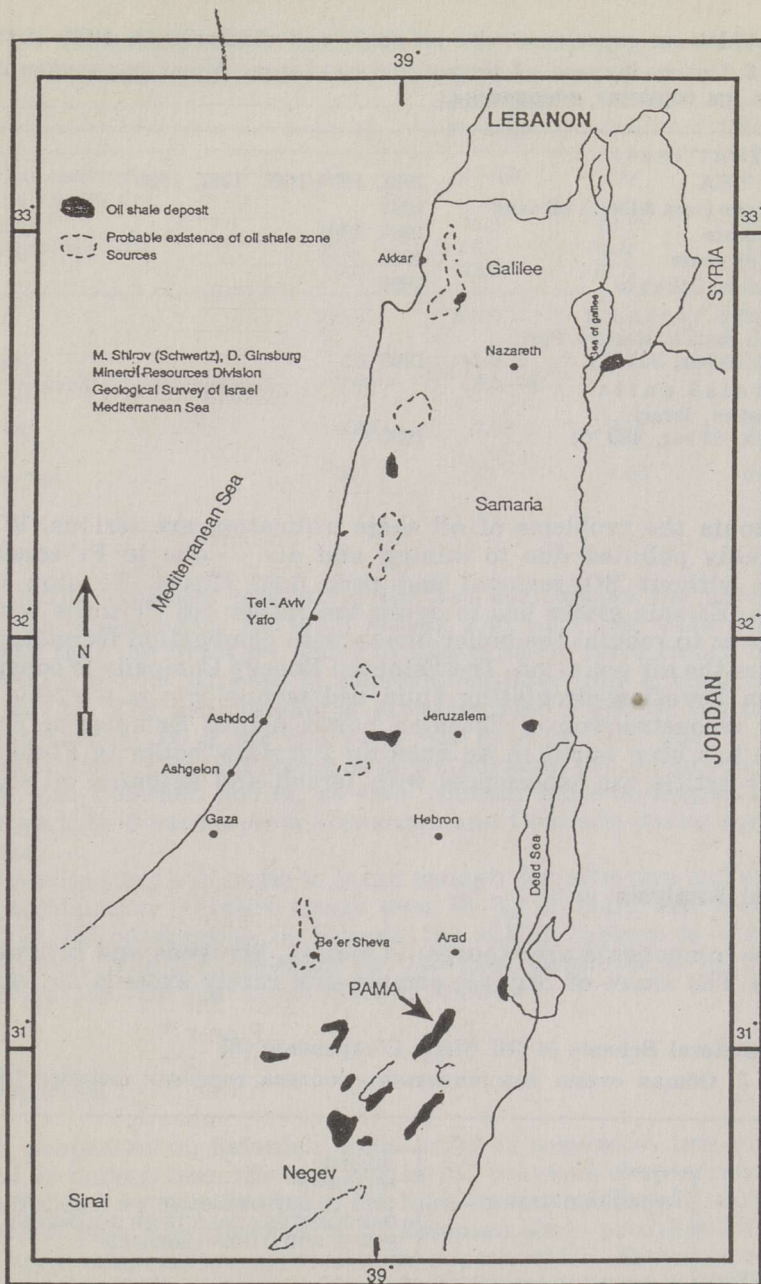
Fig. 2. Oil shale deposits and occurrences in Israel
Рис. 2. Месторождения и проявления горючих сланцев в Израиле

main interest of PAMA. Ahlstrom tested Israeli oil shale combustion in the Pyroflow pilot plant in Karhula 1982 and 1984. A contract to build a 50 t/h, 43 bar, 480 °C commercial plant in Rotem, Northern Negev, Israel, was awarded to Ahlstrom 1987. PAMA is situated at the border of the largest oil shale field in Israel (see Fig. 2). PAMA uses the plant to demonstrate the feasibility of power generation and suitability of equipment for a large scale utility, additionally producing steam and electricity for the phosphate plant.

Tabel 2. **Ahlstrom experience with oil shale and similar fuels 1981—1990**

Таблица 2. **Опыты фирмы «Алстром» по сжиганию горючих сланцев и подобных им горючих ископаемых**

Pilot plant tests	
Diatomite, USA	1981, 1984/1985, 1987, 1990
Syncrude coke from Alberta oil sand	1981
Israeli oil shale	1982, 1984
Jordanian oil shale	1988
U.S. oil shale, Colorado	1989
Full scale tests	
Estonian oil shale at Kemira, Pori	
(28 kg/s, 85 bar, 525 °C)	1990
Commercial units	
PAMA, Rotem, Israel	
(13.9 kg/s, 43 bar, 480 °C)	1990

In Estonia the problems of oil shale utilization are serious. Water is considerably polluted due to mining and air — due to PF-combustion of shale without SO_2-removal and poor dust filters. To stop the air pollution, Estonia either has to equip the rather old PF-units with SO_2-removers or to rebuild the boiler blocks with combustion technology that eliminates the air pollution. The Estonian Energy Company is considering Ahlstrom Pyroflow-circulating fluid bed technology as a viable candidate for reconstruction of Estonian power plants. Samples of Estonian oil shale has been burnt in an existing Pyroflow boiler in Finland.
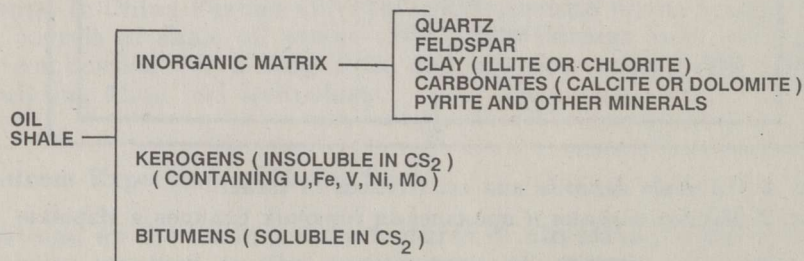
In this article the experiences with Israeli and Estonian oil shale are reported.

Oil Shale Analysis

Oil shale components are: inorganic matrix, kerogens and bitumens (see Table 3). The share of organic components rarely exceeds 25 wt.%.

Table 3. **General Scheme of Oil Shale Components [8]**

Таблица 3. **Общая схема компонентного состава горючих сланцев [8]**

Typical oil shale analyses for Ahlstrom projects are given in Table 4. All of them are characterized by very high ash contents, 50—70 wt.%, and high carbonate contents. We see that Estonian oil shale is a very rich one among the others. It has the highest content of combustibles, 35 % and therefore the highest heat value, HHV 11 MJ/kg. The Israeli oil shale belongs to the lower rank of shales when energy content is concerned. The content of combustibles are low, only 14 wt.% (dry basis)

Table 4. Oil Shale Comparison /wt.%

Таблица 4. Характеристика горючих сланцев, % (по массе)

	Israel	Estonian	Jordan	Colorado
Moisture (as received)	18	11—13	8.5	1.0
On the dry basis				
Combustibles	14.3	34.9	18.1	18.3
CO_2 in carbonates	26.5	16.7	14.8	13.5
Ash	59.2	48.4	67.1	68.3
Sum	100.0	100.0	100.0	100.0
HHV (dry)	4.2	11.0	6.6	6.6
LHV (as received)	2.93	8.5—9.		
C/H, wt/wt	9.33	7.98	8.14	7.76
Ca/S, mol/mol	5.6	2.7	4.56	6.4

and the high carbonate content in the ash still lowers the useful heat available in combustion, HHV 4.2 MJ/kg and LHV less than 3 MJ/kg. We believe that the Pyroflow boiler in Negev has a world record in using commercially a fuel with 86 % non-combustibles and a heat value of only 3 MJ/kg. The ash content is probably also a record for oil shale as the main fuel, 200 g/MJ (LHV) or 410 g/m^3(n) flue gas.

As to oil yield, the C/H value is more suitable for oil production in Estonian and Colorado shales, as they contain more hydrogen in their kerogen part. In other respects Jordanian and Colorado shales seem to be very alike.

In all shales the Ca/S ratio is large enough for effective sulfur retention in combustion (capture range over 95 %) if fluid bed technology is used. In PF combustion in Estonia the sulfur capture is within the range of 60 %. The SO_2 emission per MJ heat generated is high in PF-firing when the fuel has a low heating value.

Ash Properties

The ash properties of Estonian shale make it somewhat less attractive as a fuel in boilers than the analysis in the previous chapter would suggest. In Table 5 we can see that it has high content of Cl, 0.75 wt.% in the combustible part. The combustion of Estonian shale produces HCl which causes high temperature corrosion in superheaters. Estonian oil shale has also high alkali content, 2.65 wt.% K_2O and 0.34 wt.% Na_2O in the inorganic part, which causes severe fouling of the heat surfaces in PF combustion.

Israeli oil shale is free of Cl and has low content of alkalies. It has a high content of P_2O_5 but in spite of that the ash composition does not lead to harmful ash softening phenomenon at the temperatures used in CFBC firing.

The large amount of carbonate in the ash is important, because when it decomposes in combustion, the reaction is endothermic, and less net heat is available for steam production.

$$CaCO_3(s) \rightarrow CaO(s) + CO_2(g) \qquad (1)$$
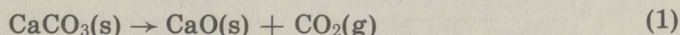
$dHr = + 178.9 \, kJ/mol \, (CO_2)$ or 0.8 MJ/kg oil shale.

The amount of carbonates decomposing is 75—90 % when combustion temperature in the furnace is between 750—850 °C. The reaction starts at about 700 °C.

The sulfatization reaction brings heat to the system. However, the amount of heat generated is small compared to reaction (1) because Ca/S ratio is large in Israeli oil shale, i. e. Ca/S = 7 . . . 9 mol/mol. The reaction starts at temperatures higher than 600 °C.

$$CaCO_3 + SO_2 + 1/2O_2 \rightarrow CaSO_4 + CO_2 \tag{2}$$
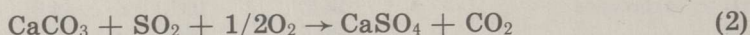
$$dHr = -322.6 \text{ kJ/mol (CaSO}_4).$$

The reaction between free CaO and SiO$_2$ in the ash is also exothermic.

$$CaO + SiO_2 \rightarrow CaSiO_3 \tag{3}$$
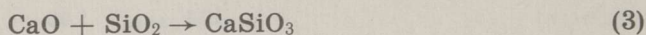
$$dHr = -1452.3 \text{ kJ/mol (CaSiO}_3).$$

It is kinetically favorable only at higher temperatures 850—950 °C, which are not needed in FB combustion because oil shale is reactive already at temperatures 750—850 °C.

Due to the formation of oil shale in history through precipitation of chemicals in water and embedding of combustible particles finely distributed in the matrix, oil shale forms very fine grained fly ash in combustion. The original particle size which forms bigger oil shale agglomerates is 1—5 microns.

Big agglomerates partly disintegrate and wear off from surface and

Table 5. **Oil Shale Comparison wt.%, dry basis**
Таблица 5. **Сравнительная характеристика горючих сланцев, % (по массе, на сухое вещество)**

	PAMA	Estonian
C o m b u s t i b l e p a r t		
C	67.83	77.45
H	7.27	9.70
S	6.71	1.76
N	2.10	0.33
O	16.08	10.01
Cl	0.00	0.75
S u m	100.00	100.00
I n o r g a n i c p a r t		
CaO	42.99	31.31
SiO$_2$	10.62	24.88
Al$_2$O$_3$	5.24	6.85
FeS$_2$	—	5.17
Fe$_2$O$_3$	2.19	1.18
FeO	—	0.12
TiO$_2$	—	0.29
MgO	0.73	1.33
Na$_2$O	0.20	0.34
K$_2$O	0.40	2.65
SO$_3$	1.13	0.21
CO$_2$	30.92	25.69
Crystal H$_2$O	1.98	—
S pyritic	0.75	—
P$_2$O$_5$	2.85	—
S u m	100.00	100.00

form very fine fly dust with particle size 1—5 microns. Thus, large amounts of fly ash pass the back pass in the boiler. FBC has the advantage, compared with PF firing, namely the temperature in the inlet to the second pass is not exceeding the softening temperature of the dust. Thus cleaning of superheaters is easier than in PF-systems.

Plant Description, PAMA Cogeneration Demonstration Plant

The PAMA plant in Israel produces steam, 50 t/h, 43 bar, 480 °C, commercially to the Negev Phosphates plant in Rotem and gives besides 6 MW electricity to the grid of the plant. The commercial operation of the plant started in February 1990 and since then it is in continuous operation.
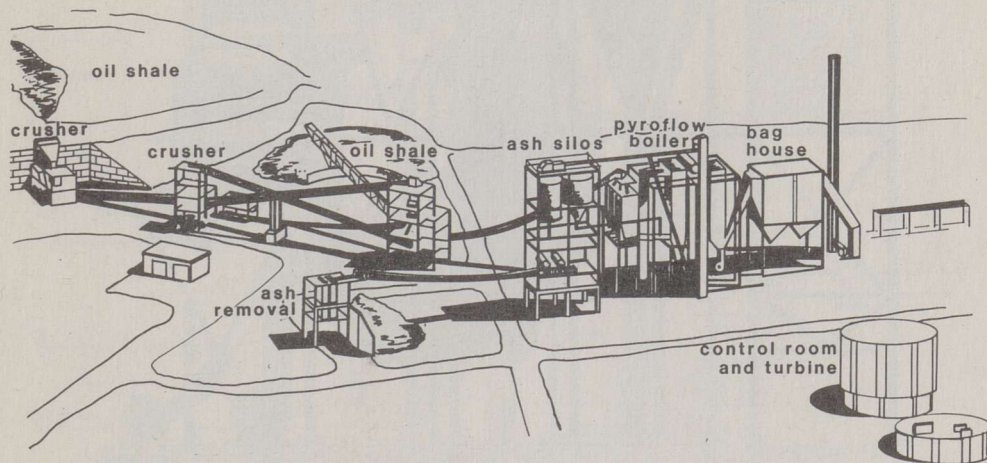

Fig. 3. PAMA demonstration plant (13.9 kg/s, 43 bar, 480 °C)
Рис. 3. Общий вид установки в Ротеме

Table 6. Main data of PAMA demonstration plant
Таблица 6. Основные данные установки ПАМА

Steam Data		Design Performance	
Total Heat Output	41 MW$_{th}$	Furnace temperature	800 °C
Steam Flow	13.9 kg/s	Flue Gas Exit	
Steam Pressure	43 bar	temperature	155 °C
Steam Temperature	480 °C	Feed Water	
Fuel Data	Oil Shale	temperature	105 °C
Organic Matter	13.6—16 %	Boiler Efficiency	
Sulphur	1.1 —1.7 %	(DIN)	83.7 %
Moisture	16 —22 %	Schedule	
Ash	44 —50 %	Contract Award	August 1987
Lower Heating value	3.155 MJ/kg	Start of Erection	September 1988
		Oil Shale Firing	October 1989

A view of the plant lay-out is given in Fig. 3 and the lay-out of the boiler in Fig. 4. The main technical data is presented in Table 6. Some details in design have demonstrative purpose. As for example the larger number of feeding points because the aim was to test several feeding systems. As a whole it is more like a big material processing than a conventional boiler plant. To produce 1 t of steam one needs 1.1 t of oil shale.
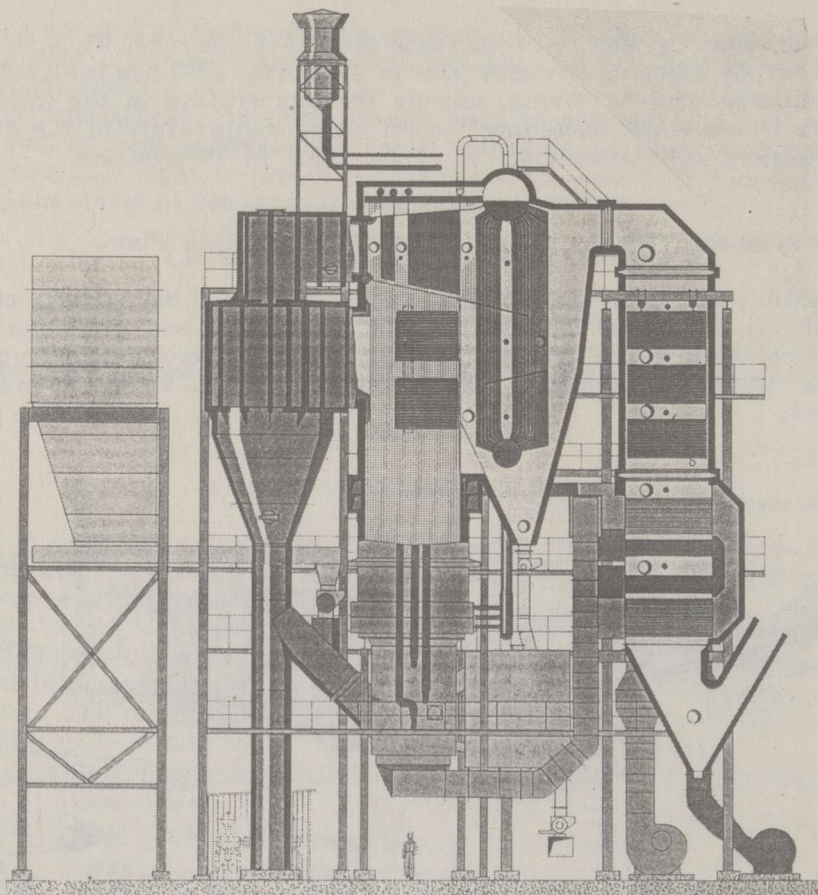
Oil shale combustion in Ahlstrom pyroflow CFB-boiler: H. Holopainen
Котел типа «пайрофлоу» фирмы «Алстром»: X. Холопайнен

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Fig. 4. Ahlstrom Pyroflow boiler (PAMA LTD., Rotem Plain)
Рис. 4. Общий вид котла в Ротеме

Mined oil shale is conveyed by trucks to a storage pile. It is loaded then by a tractor to the crushing station and is crushed in two stages. The first crusher is of jaw type and the second of impact type. The crushed material is conveyed to a screening station where it is screened to —6 mm. The fraction +6 mm is recycled to the impact crusher. The belt conveyors take the fuel to two silos, each 280 m³. The fuel is conveyed from silos by four link chain conveyors to the boiler. Two feeding points are through the loop seals and two points through the side walls, one point through a screw and one through a free falling chute. Only two feeding points are used simultaneously. Ash is taken out at the bottom through a fluidized bed ash cooler, which has cooling surfaces. The ash is cooled down to 250—300 °C. The rest of it goes through the back pass and is taken out from the hoppers below the boiler bank, the air preheater and the baghouse. The ash is conveyed by redlers and bucket conveyors to ash silos (one is for bottom ash and the other for fly ash). The bottom ash and fly ash are mixed together with water in rotating drums to form agglomerates. Then it is transferred by belt conveyors to silos for loading into trucks. The ash is stored temporarily in piles but the ultimate destination is to dump it in the mining areas. PAMA is testing the possibilites of using the ash for paving roads etc. Ash would be suitable for building materials and cement production also but the market of Israel can not take such large amounts of it.

The boiler is a normal CFB with some modifications to meet the high ash load of oil shale. The gas velocity in the combustion chamber is designed 5 m/s at full load and combustion temperature of 800 °C.

The water and steam flowsheet is normal, see Fig. 5. As the boiler is operating at a low pressure, 43 bar, and the fuel has a low heat value, a boiler bank with two drums is needed in order to get enough evaporating surface. One special feature in the water flowsheet is that 105 °C feed water flows first through the ash cooler surface which is economizer I. After that water goes to economizer II in the back pass. The air heater is designed to preheat primary and secondary combustion air before entering the steam drum. The flue gas after air preheater is designed for 155 °C at full load 50 t/h. A baghouse is used to filter fly ash.
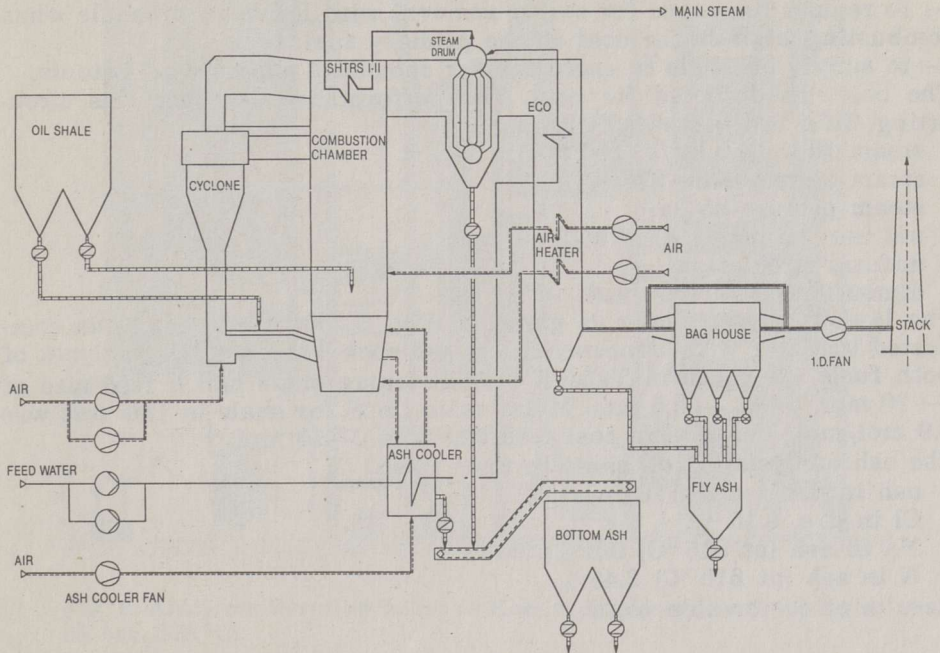

Fig. 5. PAMA oil shale power plant, Israel. Process flow sheet
Рис. 5. Схема процесса

Process Experience, PAMA

When operated at 45 t/h load at 810 °C combustion temperature, following results were obtained:
O_2 in flue gas 3.65 %;
combustion performance CO 150 ppm;
unburnt carbon, 0.07 wt.%;
combustion efficiency (on energy basis) 99.5 %;
carbonate decomposition 90 %;
SO_2 1—2 ppm;
NO_x 70 ppm;
    dust in stack 37 mg/m^3(n).
Thus combustion is very good and emissions at a low level.

Utilizing Israeli oil shale in the PAMA demonstration boiler has given a lot of experience in designing the boilers for Israel Electric and large industrial power producers in Israel.

Combustion Test with Estonian Oil Shale at Kemira OY, 100 t/h Commercial Industrial Pyroflow Unit

It was proposed that Estonian oil shale could be supplied to Kemira Oy in exchange for chemicals exported from Kemira to Estonia. The oil shale could replace the limestone, normally used for sulphur capture.

Estonian Energy Company together with Kemira OY conducted tests with Estonian oil shale. Ahlstrom's research laboratory was invited to participate in this work. The test burning was carried out in the commercial Pyroflow unit at Kemira Oy, Pori, Finland. The aim of the tests was:

— to study combustion of Estonian oil shale in a Pyroflow boiler;
— to replace limestone for sulfur removal with Estonian oil shale when combusting high sulfur coal as the primary fuel;
— to supply oil shale in exchange for chemicals exported to Estonia.

The boiler is designed for coal. The performance data for this circulating fluid bed boiler is following:

    steam flow 28.0 kg/s (100 t/h);
    steam temperature 525 °C;
    steam pessure 85 bar;
    net heat to steam 81 MW_{th};
    natural circulation;
    dimensioning fuel — coal.

The lay-out of the boiler is given in Fig. 6. 600 t of shale was combusted together with Venezuelan low ash coal. The data for analyses of both fuels are given in Tabel 7. The Estonian shale had a feed size of 0—20 mm, 50 % — 2.5 mm. Molar ratio Ca/S for shale in this test was 8.9 mol/mol. Venezuelan coal feed size was 0—16 mm.

The ash analysis for oil shale in tests was:

    ash in d. s. (at 815 °C) 47.8 %;
    Cl in d. s. 0.15 %;
    Na in ash (at 815 °C) 0.2 %;
    K in ash (at 815 °C) 2.45 %.

Results of combustion tests:

	Test 0	Test 1	Test 2
Share of shale of tot. heat input, %	0	50	75
Steam load, kg/s	23.3	22.3	21.6
Comb. temp., °C	885	871	859
Oil shale feed, kg/s	—	3.2	4.7
Coal feed, kg/s	2.4	1.4	0.7
Limestone feed, kg/s	0.1	—	—
O_2 (wet), %	3.5	5.9	4.8
SO_2 emission (wet), ppm	100	16	14
NO_x (wet), ppm	n. a.	196	240
CO (wet), ppm	n. a.	95	140
Dust after ESP*, $mg/m^3(n)$	35	1.8	n. a.
Ash distribution:			
bottom ash, %	n. a.	9	6
fly ash, %	n. a.	91	94

* Electrostatic precipitation.

Thus SO_2 emission was reduced to very low values, although no limestone was used for sulphur removal.

Virtually all oil shale ash seems to come out as fly ash from the system. The fly ash of Estonian oil shale has very suitable electrical surface properties for dust removal by an ESP. The dust contents measured after ESP were consistently very low in test No. 1.
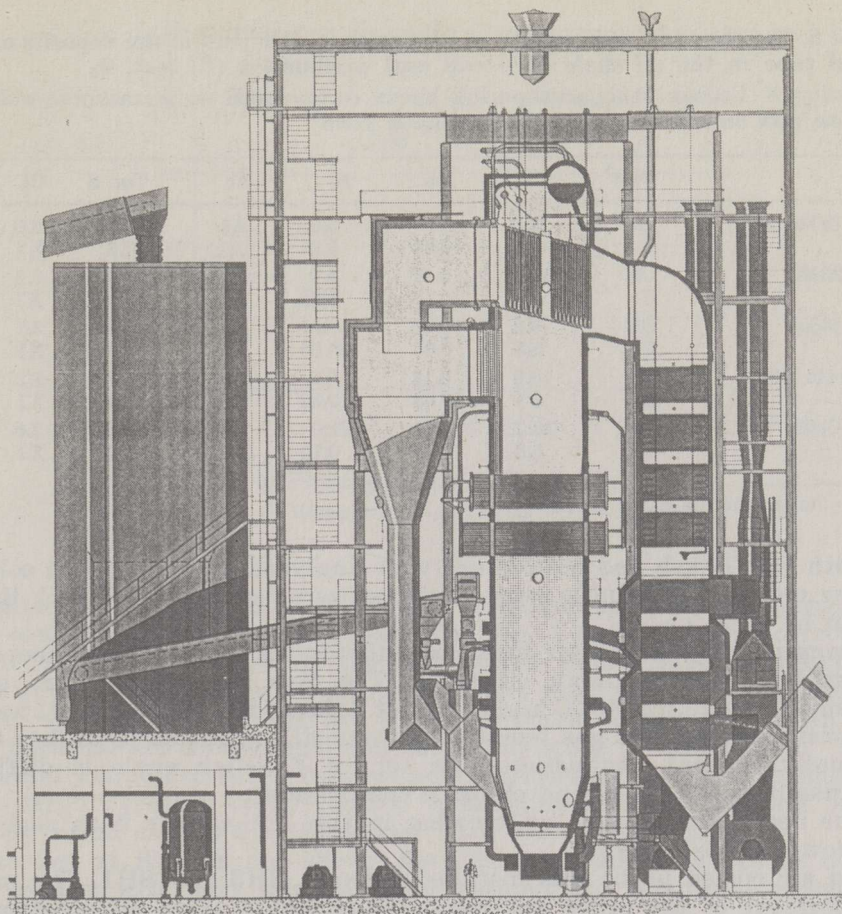
Fig. 6. Ahlstrom Pyroflow boiler at Kemira OY Vuorikemia (28 kg/s, 85 bar, 525 °C)

Рис. 6. Общий вид котла в Кемире

Table 7. **Fuel analysis in combustion test with Estonian oil shale + Venezuelan coal at Kemira Oy, wt.%**

Таблица 7. **Характеристика эстонского сланца и венесуельского угля использованных в опытах на химическом заводе Кемира**

Analyzed species	Venezuelan coal	oil shale
Dry solids	91.6	88.6
Volatiles in d. s.	37.0	47.2
Ultimate analysis:		
Ash (in d. s.)	4.72	47.8
C ,,	80.5	32.8
H ,,	5.47	2.86
N ,,	1.50	0.24
S ,,	0.534	1.31
O (as difference)	7.28	14.99
Ca in ash	5.7	30.5
Heat value:		
HHV (MJ/kg in d. s.)	32.70	12.17

Table 8. **The chemical composition of the water soluble part of the deposits on the metal tube in the oil shale (OS) and coal combustion (C) test, %**

Таблица 8. **Состав водорастворимой части отложений на металлической трубке при ожигании горючего сланца и угля**

	Test	pH	Na	K	Fe	Tot. S	Cl
X12 CrMo 21	OS	9.6	0.17	3.5	X1	5.3	3.0
	C	5.9	0.37	0.33	X1	10.2	X1
SIS 2343	OS	10.0	0.36	9.9	X1	9.1	6.5
	C	6.0	0.72	0.62	X1	13.5	X1
SIS 2333	OS	9.8	0.26	9.8	X1	9.9	3.7
	C	5.5	0.65	0.56	X1	5.4	X1
10 CrMo 910	OS	10.0	0.18	6.0	X1	5.6	1.2
	C	5.4	0.68	0.32	3.3	8.3	X1
X20 CrMo V121	OS	10.2	0.30	11.0	X1	11.3	2.5
	C	5.3	0.91	0.70	X1	6.6	X1

X1 — below the diagnosis limit.

Both the fly ash and bottom ash were analyzed with regard to soluble heavy metals. All soluble concentrations were far below the U.S. limits given by EPA.

Slagging of superheater surfaces and fouling of other surfaces was a problem with Estonian oil shale. The flue gas temperature after the superheaters was 40 °C higher in test 2 than with coal alone. After the air preheater the flue gas temperature was still about 35 °C higher than normally in coal combustion. The ash of Estonian shale is difficult because it is rich in K and chlorine compounds.

The heat surfaces and sootblowing in this boiler have been designed for low ash coal only.

An air cooled probe was installed between SH3 and SH1. The metal temperature of the probe was regulated at 500 °C. Five different materials were installed in the probe. The chemical analysis of the deposits is given in Tabel 8. It is obvious that KCl and K_2SO_4 compounds have
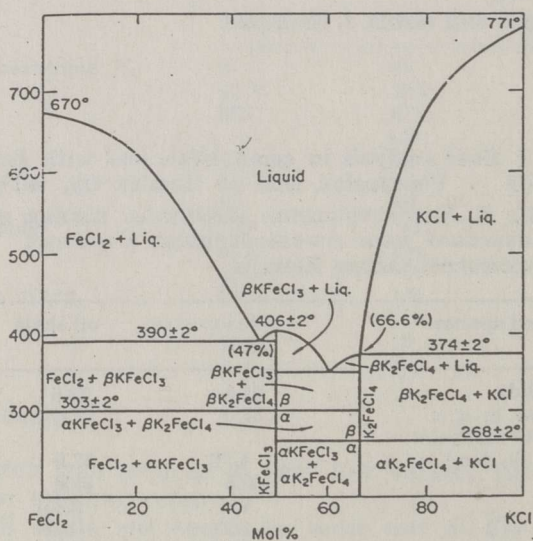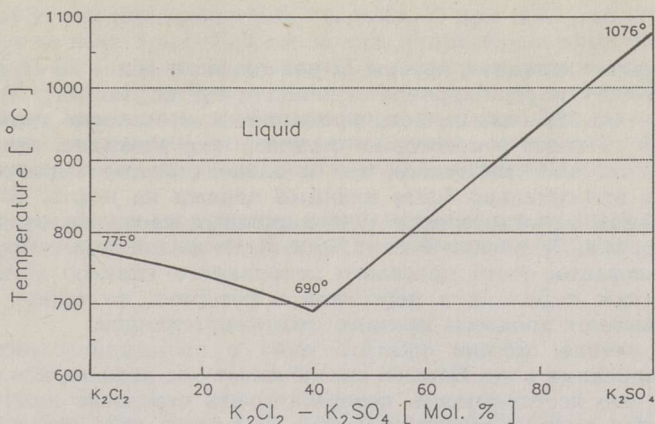

Fig. 7. Phase diagram KCl—FeCl₂
Рис. 7. Фазовая диаграмма KCl—FeCl₂

Fig. 8. Phase diagram KCl—K₂SO₄
Рис. 8. Фазовая диаграмма KCl—K₂SO₄

deposited on the probe. Some melting of these compounds has occurred or they condensed from gas phase (see also Fig. 7 & 8). Chlorine corrosion would have been obvious if the test period would have been longer. Even now after three days testing there was some corrosion and weight loss in specimens nr. 1 and nr. 4. The reactions taking place with the tube material are complicated and out of the scope of this article.

Specially designed easily overhauled superheaters should be considered when large Pyroflow boiler for 100 % Estonian oil shale feed are built. The corrosion can be also alleviated with material selection.

The test at Kemira has shown that Estonian oil shale can be burnt in Pyroflow with very low emissions without any scrubbers compared to PF-firing, now used in Estonia.

Future Outlook

As the world market leader in CFB-boilers, Ahlstrom has experience of more than 90 Pyroflow CFB-boilers. Due to experience from PAMA-demonstration plant and R&D work with different oil shales Ahlstrom is also well prepared to cope with the problems that oil shale utilization brings along.

However, oil shale mining and end use of oil shale ash must be solved case by case in co-operation with the local authorities and power companies. Huge amounts of ash are the largest obstacle in utilization of oil shale for energy production. Any economical utilization of ash, e. g. use in cement production, road building etc. can determine the feasibility of the whole project. With Pyroflow-technology the air quality problems are to overcome.

Estonia is expected to rebuild some of its oil shale boilers using CFB-technology. Israel Electric Corporation has plans to build utility size boilers based on fluid bed combustion. Some projects are also evolving in China. In USA the development of the projects is fully dependent on the crude oil price.

Oil shale combustion in Ahlstrom pyroflow CFB-boiler: H. Holopainen
Котел типа «пайрофлоу» фирмы «Алстром»: Х. Холопайнен

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РЕЗЮМЕ

Ресурсы горючих сланцев, которыми располагают более 30 стран мира, оцениваются в 3424 млрд. баррелей эквивалентной нефти (рис. 1). Однако, несмотря на столь богатые запасы, промышленное освоение горючих сланцев осуществляется лишь в некоторых странах, что, очевидно, связано с рядом трудностей как экономического, так и экологического характера, а также обусловлено относительно более низкими ценами на нефть. К странам, где горючие сланцы используются в промышленном масштабе, относятся Китай, Россия, Израиль, Эстонская Республика. Если до сих пор в крупномасштабном использовании этого полезного ископаемого главное внимание уделялось процессам пиролиза и перегонки в ретортах, то теперь все больший интерес вызывают процессы прямого сжигания сланцев.

Горючие сланцы можно сжигать либо в пылевидном состоянии, либо в псевдоожиженном слое. Первый способ имеет ряд недостатков по сравнению со вторым: это необходимость перерабатывать огромные количества тонкоизмельченного материала (из-за малой удельной теплоты сгорания горючего сланца), потребность в дополнительных газоочистителях для обессеривания топочных газов (высокие температуры препятствуют образованию $CaSO_4$ в камере сжигания), значительное загрязнение отложениями поверхностей нагрева, обильное выделение окислов азота (NO_x).

В Эстонии самыми крупными производителями энергии являются Прибалтийская (18 котлов общей мощностью 1435 МВт) и Эстонская ГРЭС (1610 МВт), на которых используется метод пылевидного сжигания, что обусловливает сильное загрязнение воздуха в окрестностях этих предприятий вследствие недостаточного улавливания соединений серы и некачественных фильтров для пыли.

В Китае (в Маомине и Фушуне) сланцеперерабатывающие заводы вырабатывают около 1,6 млн. баррелей сланцевой смолы в год. Только в последнее время там тоже начали испытывать способ циркулирующего сжигания в псевдоожиженном слое под котлами.

А. Алстром корп., как ведущий производитель установок для сжигания твердых топлив в псевдоожиженном слое, была привлечена к совместной работе с израильской фирмой энергетических ресурсов ПАМА, а также с Эстонским управлением энергетики.

В 1982 и 1984 гг. на установке фирмы в Кархула проводили опыты по сжиганию израильского сланца (рис. 2). В результате, в 1987 г., был подписан договор о том, что для фирмы ПАМА будет сооружена промышленная установка со следующими параметрами: 50 т/ч, 43 бар, 480 °C. Эта установка с турбогенератором 6 МВт смонтирована в Ротеме и с февраля 1990 г. снабжает паром и электроэнергией фосфатный завод. Общий вид установки приведен на рис. 3, котла на рис. 4, схема процесса — на рис. 5. Опыты показывают, что горение местного сланца протекает стабильно и эффективно, с к.п.д. 99,5 %. В отходящих газах концентрации вредных для окружающей среды компонентов низкие: при содержании кислорода в газах 3,65 % концентрация CO составляет 150×10^{-6}, SO_2 — около $(1-2) \times 10^{-6}$ и NO_x — 70×10^{-6}, содержание пыли на выходе из дымовой трубы равно 37 мг/м^3 (норм.).

Что касается сотрудничества между А. Алстром корп. и Эстонским управлением энергетики, то эстонская сторона видит в этом перспективы разрешения своих экологических проблем.

Исходные данные анализа разных видов горючих сланцев для проектирования установок «Алстрома» приведены в табл. 4. Как видно, среди исследованных у эстонского горючего сланца самое большое содержание горючих компонентов (35 %), а также самая большая удельная теплота сгорания (11 МДж/кг). Соответствующие данные для израильского сланца — 14 % и 4,2 МДж/кг. Все виды сланцев высокозольные — 50—70 %.

Опыты с эстонским горючим сланцем проводили на химическом заводе Кемира в г. Пори. Исследовательская лаборатория фирмы «Алстром» имела целью выяснить особенности процессов сжигания при использовании эстонского сланца, а также изучить возможности замены известняка горючим сланцем в процессе обессеривания газов. Общий вид котла приведен на рис. 6; его параметры — 100 т/ч, 83 бар и 525 °C. 600 т сланца были сожжены вместе

с венесуэльским углем (низкозольный, см. табл. 7) при нагрузке котла около 80 т/ч. Несмотря на некоторые сложности, как, например, загрязнение поверхностей нагрева из-за высокого содержания в эстонском горючем сланце соединений калия и хлора, пайрофлоу-технология вполне перспективна для решения проблем, связанных с загрязнением воздуха. Так, концентрация SO_2, которая при сжигании венесуэльского угля составляла 100×10^{-6}, в опытах по совместному сжиганию этого угля с эстонским сланцем падала до $(14—16) \times 10^{-6}$.

В Эстонии намеревается сооружение нескольких котлов по технологии фирмы «Алстром». Некоторые проекты фирмы осваиваются в Израиле и в Китае.

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