5. REDUCTION OF COAL TPS ENVIRONMENTAL IMPACT IN RUSSIA

5.1. Coal used at Russian TPS

5.1.1. General

Russia possesses rich coal resources. The largest and most economically important of these are the Kuznetsk (Kuzn.) and Kansk-Achinsk (K-A) coal fields located in the southern part of Central Siberia. The production of coal now amount to about 270×10^6 t/y.

In the European part of the country much coal is produced in the south, in the Eastern Donbass (Donb.) and to the north, in the Pechora (Pech.) coal fields. Production of the expensive and low-grade brown coals found near Moscow is rapidly decreasing.

There are many coal fields covering the (rather high) demands of the nearby regions.

A large amount of Ekibastuz (Ekib) coal produced in Kazakhstan is fired in Russian TPS.

The quantities and properties of coal fired in Russian TPS are illustrated in Table 19 [3].

Coal production conditions are most favorable in the K-A field, where large, horizontal seams, tens of ms thick, are located near the surface. The field is in an easily-accessible area with acceptable climatic conditions. The coal is produced by the open-cast (strip-mining) method at rather low cost.

The geological conditions in the highly-developed Kuzn field are now rather complex. The industry environmental impact here is high in many areas and the infrastructure is inadequate.

In the European part of the country the coal is mined underground which makes it cost very high. The geological conditions of the heavily mined areas (Eastern Donb and the Moscow area fields) are unfavorable. The Pechora coal field is located in a severe climatic area.

The Eastern regions of the country supply mostly low-grade, high-moisture, and high-ash local coals to be fired at power stations. Many old coal fields are exhausted and vast territories are energy-deficient. Coal will continue to plat an important role for the Russian power industry in the near future. The direction and specifics of the evolution of the coal industry in Russia are briefly discussed in Section 3.

5.1.2. Characteristics of Bituminous Coals

Russia mostly uses the Kuzn bituminous coals from the Southern Part of Central Siberia. These high-grade, low-sulfur coals are adaptable for transport over large distances. Coals of various petrographic composition and degrees of carbonization are used to fire utility boilers. The properties of these coals are given in Table 20 wherein LF stands for long-flame, G denotes gas-coals, WS designates weakly sintering, L means lean and A – anthracite. Wider limit of variation of some properties – maximum moisture content up to 18-21 percent, lean coal volatile matter content of 5.5-14 percent, heating value of 16.5-27.7 MJ/kg are characteristic of open-cut produced coals of respective grades [26].

Besides the graded coals, TPS are supplied with various by-product and slurries from coal-beneficiation operations. The properties of such materials vary widely (refer to the last column of Table 20).

In terms of geology and available transportation asset, production of these superior coals could be significantly increased. However, the region in which they occur is saturated with various large, basic industries such as coal, metallurgy, chemicals and others. This has strained the local infrastructure to the point that increasing coal output substantially would require large capital investment.

Despite all this, the Kuzn coal field is still a major coal base of Russia and the coals from this field are used at many existing TPS, including those in the European part of the country. This coal is fired at a great number of cogeneration and condensing power plant employing 150- and 200-MW subcritical unit, and also at TPS with 300-MW supercritical unit. 800-MW unit Installed at the Perm, and designed to fire Kuzn coal are also operated on natural gas.

Characteristics of bituminous coals from other fields in Russia are shown in Table 21.

Only a small area of the Donetk coal field remains in the Rostov region (the south of the European part of the country) of Russia. The power industry uses mostly the high-sulfur lean coals and anthracite culm (AC) produced there.

The Pechora coal field is located in the northern part of European Russia. Inta coals, produced there, have a high sulfur and high ash content which is difficult to reduce by beneficiation.

In both coal fields the coal is mined underground at high cost.

The coal from the Ekib field in northern Kazakhstan, widely used at Russian TPS, is weakly sintering mostly because of the high content of mineral matter. In view of seam peculiarities, the Ekib coal is mostly produced in bulk where the ash content reaches 55 percent.

Twenty to thirty percent of the ash of the Kuzn, Donetk, Pechora and Neryungri coals consist of the basic oxides: Fe_2O_3, CaO, mgO, K_2O, Na_2O with the major share of Fe_2O_3. Because of that, the ash fusion temperature for Kuzn coals is in the range of 975-1,050 °C. It was found to decrease with increasing concentration of alkali element Na and K in the ash [27].

In firing most Kuzn coals, no substances are formed or selectively released that form stubborn deposit on heating surfaces because the coals are weakly sintering.

Donetk coals have characteristically high sulfur content, up to 70 percent of which is in the form of pyrites.

Low-reaction Donetsk coals are usually fired in wet-bottom furnaces and at high temperatures which cause the melting out and averaging of the entire fly ash. That is why the heating surface deposit are friable; even at the slagging temperatures given above self-removal of deposit is observed.

In rare cases, when firing Donetsk coals in dry-bottom furnaces, a dense layer of primary deposit with a concentration of Fe_2O_3 up to 40 percent is formed on tubes of platens and on the first rows of the convective superheater.

5.1.3. Characteristics of Brown Coals

The brown coals play a rather important role in the structure of fuel supply to Russian TPS. Out of about 150×10^6 t of coals fired at TPS in 1993, the share of brown coals was about 50 percent (Table 19). The brown-coal fields are mostly located in Siberia and the Far East. The largest is the K-A field located in the southern Part of the Krasnoyarsk region. It is a unique natural phenomenon due to the size of the coal deposit and structure of it's coal seams. Of the 19 fields in the K-A basin that have been explored, three seams are currently being developed; Nazarovo, Berezovo and Borodinsk with a total production capacity of 58×10^6 t/y.

K-A coals have good firing and ecological characteristics: ash content 4.0-16 percent, sulfur content 0.3-0.4 percent, heating value 11.8-15.6 MJ/kg, and volatile yield 47-48 percent.

The K-A coal ash chemical composition is illustrated in Table 22 showing high (up to 42 percent) CaO content, and an increased content of Na and K oxides [27].

Brown coals used for power generation in eastern Siberia and the Far East differ from K-A coals both in firing properties (Table 19) and coal ash characteristics (Table 22).

In the European part of Russia, brown coals are mostly produced in the near-Moscow coal field. However, because of the high cost of mining and the low quality of these coals (S = 2.3-2.5 percent, A = 35-38 percent, W = 30 percent, LHV = 7-9 MJ/kg) their use for power generation is decreasing.

The open-cut produced K-A coals are the cheapest and their increased use for power generation is an important economic goal. Production of these coals can be increased up to 80-130 $\times 10^6$ t/y as long as the country's economy will improve.

Despite the available positive experience of transporting considerable amount of K-A coals by rail (up to 1.5 $\times 10^6$ t) to TPS and storing it in open piles for a year and longer, more efficient long-distance transport of K-A coal-derived product are under consideration in order to reduce transportation cost on-site processing.

Among such possibilities are:

- preparation of the required coal dust at central pulverizing plant;
- preparation of crushed coal to be used in CFB boilers;
- production of coal briquettes;
- preparation of coal-water slurries;
- various kinds of pyrolysis to obtain semi-coke and liquid fuel.

Based on performance characteristics and feasibility by the year 2005, the first priority is the production of coal briquettes. It will enable reduction of cost for transport and services for coal storage, increase the reliability of fuel handling and pulverizing systems, and reduce environmental impact.

5.2. Power and Environment Protection Technologies in Use

Conventional bituminous coal-fired dry- and wet-bottom boilers are available.

Kuzn, Pech, and Yuzhno-Yakutk coals are close in their physical/chemical characteristics and are almost consistent with bituminous steam coal standards adopted for the World Market.

Ekib coals have a high ash content, are highly abrasive, non-slagging, and explosion-proof.

Donetsk AC are characteristically of very low reactivity (volatile yield of 4 percent); and are difficult to fire even with liquid slag removal.

The peculiarities of firing brown K-A coals and cleaning the flue gases formed result from the properties of these coals, which feature a high volatile yield, high reactivity, and a tendency to intensively slag boiler heating surfaces. They also readily self-ignite in storage, and the dust is explosive.

The history of using K-A coals goes back to firing Nazarovo and Irsha-Borodinsk coals in 320-500 t/h dry- and wet-bottom boilers.

The basic problems when firing the above coals are the accelerated slagging of furnace waterwalls and the impaired removal of liquid slag due to varying coal properties (when various-seam coals are supplied) and ash content. To overcome these problems, pilot boilers have been designed using special firing systems. These are briefly described in Section 2. Though they have been investigated in detail and numerous modifications of their component have taken place, the boilers have not found further application.

In view of the available commercial experience and the result of testing K-A and other brown coals from the eastern fields, the most suitable combustion is a low-temperature one (below 1,200-1,300 °C) combined with gas drying and ballasting of the flame with combustion product. This has been implemented with the simultaneous modification of the modes and design of the tangential-fired furnaces with straight-flow burners on the new E-500 and P-67 boilers (see Section 2).

The experience with firing the most slagging Berezovo coal in the E-500 and P-67 boilers showed that the furnace temperature level should not exceed 1,300 °C to prevent quick slagging [28,29,37].

The firing process can be improved by using more uniform coal dust, uniform flow of air and recirculated gases over burner tiers and channels, intensifying the fuel ignition, reducing the active burning zone temperature by increasing swirl in the upper part of the furnace chamber, and increasing to 40-45 percent the amount of recirculated gas to these zones.

When bituminous coal ash contacts water no hard deposit are formed. This makes possible the wide application of wet ash collectors and hydraulic ash removal systems at old TPS firing Kuzn coals in boilers producing up to 670 t steam/h (186 kg/s). The above systems are also installed at AC and Ekib coal-fired boilers, with reference to the latter up to 500-MW unit. However, these systems are not sufficiently effective on ash separation and provide problems with further ash utilization. At newly installed bituminous coal-fired boilers of up to 1,000 t/h and more of fly ash is caught by ESP. When these power unit were designed ESP efficiency at 90-96 percent had been thought quite sufficient and an ESP of limited size with up to 3 m/s gas velocity – economically reasonable.

The Ekib coal-fired 500-MW unit employ two-stage ash removal systems with a wet venturi scrubber being installed as the first stage and an ESP as the second stage, with an overall efficiency of 99.5 percent [28].

The K-A coal-fired TPS are now equipped with two types of ash collectors – multicyclones (66 percent) and ESP (34 percent). The fly ash removal in multicyclones is 92 percent maximum, while that in an ESP is 94-97.5 percent and depends on their type and size (generally, they fail to provide for the required residence time) and the boiler outlet temperature (often at 160-180 °C). These figures cannot be considered satisfactory.

In retrofitting/repowering existing and constructing new TPS upgraded ESP and baghouse filters will be applied to ensure the particulate matter emissions at 50-100 mg/m^3 or below. Now in Russia a new type of ESP with a 460 mm electrode spacing has been mastered. It will be equipped with a variable current supply, automatic control and monitoring, and a pneumatic fly ash discharge from the hoppers.

The fly ash of low-sulfur Kuzn and Neryungri coals, and, particularly, of Ekib coals is of increased electrical resistivity. This may impair ESP operation and reduce the collection efficiency. In many cases, especially in retrofitting/repowering of existing TPS which lack space to install additional ESP fields or to extend the ESP area, flue gas conditioning at the ESP inlet is advantageous. Conditioning includes temperature reduction (which may also increase fuel utilization), using chemical additives (for example, SO_3) or electromagnetic radiation which transforms lower SO_x and NO_x to higher oxides.

At some TPS by using simple flue gas conditioning before ESP (for example, reducing the temperature by injection of water-treatment plant salted effluent) fly ash emissions were decreased by 2-3 times.

Fabric filters are attractive as a means of fly ash collection, but there is practically no operating experience with them in Russia. In this connection, the risk exist that with the high ash content (up to 25-35 percent) of many steam bituminous coals, the use of the fabric filter may entail difficulties or be inefficient.

Small-capacity demonstration fabric filters have been in successful operation with a K-A coal-fired boiler for some years. Baghouse filters in sizes of 110,000, 280,000, and 940,000 m^3/h have been made commercially available. They are employed in the metallurgical industry. A project is under way to install baghouse filters on the 500-t/h K-A coal-fired industrial boiler at the Minusinsk cogeneration plant.

In cases where it is profitable to keep a wet ash collection system and increase scrubber efficiency by using a higher spray rate, or by applying emulsifiers with a high rate of ash removal, it seems reasonable to use them to collect part of the SO_2 contained in the flue gases. Experience indicates that SO_2 reduction in these cases can be 50-70 percent.

The increased ash collection efficiency and reduction of particulate matter emissions up to < 50 mg/m^3, which is technically feasible, also solves the problem of heavy metals and toxic product of incomplete combustion, which emissions are not regulated now.

Kuzn and Pech coals contain of 2.1-2.7 percent fixed nitrogen. High flame temperatures are required to ensure the complete combustion of the above and other bituminous coals with a moderate volatile yield. These circumstances facilitate NO_x formation in firing bituminous coals and make it difficult to attain the environmental requirement through technological methods only. Nevertheless, application at existing boilers (including wet-bottom boilers) of various methods capable of improving combustion (feed of coal dust of high concentrations, use of special burners, stage combustion) enabled NO_x reduction of up to

450-600 mg/m^3 [28-32].

At low-temperature, combustion of brown coals, and K-A coals in particular, NO_x are primarily formed from the fuel nitrogen compounds. Theses compounds during volatile yield and firing can be converted to NO or N_2 depending on the conditions.

In firing slagging coals, care is needed in the application of known firing methods for NO_x suppression.

The boiler test showed that NO_x concentrations could be reduced to 200-350 mg/m^3 simply by decreasing excess air (SR). However, in this case, starting from a certain SR value, slagging of waterwalls was found to be accelerated. Boiler operation at minimum excess air is an urgent problem. The solution of the problem could be facilitated by mode optimizing with respect to the slagging and NO_x formation, automatic control of furnace processes (flows of coal dust, air, recirculation gases), use of finer coal dust particles, and better waterwall cleaning.

Work is under way to modernize burners through the optimization of velocities of coal-air mixtures, secondary air and recirculation gases, stream outlet angles in horizontal and vertical planes, etc. Of interest is the application of bottom burners to fire high-reactivity, low-ash, strongly-slagging coals that make the flame longer (burning start at the furnace bottom) and move the flame from the furnace walls.

Simplified reburning of brown coals was implemented at 270-t/h and 420-t/h boilers at the Irkutk cogeneration plant. Both boilers have tangential-fired, dry-bottom furnaces with a two-tier arrangement of straight-flow burners. The upper-tier burners operated at SR<1.0, where the air required for complete combustion was fed via overfire nozzles. The result obtained on the 420-t/h boiler are illustrated in Figure 15: NO_x concentration was reduced by 35-45 percent [25,29].

Reburning will be more extensively tested in the near future in a 500-t/h boiler.

To decrease NO_x formation, a scheme with brown coal dust preheating in a direct fired system has been designed. When firing the coal dust preheated to 600-950 °C at the pilot facility, NO_x formation was reduced 2.5 times, and in the case of reburning, more than 3 times. At the pilot 35-t/h boiler, NO_x concentration was reduced from 400-500 mg/m^3 to 220-300 mg/m^3. Further NO_x reduction could be predicted to 200-250 mg/m^3 [28]. Technical solutions for coal dust preheating and staged combustion have been designed for a P-67 800-MW unit and 500-t/h boilers.

As mentioned above, there are possibilities of long-distance transport of K-A coals. As briquettes, for example. In this case, the firing conditions will be different but not new to the Russian industry. For example, there are many years of experience with the combustion of dry, centrally-treated Nazarovo field K-A coal dust in wet-bottom boilers. NO_x emissions were reduced under such conditions by using a highly concentrated coal-air mixture: 50 kg of coal dust per 1 kg of air. The typical dependence of the furnace outlet NO_x concentration upon excess air is shown in Figure 16 with reference to a 680-700-t/h boiler [31,7].

All of the low-NO_x burners and reburning technologies (7-40, 7-42, 7-44, 7-52) demonstrated under the DOE Clean Coal Technology Program (CCTP) for bituminous coal-fired boilers can be implemented when firing the Russian coals discussed above. The U.S. technical solutions will compete with those available in Russia. Joint development using, for example, U.S.A. burners, mills for superfine grinding of coal for coal reburning, measurement and control devices, etc., could be attractive.

Where primary technological measures fail to attain the required NO_x emissions, noncatalytic and catalytic de-NO_x systems will be used.

Russia has experience with the noncatalytic system of NO_x reduction by injection of ammonia water into the high-temperature (about 1000 °C) boiler path. Test were conducted at two 420-t/h natural gas and Kuzn coal-fired boilers. When firing coal, NO_x concentrations with ammonia water injection were decreased by almost 2 times [28]. Now the system is automated, based on U.S. measurement devices.

Projects have been designed for catalytic de-NO_x systems for 500-MW Ekib coal unit (see below) where the catalytic reactor is located before and after the particulate matter and the SO_x gas cleaning devices in the dust-laden flue gas boiler duct. Pilot and industrial test are being carried out on Russian- and foreign-developed catalyst for de-NO_x systems using real dust-laden flue gases.

The flue gas SO_2 concentrations when Kuzn coals are fired are generally within 300-350 mg/MJ (800-1,100 mg/m^3). For the Neryungri coals the figures are half as high. As specified in the prepared National Standard, such emissions allow for boiler operation with no special flue gas SO_2 cleaning measures.

Wherever required in firing Kuzn, Neryungri and Ekib coals, use may be made of simple de-SO_x technologies employing wet ash collectors (see above) and wet/dry devices, in particular, those that are integrated into the gas duct. Their efficiency will be at 50-70 percent. Among the CCTP DOE technologies that can be used are those demonstrated in project 7-54, 7-56, 7-58, 7-60, and 7-62.

In ecologically dangerous locations when Ekib, and to a lesser extent Kuzn and Neryungri coals, and as a rule Pech and Donetk coals are fired, the use of wet/dry technologies in special apparatus for about 90 percent sulfur capture can be required. Such technologies are being developed, in particular, under CCTP DOE project.

As mentioned previously, low-sulfur, low-ash K-A coals feature high-calcium-content ash (CaO = 26-42 percent for different coal fields, including 17-32 percent of free CaO; CaO/SO_2 = 2.5-5.3; free CaO/SO_2 = 1.1-3.5). With low-temperature, dry-bottom furnace combustion of such coals, up to 40-60 percent of the sulfur (Figure 17) is captured in the furnace volume [33]. Injection of activated ash containing much unused active CaO into the gas duct adds to the degree of sulfur capture by about 20 percent. The jet-mill, crushed ash is better if injected into the furnace top; and that which is processed in the digester is better if injected into the convective section where gas temperature is 500-600 °C.

If a baghouse is used to clean the gases of particulate matter, additional sulfur is captured in the ash layer that forms on the filter material. Ultimately, with additional injection of activated ash, the overall sulfur capture in the dry system without external sorbent may reach 80-90 percent [37].

To clean combustion product resulting from the combustion of near-Moscow field 3 percent S brown coal, a demo plant of 400,000 m^3/h capacity, based on the ammonia-cyclic-technology has been constructed at one of the utility boilers of the Dorogobuzh TPS. This method is based on the SO_2 absorption by ammonia sulphite and the formation of hydrosulfite and sulphate. The final product are 10 percent liquid SO_2, crystalline ammonia sulphate and colloidal sulfur. Basic characteristics of the plant are given below.

Flow of flue gases to be cleaned, m^3/h	400,000
Flue gas temperature, °C:	
Before de-SO_x system	150
Past de-SO_x system	45-55
Flue gas SO_2 concentration, mg/m^3:	
Before de-SO_x system	5500
Past de-SO_x system	300-350
Flue gas NO_x concentration, mg/m^3:	
before de-SO_x system	350-400
past de-SO_x system	200-250
Yield of de-SO_x system by-product with 7,000-hour operation, t/y:	
Liquid SO_2	18,000
Ammonia Sulphate	14,200
Colloidal Sulfur	214,500
Annual ammonia consumption, t/y	1,830

The plant efficiency and the consumption of the reagent required for operation are being refined.

The lowest emissions, sometimes below those specified in the Standards, and the highest flue gas cleaning efficiency will be required for cogeneration plant located in towns, sometimes in residential areas, and also for industrial cogeneration plant in highly contaminated areas.

In all cases of conventional bituminous coal combustion, the washing of raw coals would be reasonable to decrease the ash content. This would facilitate the ash collection and removal and also facilitate the use of the various technologies for emission reduction and flue gas cleaning.

6. BASE OPTIONS OF ADVANCED COAL THERMAL POWER PLANT

The following base-option project were deemed to be winners of the competition by their inclusion in the "Clean Coal Technology" section of the State Program "Ecologically Clean Power Generation." [35, 36]

Basic parameters of the TPS employing various technologies are shown in Table 23.

It is difficult to compare the technologies on the basis of economic parameters for the following reasons: They have been designed around coals of differing properties and cost. The TPS have been sited in differing geographic locations. Different operating modes have been employed. Finally, equipment and construction cost have been unstable and not always fully justifiable.

The lowest specific cost relate to TPS with low-cost 500-MW unit firing Ekib bituminous coal. TPS with brown K-A coal fired 800-MW unit are higher in cost because the lower combustion temperatures necessary to prevent ash slagging dictate larger physical dimensions for the furnace (see Section 2). The lack of Russian experience with direct flue-gas removal of SO_x and NO_x has led to conservative cost estimates for such equipment and TPS utilizing it. By contrast, the specific cost for CFB boilers seems optimistic for the very same reason.

6.1. 6.4-GW TPS Project with 800-MW, Brown K-A Coal-Fired Unit

The 6.4-GW TPS featuring 8 800-MW supercritical boilers firing brown coal from the Berezovz field is a base option.

Principal features of the P-67 boiler (Figure 5) at the Berezovo TPS-1 are: Dry-bottom, tangential-fired furnace. Low active combustion zone heat-release rate. Low flame temperatures, i.e., 1,300-1,400 °C maximum. Early ignition and intensively pulverized coal (PC) burnup at the initial point.

Specific coal composition as regards mineral and organics content allowed SO_x and NO_x reduction and attainment of ecologically-required levels of SO_x and NO_x of 200-300 mg/m^3 without special de-SO_x and de-NO_x systems [7, 28, 37].

The following methods will be employed for NO_x reduction: fuel preheated to 650-850 °C, staged low excess air combustion and combustion gases used for fuel drying in the pulverizing mill fans system. A schematic drawing of the coal preparation and firing systems for the P-67 boiler is illustrated in Figure 18. The raw coal from the hopper enters the drying section at 33 percent moisture. This is reduced to 13 percent by the 590-650 °C combustion gases. Also, the fuel is classified by the mill fan into high and low solids concentration streams. A portion of the coal-air mixture is fed to the muffle burner where it is used for heating the main stream in the PC preheater. To ensure complete combustion and minimize slagging of the boiler's heat-exchange surfaces, simultaneous coal particle size reduction from R_{90} = 40-60 percent to R_{90} = 20-30 percent and R_{1000} < 1.5 percent is required.

Low-temperature combustion allows for sulfur capture within the furnace of up to 50 percent by the calcium in the ash. Fabric filters are used to clean the flue gases and additional sulfur is captured in the fly-ash layer on the filter bags. Also, feed of activated ash into the furnace and the convective path is provided.

Firing Berezovo coal with 0.4-0.5 percent sulfur in pilot test showed that the 200 mg/m^3 maximum requirement can be assured by the above methods of sulfur capture in the furnace and on the flue gas filter bags. The cleaning efficiency of the fly-ash layer on the filter bags is sufficient to meet the specified ecological maximum of 50 mg/m^3.

Technical data for the FRO-12000 baghouse module is shown in Table 24. Figure 19 illustrates the two-storey layout of the baghouse bay adopted for the TPS.

Operation on coal with 7 percent average ash content will yield 1.5×10^6 t/y of ash and slag wastes.

Because the K-A coal ash contains CaO, provision is made for its granulation (as $CaSO_4$) by treating with acid waste water from the make up treatment system to improve salability properties and prevent environmental impact when land filling.

The 6.4-GW TPS is constructed within two main buildings. Each contains 4 of the 800-MW unit. Each unit has it own 84 m wide bay. Overall, each main building is 434 ms wide and 177 ms deep. The baghouses and the induced-draft fans are located in separate buildings. Two 250 m-high stacks are provided, each serving four unit (Figure 20).

The proposed new technologies for the project are being perfected in the 35 t/h pilot boiler: The influence upon NO_x of the high temperature preheating of the PC and staged combustion, SO_x capture in the boiler gas path and in the baghouse, and injection of ash activated in the jet mill or digester at various point in the gas path are being quantified.

These techniques will be further tested in a 500 t/h boiler presently under construction and due to be started up in 1996.

The result of experiment aimed at validating this project were considered briefly in Section 5.2.

Basic parameters of the TPS employing 800 MW unit designed under this project are shown in Table 23. It is compared with alternative TPS based on the same coal technology below:

	Existing unit w/o de-SO_x/de-NO_x systems	Existing unit with de-SO_x / de-NO_x systems	Base option
Efficiency at nominal output, %	38.50	37.50	39.20
Mean annual efficiency, %	38.07	37.28	38.85
Mean annual specific standard fuel consumption, g/kWh	323.10	329.90	316.60
Relative specific investment	0.978	1.24	1.00
Relative averaged electricity cost	0.996	1.23	1.00
Specific emissions, mg/m_3			
NO_x	600	200	200
SO_x	600	300	300
Particulate matter	150	50	50

6.2. Yuzhno-Ural Ekib Bituminous Coal-fired 4-GW TPS with 500-MW Unit Project

The base option is a 500-MW supercritical unit with conventional PC firing [38]. Some parameters of the unit and TPS are shown in Table 23.

The P-57, 1,650 t/h, 24 MPa, 545/545 °C boiler manufactured by the Podol'sk Machine

Building works in 1986 was adopted as the prototype.

Conventional firing of Ekib coal in the P-57 boiler generates rather high NO_x – in the order of 800-1,300 mg/m^3. Two versions of the furnace have been specifically designed with technologies intended to reduce NO_x emissions.

The furnace is equipped with two tiers of wall swirl burners (Figure 21), and has additional straight-flow burners arranged 3-4 m above the second tier. These burners, operating with SR = 0.7, handle 20 percent of the fuel. Above them, at 26-30 m elevation, nozzles are arranged to feed 10-24 percent of the total air.

The tangentially-fired furnace (Figure 22) has 24 straight-flow burners arranged in three tiers of eight burners (two set of four) each on the side walls with the coal/air channels of each set aimed at the perim of a 1,200 millim diameter circle situated in the space between them so as to generate a counter-clockwise "swirl." Burners of the first and second tiers operate at excess air of SR = 1.1 and those of the third tier with SR = 0.7. About 15 percent of the secondary air is fed through the tertiary air nozzles located about 8 ms above the third tier of burners.

The result of pilot and industrial-scale tests at the Ekib TPS-2 indicate that this technique can reduce the NO_x emissions in the P-57R boilers to 500-550 mg/m^3.

Further reduction of NO_x will be effected by application of selective catalytic reduction (SCR) using ammonia. The specific location for the SCR catalyst has been analyzed in view of the high dust content and dust abrasivity of the Ekib coal. A line drawing showing the de-NO_x system after the hot electrostatic precipitator and before the air heater, and another showing it after both the de-SO_x unit and the air heater appear as Figures 23 and 24, respectively. Operating conditions and some characteristics of the catalyst for these schemes are illustrated in Table 25. The de-NO_x system located in the flue ahead of the air heater is more efficient.

Reduction of SO_x will be accomplished in a wet lime scrubber with gypsum produced as a by-product. A schematic of the process appears as Figure 25 with basic process parameters presented in Table 26.

Fly ash production is one of the most serious problems with Ekib coal combustion. Ash removal efficiency of 99.9 percent is required to reduce the dust content from the reference value of 90 g/m^3 to 100 mg/m^3. This is difficult with Ekib coal because of increased electrical resistivity of the fly ash. Within the temperature range of 140-180 °C, this causes back corona in the electrostatic precipitator which impairs ash separation.

The required efficiency can be reached by maintaining the stack gas at 95-100 °C along with adequate gas velocity and residence time within the ESP active zone. Utilizing four 8-pole ESPs, each with 12 m high electrodes and an active cross-section of 197.5 m^2, the cleaned gas velocity will be about 1 m/s and the residence time within the ESP more than 30 s. These conditions ensure a 100 mg/m^3 maximum fly ash content in the cleaned gas stream. The elecrostatic precipitators are equipped with variable voltage supply sources which prevent back corona and increase operational reliability.

Reduced power output and efficiency caused by the use of the gas cleaning systems is to some extent compensated by extra syngas production as a result of steam condensed instead of being extracted. This is because some condensate and, in some cases, feedwater, are heated by boiler flue gases as a result of less steam flow to preheating. The temperature of the flue gas is reduced from 160 °C to 90-100 °C to meet ESP operating conditions. For this temperature reduction, low-temperature economizers or heating of excess air have been designed. In the latter case, a larger amount of air than required for combustion is passed via the air heater, while part of the air preheated to 300-330 °C recirculates, heating feedwater and condensate (Figure 26, and mean SR). The requirement of low gas velocities for the ESP greatly influences the system layout.

The plant configuration with included de-NO_x system and an 84 m wide bay housing the electrostatic precipitators is shown in Figures 27 and 28.

Table 27 compares the performance of the existing Ekib TPS-2 power plant without gas cleaning equipment, a 500 MW unit with the de-NO_x system located in the furnace flue-gas stream, and a 500 MW unit with the de-NO_x system located after the ESP and the de-SO_x system.

Different combustion systems have been tested to validate this project. A tangential-fired furnace has been implemented at the Ekib TPS-2 500 MW plant. This has resulted in a reduction in NO_x emissions to 500-650 mg/m^3, i.e., almost 50 percent, compared with emission of 1,100-1,200 mg/m^3 from other boilers.

The swirl burner with simplified reburning has been tested on a 210 t/h Ekib coal fired boiler. In this case, NO_x emissions were reduced 47 percent, from 1,100 mg/m^3 to 520-570 mg/m^3.

Long-term test of the de-NO_x system catalyst have begun on heavily dust-laden Ekib coal fired combustion product. The catalyst are installed in a bypass duct of the existing 500 MW boiler flue, and see about 5,000 m^3/hour of gas flow.

A low temperature economizer reducing flue gas temperature to 90-100 °C, is installed on a 420 t/h boiler. The resulting change in the electrophysical properties of the fly ash improved ESP efficiency and reduced fly ash emissions by factors of 3.

Pilot tests were conducted of the simplified de-SO_x system which is close in concept to the LIFAC system. Sulfur capture and the effect upon the system of lime injection into the high temperature (800-1,000 °C) flue gas stream were tested, as well as sulfur capture with this system using various methods of humidification of the CaO-laden flue gas stream.

Effort are under way to develop heat exchangers for de-SO_x and de-NO_x systems.

6.3. 2,400MW TPS with CFB Boilers Firing Poor-Quality Anthracite Culm (AC)

Circulating Fluidized Bed (CFB) combustion is a promising approach to firing poor fuels [8, 11, 39]. A project utilizing this technology has been developed featuring a 2,400 MW TPS with 300MW unit located in the Eastern Donbass.

The TPS employs once-through, two-furnace, 2,500 t/h, 24.5 MPa, 545/545 °C CFB boiler and K-300-240 steam turbine. The fuel is poor quality anthracite culm with 36 percent ash, 1.4 percent sulfur, 10 percent moisture and 4-6 percent volatiles. The boiler features a high recirculation ratio, external "hot" (900-940 °C) cyclones and special external heat exchangers for cooling a portion of the cyclone ash before it is returned to the furnace. For boiler start-up and for operation at loads less than 30 percent of nominal design, each combustion chamber has 6 gas/oil burners arranged on the front and rear walls and is equipped with primary air preheating up to 650-700 °C.

The coal and limestone preparation system uses common hoppers and cyclones and the crushed coal and limestone are combined as feed to the boiler. The coal and limestone mean particle size are 0-4 mm and 0.55 mm, respectively.

Reduction of the stack gas temperature to 100 °C while heating ambient air (see Figures 26 and 29) for use as combustion air serves to increase ESP efficiency and result in particulates emissions below 50 mg/m^3.

Figure 29 is a schematic drawing of the unit. Layout and operation are simplified, and capital investment reduced, by elimination of the deaerator in favor of two, direct-contact, low-pressure heaters. Air preheating is used to prevent boiler cooling during hot startup of the unit operating in a shifting mode. The boiler is provided with a full-flow separator, and the waterwall hydraulics are designed to start the unit at sliding pressure across the entire boiler system. The two-bypass starting scheme is provided to improve temperatures when the turbine is placed in operation.

The once-through CFB boiler design is illustrated in Figures 30 and 31. The firing system consist of 2 modules. Each module has it own furnace, two cyclones and two external heat exchangers located under the cyclones. The combustion product from both modules are directed through a common convective section.

The primary air fed through the fluidizing screen is about 50 percent of the total required for complete combustion. The velocity of the combustion gases at the outlet of the dense bed is 6.4 m/s. Fuel is fired in the combustor freeboard (the upper part) using secondary air supplied by special nozzles.

The combination of two-stage air feed, high fly ash recirculation ratio, 900 °C furnace temperature and limestone injection insures low concentrations of SO_x and NO_x in the flue gas. Complete combustion, i.e., 94-97 percent, of the anthracite culm fuel and possible reduction of boiler loads to 30-50 percent of nominal design rates are attained without firing fuel oil or gas. The external heat exchangers, along with the last stages of the primary superheater and reheater, are designed for 60 percent heat recovery from the CFB firing circuit.

The design and thermo-hydraulic boiler parameters can be seen in Tables 28 and 29.

The ash will be landfilled on site and/or, depending upon it properties, used for water treatment, to reduce effluent volumes and the requirement for treatment chemicals.

The layout of the CFB boiler in the main building and of the TPS as a whole are shown in Figures 32 and 33.

The performance of the TPS with CFB boilers is illustrated in Table 23, which also compares the TPS with pc-fired boilers both with and without de-SO_x and de-NO_x systems. Given identical environmental impact, construction of a 300-MW TPS with CFB boilers under this project will be 20-25 percent cheaper than a pc-fired unit with de-SO_x and de-NO_x systems.

Comprehensive testing was done in order to validate the engineering assumptions used in designing the above boilers. Conditions tested were: Kuzn coal and anthracite culm firing, NO_x and SO_x suppression, hydrodynamics of dust-laden flows under typical CFB duct conditions, and boiler startups and shutdowns. The result obtained made possible the determination of the main characteristics of the processes; kinetic constant necessary for calculations; measures necessary to ensure complete combustion of the anthracite culm; sulfur capture and suppression of NO_x formation in the furnace, e.g., temperature conditions, air feed staging, sorbent dosing; and also pointed to the improvement of CFB boiler critical component, e.g., cyclones, fly ash reintrainment path lockhoppers and others.

The highest anthracite culm firing efficiency – 96 percent – was obtained by supplying 60 percent of the total air to the primary zone. At conditions of equal flow between primary and secondary air, i.e., 50-50 percent, and overall furnace excess air of SR = 1.15-1.25 the flue gas NO_x concentration was 200 mg/m^3 maximum. Also, NO_x formation is perceptably influenced by both sorbent feed rate to the boiler and Ca/S ratio. At furnace temperatures of 740-940 °C, 90-95 percent of the sulfur is captured at Ca/S = 1.7-2.0. With further increase of the Ca/S ratio, sulfur capture remains essentially constant at about 95 percent (see Figure 34).

Investigations were done on the quality of the ash from CFB coal combustion with limestone addition. As a result, technical solutions were found that ensure ESP performance with increased electrical resistivity of the fly ash

Fuel and limestone preparation equipment for CFB boilers has been tested and coal and limestone crushers have been designed which provide for the proper size composition.

CFB combustion technology also holds promise for brown coals. Some result of work in this area were illustrated in Section 2. The largest and most interesting systems for firing brown coals are the 420 t/h bubbling-bed and the 500 t/h CFB boilers.

In the 420 t/h boiler fuel preparation system, K-A coal is separated into fractions. The 1-25 mm sized coal is fed beyond the bed, while the 0-1 mm sized material is injected directly into the bed by pneumatic-screw type pumps. The fly ash reentrainment system includes the louvre-type ash collector, 8 cyclones and ejectors to feed the collected fly ash to the lower section of the bed.

K-A coal properties are rather attractive for CFB combustion technology: up to 95 percent sulfur capture by the CaO in the ash can be expected at 850-900 °C, no slagging of heating surfaces, NO_x reduction, lower sensitivity of the system to the quality of fuel fired, and better ash properties for further utilization.

Investigation of Irsha-Borodino brown coal combustion in the pilot plant and foreign operating experience with CFB boilers indicate that with K-A coals, emissions of NO_x and SO_x will be 200 mg/m^3 maximum.

The good ecological characteristics of the CFB boilers give them an initial advantage for both new and reconstructed city cogeneration plant.

The Barnaul Boiler Manufacturing Works designed 500 t/h boilers based on "cold" cyclones [40] for combustion of high-sulfur brown coal from the Moscow area (Novomoscovskaya TPS) and K-A coal (Omsk cogeneration plant No. 6). The drum boiler with heating surfaces in a tower arrangement has a furnace plan section with dimensions of 19.3 × 8.0 m (Figure 35). The furnace is the key element in solids circulation. It has an all-welded, gas-tight waterwall design. At the bottom of the furnace is a cap-type, perforated-screen air distributor with directed blasting, through which about 50 percent of the total air passes as primary air. The remaining air is fed through secondary air nozzles arranged in three tiers on the side walls. Provision is also made to feed recirculation gases into the primary air stream. The construction of such boilers is presently delayed by economic problems within the country.

6.4. IGCC TPS Project with Entrained-Flow and Moving-Bed Coal Gasification

A large-capacity (4.0-6.5-GW) Integrated Gasification Combined-Cycle (IGCC) TPS has been designed to use Kuzn and K-A (Berezovo) coals.

The 600-700-MW Combined-Cycle (CC) plant includes two gas turbine/generators (GT) of 200-MW each, two heat recovery boilers and a single 240MW steam turbine/generator (ST). Some of the characteristics of this equipment can be seen in the Appendix (pages 67-71).

The CCP designs are based on two different gasification technologies: moving bed and entrained flow. Each system was designed with both air blown and (95 percent pure) oxygen-blown options. The technical considerations and the equipment are to a great extent universal and, therefore, various grades of coal can be used including those with high sulfur content.

Gasification proceeds at about 3MPa pressure. In both systems, slagging gasifiers are fed dry coal through lockhoppers.

As feed for the moving-bed gasifier, coal is first dried and crushed to <50 mm size. This coal is screened. Material <50 mm and >5 mm is stored in a hopper and fed into the top of the gasifier vessel via a lockhopper system. The coal fines (<5 mm) are milled and fed via a second lockhopper system to the tuyeres through which they are blown into the gasifier. Technology also was tested whereby excess fines are pressed into pellet of 6-10 mm size. These are fed into the gasifier with the screened coal.

As feed for the entrained-flow gasifiers, the coal is milled, passed through lockhoppers and conveyed into the gasifier as highly concentrated dust (0.015 kg of nitrogen per 1 kg of coal).

Coal-derived gas (syngas) is used for sealing purposes and as a transport agent in the air-blown systems. In oxygen-blown systems, nitrogen, coproduced with the oxygen, is used for these purposes.

The composition of the syngas produced by gasification of dried coal depends largely upon the process conditions, e.g., kind and temperature of the blast, steam consumption, temperature, pressure, etc. Syngas composition is only very sleghtly influenced by the elementary composition of the coal.

The temperature of the syngas at the reactor outlet is dependent upon the process: moving bed, oxygen-blown = 500-559 °C; moving bed, air-blown = 900-960 °C and entrained-flow = 1,300-1,600 °C.

Preliminary cooling of the entrained-flow gasifier syngas to 900-950 °C is done either in a radiant gas cooler featuring platen-type heat exchange surfaces, or by quenching with recirculated, cooled gas to the reactor outlet. Further cooling of the gas stream to 500-550 °C, at which temperature it can be cleaned, is done in convective coolers.

As much as 30 percent of the steam consumed in the steam turbine/generator is produced in the gasifier waterwall and the radiant and convective syngas coolers.

The raw syngas is cleaned of sulfur at 500 °C by passing the gas stream through a fluidized bed of oxidized metal, e.g., iron. The sorbent is regenerated and the regeneration gases used to produce sulfuric acid (see Appendix).

For the oxygen-blown cases, standalone air separation facilities are required (see Appendix).

Air-blown gasification systems feature two trains of gasification for each gas turbine/generator. In oxygen-blown cases this is one-to-one.

Figure 36 is a flow sheet of an IGCC with moving-bed, air-blown gasification. An IGCC featuring entrained-flow, oxygen-blown gasification is shown in Figure 37. Both of these are considered principal technologies and have received detailed study.

The layout for a moving-bed, slagging gasifier is illustrated in Figure 38, and it associated convective gas cooler shown in Figure 39.

The design of one version of an entrained-flow gasifier is shown in Figure 40.

Figure 41 is a schematic drawing of a syngas cleaning system. Figure 42 is a flow sheet for the generation part. Parameters and descriptions for the gas turbine, the heat-recovery boilers and the steam turbine are in the associated appendix. Figure 43 is a sectional view of the heat-recovery boiler.

The exhaust gas flow from the gas turbine is greatly dependent upon ambient air temperature, and ranges from 560-580 kg/s at +30 °C to 830-850 kg/s at -30 °C. At the average ambient air temperature of -5 °C, the gas flow is 700-730 kg/s.

For the air-blown gasification case, approximately 100 kg/s of air is extracted from the gas turbine compressor for gasification air. After extraction, this air stream is cooled and fed to a 15-MW booster compressor whose outlet temperature is held at 500-540 °C maximum. The booster compressor is driven by a condensing steam turbine consuming about 50 t/h of steam. The resulting air pressure is 3.2 MPa. The gasifier also is fed superheated steam.

The heat recovery boilers are dual-pressure, wherein 13.8 MPa/520 °C and 0.4 MPa/240-250 °C steam is generated by the heat from the turbine exhaust. Given 2 turbines and 2 heat recovery boilers, 2 × 205 = 410 t/h of high pressure steam is generated. Additionally, about 170 t/h of high pressure steam is supplied to the steam turbine by the gasification plant. This steam is expanded in the high pressure cylinder of the steam turbine and then reheated in heat-recovery boilers. The steam flowing to the steam turbine's intermediate-pressure cylinder is at 2.2 MPa/460 °C.

A portion of the low-pressure steam produced in the heat-recovery boilers is used for coal drying. This amount to 85-130 t/h out of the total make of 185-210 t/h. The remaining low-pressure steam is fed to the low pressure cylinder of the steam turbine.

For the oxygen-blown gasification, a KT-70, 66,000 m^3/hr air separation plant is used to produce the required oxygen. Specifications for this plant can be found in the Appendix.

More steam is produced in the entrained-flow, oxygen-blown integrated gasification combined-cycle than in the air-blown plant. This amount to 607 t/h, as compared with 580 t/h in the air-blown case.

The layout of the main building for the commercial TPS with 10 IGCC unit is shown in Figure 44. A cross-section of the building along the gas turbines and heat recovery boilers and a cross-section of the ST building is shown in Figure 45. The section of the gasifier plant with a moving-bed and air-blown design is shown in Figure 46. Figure 47 illustrates the general layout of a TPS with 10 gasification combined cycle units using K-A coals.

Basic parameters of the IGCC plant at standard ISO conditions are given below:

Param	Type of Gasifier and Oxidizer			
	Moving bed		Entrained Flow	
	Oxygen	Air	Oxygen	Air
Two GT Output, MW	418	413	414	372
ST Output, MW	188	220	233	227
CCP Output (gross), MW	606	633	647	600
Auxiliary Power, MW	68	32	94	31
CCP Output (net), MW	538	601	553	569
CCP Efficiency (net), Percent	43.4	44.2	43.8	44.1
Live Steam HP Flow, t/h	454	532	574	551
Live Steam HP Temperature, °C	535	540	540	540
Fuel Saving, Percent	10.1	11.8	11.0	11.6

The fuel saving compares IGCC with that of a conventional steam supercritical unit operating at 39 percent efficiency. The data are shown in more detail in Table 30.

During commercial operation the average IGCC output and efficiency will be lower by 30-35MW and by 1.0-1.5 percent respectively.

The efficiency of CCP utilizing various gasification technologies is almost the same. With the oxygen-blown option, efficiency is 1.7-2.5 percent lower than with the air-blown configuration.

Combined-cycle plant capital investment, percent:

Portion of IGCC Plant	Type of Blowing	
	Oxygen	Air
Power Generation	38.75	40.25
Oxygen Plant	15.85	—
Gasifiers	5.80	11.60
Syngas Cooling	3.30	6.55
Fuel Preparation and Feed	5.65	5.65
Desulfurization	5.95	11.50
Particulate Removal	5.35	7.45
Other Expenditures	19.30	19.40
Total	100.00	102.40

Basic characteristics of IGCC TPS with 600-700-MW CC unit using Kansk-Achinsk coal are shown in Table 23. The comparison with alternative PC TPS is given below:

Param	Commercial PC 800MW		IGCC	
	Without De-SO_x De-NO_x	With De-SO_x De-NO_x	Oxygen-Blown (Base)	Air Blown
Nominal Efficiency, Percent	38.50	37.60	42.50	43.50
Mean Annual Efficiency, Percent	38.07	37.28	42.17	43.23
Mean Annual Specific Standard Fuel Consumption, g/KwH	323.10	329.90	291.70	284.50
Relative Specific Investment Cost	0.925	1.118	1.000	1.024
Relative Average Electricity Cost	0.962	1.159	1.000	0.962
Specific Emissions, mg/MJ:				
NO_x	600 (325)	200 (80)	40* (30)	30* (25)
SO_x	600 (235	300 (120)	3.5* (2.5)	10* (8)
Particulate Matter	150 (60)	50 (20)	0.7* (0.6)	0.7* (0.6)

* at O_2 = 15 percent as it is adopted for GT.

As a prototype for a full-scale oxygen-blown IGCC plant, a demonstration plant has been designed with K-A coal gasification based on a 100-130MW gas turbine/generator combined with heat generation of 230-280MWt [35].

Conceptual designs have been made for the gasification plant including the PC feed system; the air separation plant; the gasifier; convective syngas coolers; gas/gas heat exchanger and desulfurization equipment, e.g., Selexol, Klaus, etc.

To validate the technical solutions, pilot test were made of the kinetics of entrained-flow PC gasification, industrial test of fines filters and pilot project for testing the lockhopper equipment to feed PC to the gasifier and coal-derived syngas firing in the gas turbine combustor.

Appendix

IGCC Equipment

Gas Turbine

The GTE-200 gas turbine was designed some years ago by LMZ. This is a simple-cycle, single-shaft unit.

The GT as a unit includes an axial compressor, a turbine and a combustion section consisting of 14 combustor cans. It layout is like that depicted in Figure 11. The overall dimensions of the machine – 16.6 m × 5.0 m × 5.1 m, and it weight is 210 t – allow it to be transported by railroad car as a single assembled unit. The compressor flow path is identical to that of the GTE-150 GT which is now on line. Adding two compression stages increases the compression ratio from 13.0 to 15.6 at the same air flow rate of 630 kg/s.

The GTE-200 is designed to operate on clean liquid fuel and natural gas. Operation on low-calorie syngas will require redesign of the combustors.

At the time the GTE-200 was designed, LMZ had no experience with large, high-temperature GT. Because of this, the design was a conservative one, and the possibilities of upgrading it performance have been considered in designing the IGCC plant. The machine data at ISO conditions using liquid fuel are shown below:

GT type	GTE-200
Designer	LMZ
Output, MW	198
Efficiency, Percent	34.6
Pressure Ratio	16.2
Turbine Inlet Temperature, °C	1,250
Turbine Outlet Temperature, °C	557
Overall Dimensions, m:	
length:	15.6
width:	5.0
height:	5.1
Weight of GT, t	350.0

The table below present basic characteristics of the GTE-200 GT unit using syngas produced in a steam-air blown gasifier. Gasifier air is obtained by extraction from the GT compressor in an amount equal to 75 percent of the fuel gas supplied to the combustor:

Ambient Temperature, °C	-5	+15
Turbine Inlet temperature, °C	1,250	1,250
Pressure Ratio	19.0	16.9
Compressor Air Flow, kg/s	692.2	608.4
GT Output, MW	250.0	206.3
Fuel Gas Consumption, kg/s	174.2	150.9
GT Efficiency, Percent	33.7	32.1
Turbine Outlet temperature, °C	547.6	568.3
Exhaust gas Flow, kg/s	730.8	641.1

Heat-Recovery Boiler (HRSG)

The design of the HRSG is illustrated in Figure 43. It is of the drum type, with multiple forced circulation. The heating surfaces are layed out in a tower configuration with countercurrent flow in the economizer and superheating sections and cocurrent flow in the evaporative section. The GT exhaust enters the boiler at the botton. The element are arranged in the order of: HP superheater, reheater, HP evaporator, HP economizer, LP superheater, LP evaporator and LP economizer. The feedwater is supplied to the LP circuit and the HP circuit is fed from the LP drum.

Part of the LP steam is directed to steam dryers located in the fuel preparation section, with the condensate returned to the ST condenser.

The HRSG working dimensions are: gas duct size 11,900 × 11,900 mm, the tube axis height is 25,100 mm. The outide dimensions are: 13,500 × 13,500 mm in plan, 34,110 mm overall height.

All of the heating surfaces feature tubes with cross-band fins. The weight is about 1,700 t. The gas path pressure drop at design conditions and -5 °C ambient temperature is 2.5 kPa. The stack gas temperature is 95-100 °C.

Steam Turbine

The steam turbine was selected to compliment the two HP and LP circuit and live steam flows varying with ambient temperature as follows: within -30 °C to +30 °C the mass flow rate of the live steams varies by 20 percent, from 640 t/h to 520 t/h. As a consequence of simultaneous change in the live steam temperature, the change in volumetric flow is only 12 percent.

At a design ambient temperature of -5 °C, the ST has the following characteristics:

HP Live Steam Flow, t/h	580
HP Live Steam Temperature, °C	515
HP Live Steam Pressure, MPa	12.75
Steam Pressure after Reheater, MPa	2.20
Steam Temperature after Reheater, °C	460
LP Steam Flow, t/h	120
LP Steam Temperature, °C	240
Condenser Pressure, kPa	5
Condenser Flow, t/h	550
ST Output, MW	240

With 355-MW heat delivery for heating purposes, the output of the turbine drops to 167 MW. The ST has two cylinders: a combined HP and IP cylinder and a two-stream LP cylinder.

To ensure the maintenance of adequate flows with changing ambient temperatures, sliding pressure operation is anticipated with fully-opened live steam valves: at -30 °C the pressure increases to 13.8 MPa, at +30 °C it drops to 12.1 MPa. The design cooling water temperature is 20 °C.

Gasifiers

The characteristic data of the selected coals is depicted in Table 31. The design of the moving-bed gasifier appears in Figure 38, and that of the entrained-flow gasifier with cooling by back-mixing syngas in Figure 40. The convective gas cooler is shown in Figure 39.

The composition and some parameters of the coal-derived combustible gas (syngas) are given in Table 32.

Over 70 percent of the ash is removed from the gasifiers as liquid slag. The dust content of the raw syngas is 400 g/m^3 with the air-blown configuration (11.5 kg/m^3 density at operating conditions), and 765 g/m^3 in the oxygen-blown configuration.

The removal of particulates in the gas path is done by cyclones (2 for the air-blown and 1 for the oxygen-blown). Polishing is done in filters with 0.3 m diameter × 4 m longceramic element. The gas dust content at the filter outlet is 2.5-6.5 mg/m^3.

The syngas desulfurization is carried out in fluidized-bed reactors using 4 screens located at different levels of the 18 m high and 4 m diameter column. The IGCC with air-blown gasification requires 8 while only 4 are required for the oxygen-blown application. The sorbent is regenerated in the fluidized-bed furnace at temperatures below 800 °C. The bed where heat is released during regeneration is water-cooled. The heat exchange surfaces arrabged in the bed are switched between steam and water as required. The regeneration gases contain 4-6 percent SO_2. The spent regeneration gases are used in the production of sulfuric acid. A schematic of the cleaning system is shown in Figure 41.

Some parameters of a 600 to 700 MW unit desulfurization system designed with 100 percent H_2S margin in the raw syngas are illustrated below:

	Air-Blown	Oxygen-Blown
Syngas Flow, kg/s	300	132
Flow at Operating Conditions, m^3/s	26.2	13.7
H_2S Content, Percent (Volume)	0.1	0.2
H_2S Amount, kg/s	2.16	2.26
Reactor Cross Section Area, m^2	100.0	52.8
Number of reactors	8	4
Mass of Circulating Sorbent, t	80	44

Air Separation Plant

Oxygen is produced in the air-separation plant by distillation of liquified air. The IGCC employs the Kt-70 plant designed and manufactured on a special order by the NPO "Kriogenmash." This plant has the following characteristics:

Inlet Air Pressure, Bar	6.56
Inlet Air Temperature, °C	60
Air Flow, m^3/h (normal)	350,000
Production 95 Percent O_2 at 1.03 Bar (Absolute), m^3/h	66,000

The turndown capability of this plant is to 70-80 Percent of nominal design value. Startup from cold condition takes 4-5 hours. The plant is designed for 1-2 year continuous operation with time between overhauls of 8 years.

The energy requirement are 0.35 kWh/m^3 of produced oxygen. Other gases are co-produced with the oxygen in this plant, as follows: 30,000 m^3/h of Nitrogen at 1.0 Bar absolute, 9.57 m^3/h of 40 percent concentration Neon-Helium mixture at 0.5 Bar absolute and 130 m^3/h of 0.2 percent concentration Krypton-Xenon mixture.

The overall size of the air separation plant are:

Air Separation Unit: 20 m × 13.6 m × 44.45 m.
Regenerator Unit: 22.65 m × 16 m × 16 m
Weight of the Plant: 1,210 t

6.5. TPS with Fluidized-Bed Gasification CCP Project

The Central Boiler/Turbine Institute (TsKTI, St. Petersburg) and VNIPIEnergoprom Design Institute (Moscow) have developed a TPS project with a 250 MW CCP and gasification of Kuzn coal in a fluidized-bed, steam/air-blown gasifier.

The flow sheet for the highly-integrated CCP is illustrated in Figure 48. The air for the gasifier is extracted from the GT compressor and boosted to gasifier pressure of 2.0 MPa by an auxiliary compressor arranged on a common shaft with the expansion turbine which operates on clean syngas and the auxiliary steam turbine balancing the output of the CC block. Steam for the gasifier is extracted from the HP section of the ST. Prior to entering the gasifier, it is superheated in one of the sections of the convective raw syngas cooler. Cooling of the raw syngas ahead of low-temperature gas cleanup, and it subsequent reheating after sulfur removal are done with minimal wastage of sensible heat along with production of HP saturated steam.

The design of the gasifier is illustrated in Figure 49. The octogon-shaped reaction chamber is formed by the waterwall tube membranes transitioning into the the steam generator multiple forced-circulation loop. To make the gasifier path leak-tight and protect the gasifier external shell from the effect of the reaction heat, the steam extracted from the HP side of the ST is fed through the space between the gasifier shell and the waterwall membrane. Some gasifier parameters and characteristics are shown in Table 33.

The power island on a CC with supercharged steam generator (SSG) includes a GTE-45-2 GT unit of KhTZ manufacture (See section 2.3), T-180 extraction ST made by LMZ and two SSGs of TKZ design. It sectional view is shown in Figure 9. The GT is connected with the SSGs, arranged symmetrically at both sides, by double-walled duct. The air extracted from the GT compressor is directed to the SSG through the annular space between the walls of the duct. The outer wall is cold and the inner wall contains the combustion product returning to the GT. Each SSG is fed by the syngas from it own gasification train which consist of the fuel lockhopper system, gasifier, gas coolers, gas cleaning and preheating system and turboexpander. Natural gas can be fired in the SSG, which ensures operability of the TPS when the gasifiers are down.

The schematic of the coal preparation system for a fluidized-bed gasifier is shown in Figure 50.

The fuel is fed by the station-wide fuel handling system to the raw coal hoppers after coal crushing. For the fluidized-bed gasifier, coal lumps shall not exceed 20 mm in size and the amount of the <1 mm-sized fines shall be 15 percent maximum. For this reason, the coal is again crushed in a special crusher which produces minimum fines. After crushing, the coal is dried to 10-12 percent moisture content. The GT exhaust gas is used as a drying agent. Fine fractions are entrained out of the fluidized-bed drier with the drying agent and are separated in the cyclone, with final removal in an ESP. The dust is combined with binding agent and granulated to the 3-10 mm size. The granules are then predried and strengthened. The crushed coal and the granules are fed to the gasifier through a lockhopper system, driven by syngas taken from before the gas heater, additionally cooled and compressed [42].

The syngas is cooled and heated in several exchangers. Some of the operating data for these exchangers is given below:

No. of Cooler/Heater	Gas Duct	1	2	3	4
Gas Temperature, °C					
Inlet	950	971	522	410	160
Outlet	917	522	410	220	335

The 16 MPa, 346 °C boiler water from the forced-circulation loop of the SSG is used as a cooling agent. The temperature of the tubes in this case is 400-410 °C maximum. They can be fabricated of low-alloy steel.

The gasifier shell is protected from the effect of high temperatures and the aggressive attack of the syngas by the water-wall membrane. The gas duct and the walls of gas cooler No.1 are protected in the same fashion. The gas cooling path includes 3 additional convective cooling sections operating at gas velocities of 6-7 m/s which ensures self-cleaning of the surfaces withour tube erosion. The 3rd Section incorporates a tube bundle whose purpose is to superheat the gasifier steam to 450 °C. It has austenitic tubes. The walls of the other gas coolers, operating at syngas temperatures no greater than 522 °C, are unprotected. For wet cleaning, the temperature of the syngas is reduced to 160 °C, and after cleaning increases to 330-350 °C, at which point it is fed to the expansion turbine and thence to the SSG burners. All gas coolers have 3.8 m diameter outer shells assuring transportation by normal means as assembled unit. The shell length is 17-33 m.

The coarse cleaning of the syngas is done by cyclones in two stages. The first stage is after gas cooler number 1 and occurs at 500-550 °C. The cleaning efficiency of the first stage is 65-70 percent. The second stage is located after gas cooler number three at 210 °C. The efficiency of this stage is 90 percent.

The fine cleaning of the syngas to a particle content of less than 10 mg/m^3 (under normal conditions) is by washing in a venturi scrubber followed by a cyclone mist eliminator.

The greater part, i.e., 70-80 percent, of sulfur removal occurs in the fluidized bed where limestone or dolomite sorbent is injected along with the coal feed. The test trains, which account for about 5-7 percent of total capacity, are incorporated in the system for dry, fine cleaning of the syngas particulates at 410 °C; dry removal of SO_2 by iron ore at the same temperature; and mid-temperature, i.e., 140-160 °C, catalytic SO_2 removal using activated coal. When these technologies are mastered, total sulfur capture will increase to 95 percent and above.

Low No_x emissions are ensured by:

- a considerable percentage of the nitrogen contained in the fuel is converted to ammonia in the gasifier. The ammonia is removed from the syngas by later washing.
- lower combustion temperatures of the syngas in the SSG.

One possible layout for the CCP-250 and gasification plant is shown in Figure 51.

The separate processing sections are each housed in a separate building: turbine hall (the entire CCP including SSG), fuel preparation equipment, gasification plant, additional compressor-expansion turbine, and the balance of plant equipment.

The combined cycle is arranged in a single-bay building 180 m long and 42 m wide. The building houses the steam turbine, GT, SSG and gas-water heater (HRSG) in the GT exhaust path. The deaerator and condensate feed equipment are located between the steam turbine and the GT. The maintenance sites and the through railroad track also are located in this building.

An open bay building, 39 m wide and 72 m long, shelters the two gasifiers, gas coolers and heaters, and the gas cleaning equipment.

Basic parameters of the IGCC-250 TPS and coal gasification system are shown in Tables 22 and 23. Here also are the parameters of the CCP "industrial unit" designed by TsKTI to the same process scheme but a larger and more efficient GT with an inlet gas temperature of 1,100 °C.

Test and validations for the project were conducted on the 250 kg/h coal capacity pilot plant operating at up to 3 MPa [43] and at the large-scale TsKTI test facility at up to 0.6 MPa [44].

The model for the CCP-250 gasification system was reproduced at the TsKTI test facility. Gasification test were conducted on Kuzn bituminous coals of WS grade at flow rates from 600 to 1,100 kg/h, as well as on brown K-A coals. The facility's gasifier vessel is 2.2 m in diameter and 10 m high. The actual reactor diameter is 800 mm and the syngas output is 4,500 m^3/min. The gasification was conducted with steam/air blast at 900-1,000 °C. This plant facilitated the discovery and elimination of many "children's diseases" in such areas as fuel preparation and handling, startup and maintaining gasifier operation, removal of gasifier bottom ash, ensuring maintenance of non-slagging conditions, etc.

The test were conducted at the following conditions:

Coal Characteristics:	
Heating Value, MJ/kg	16.9-27.4
Moisture Content, Percent	23.1
Ash Content, Percent	10.6-15.1
Mean Particle Size, mm	0.95-3.5
Fines Content, Percent	28-48
Coal Consumption, kg/h	600-1,100
Air Flow, kg/h	1,220-3,100
Steam Flow, kg/h	400-800
Gasifier Pressure, Bar	2-3
Steam-Air Mixture Temperature, °C	200-350
Fluidized-Bed Temperature, °C	800-950
Gas Heat Value, MJ/m^3	3.45-4.9
Unburned Carbon, Percent	2.7-10.0

At design velocities of 1.7-2.0 m/s and with moderate amounts of coal fines, the syngas was of normal quality and fly ash removal was acceptable.

Fuel preparation devices, such as the cutting 10 t/h crusher, fluidized-bed dryer/feeder, etc., as well as fines granulation technology were mastered on special pilot rigs. Fluidized-bed gasification of granules has been successfully conducted.

CONCLUSIONS

TERMS OF APPLICATION OF CLEAN COAL TECHNOLOGIES AT RUSSIAN TPS

Wide use of as-mined, high-ash coals at TPS is a characteristic of Russian power generation.

Large amounts of brown coals are produced and fired at TPS. The cheapest and most promising of these in terms of future use are strongly-slagging K-A coals.

The positive feature of the worth-while Russian coals is low sulfur content, leading to SO_2 emission standard compliance. Nevertheless, the production and use of some amounts of high-sulfur coals (from the near-Moscow, Inta and Donetsk coal fields) will continue for a long period of time.

In practice, fuel standards are not strictly met. There are cases where the ash content and heating value of a coal are beyond specified limits. Many times it has been necessary to change the grade of coal supplied to some TPS or units.

No steam coal market exists in Russia and the possibility that one might eventually materialize is not generally accepted.

<u>These conditions demand testing of the applicability of clean coal technologies for high ash fuels, brown coals with specific ash properties and the adaptability of these technologies to coals of varying properties.</u>

The Russian climate is more severe than that in the U.S. It is traditional to employ centralized heating systems for residential and industrial premises. Over half of all fossil-fueled TPS are cogeneration facilities. In terms of generation capacity, this percentage is even higher. Many of the cogeneration plants are therefore of necessity located within city areas and so the requirements for them to be reliable sources of heating as well as producing reduced emissions are foremost. The cogeneration plants employ boilers of relatively small size and capacity, e.g., 170-670 tph.

<u>Low ambient temperatures must be taken into account in the design and installation of equipment; the opportunity to locate equipment out-of-doors is relative limited; and the technologies designed for large power units need to be tested with reference to smaller applications.</u>

The most important task for the Russian power industry will be life extension for older TPS in line with increased efficiency and reduced adverse environmental impact. Such TPS represent the largest market for the environmentally benign technologies.

Russian TPS typically locate 6-12 units of the same type within a common main building. While this carries certain economic advantages, e.g., ease of construction, erection and operation, such TPS layout complicates the arrangement of additional equipment during modernization to improve performance or for gas cleaning because of lack of space.

For this reason, location of pollution control equipment and the necessary additional air, fuel and gas ducting can differ greatly from the U.S. CCTP practice. Similar difficulties appear when replacing coal-fired boilers requiring more space due to things such as large-sized, external cyclones. For this reason, the CFB boilers with in-duct ash separators developed by B&W seem more attractive.

Russia has well-equipped manufacturing facilities for power-industry equipment, and organizations with highly-qualified personnel capable of accomplishing the engineering and design, construction and operation of pollution-control equipment and systems. These assets are under-utilized at present. The Russian power industry has relied upon domestic equipment meeting high standards and providing for reliable TPS operation up until now. Russia uses its own norms and standards. Even though, in some areas Russian engineering fell behind current practice, e.g., GT, CCP, environmental protection and I&C systems, the decision makers – managers of power systems and TPS – are mostly oriented toward Russian equipment and materials.

With this in mind, the most fruitful route toward transferring the CCTP-based U.S. technologies to Russia is joint production, with Russia, of the equipment and employment of Russian personnel to solve possible technical problems. This may require revision of the U.S. technical documentation to comply with Russian standards, materials and manufacturing technologies, and prove Russian sorbents, catalysts and other materials in the technological processes, and etc.

Finally, in transferring the technologies, it is useful to take into account today's difficult economic situation in Russia. Electricity consumption has dropped, only a small percentage of the necessary investment capital is available for retrofitting/repowering of existing capacity and construction of new TPS. Financial difficulties are a major cause of long construction times in Russia.

Under these conditions, <u>lower-cost technologies become more attractive, especially if they can be implemented in stages. Design and supply of shop-fabricated, modular equipment is desirable. Careful planning and organization of the construction process should be the rule.</u>

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ACRONYMS AND ABBREVIATIONS

A	anthracite; air (table 17)
ABBCE	ABB Combustion Engineering Inc.
AC	Anthracite Culm
AFBC	Atmospheric Fluidized-bed Combustion
AOFA	Advanced Over-Fire Air
ASME	American Society of Mechanical Engineers
B&W	Babcock & Wilcox Company
BGL	British-Gas-Lurgi (technology)
BEZM	Belgorod Boiler Works
BIKZ	Biysk Boiler Works
Bit., bitum.	bituminous (kind of coal)
BKZ	Barnaul Boiler Works
Br.	brown (kind of coal)
CCP	Combined Cycle Plant
CCTP	Clean Coal Technology Demonstration Program of U.S. Department of Energy
CE	Combustion Engineering Inc.
CFBC	Circulating Fluidized-Bed (technology)
ChZEM	Chekhov Power Engineering Works (near-Moscow)
COREX°	a registered trademark of Deutsche Voest-Alpine Industrieanlagenbau GmBH
CWS	Coal-Water Slurry
CZD/FGD	Confined Zone Dispersion/Flue Gas Desulfurization process
DCh	Dow Chemical
de-NO_x	NO_x removal technology
de-SO_x	SO_x removal technology
DOE	U.S. Department of Energy
EAS	Electrosila Works (St.Petersburg)
EERC (E&ER Corp)	Energy and Environmental Research Corporation
EF	Entrained-Flow
Ekib	Ekibastuz coal field
EPA	U.S. Environmental Protection Agency
E-SO_x	SO_x Semidry Removal Technology in the Inlet of ESP
ESP	Electrostatic Precipitator
ETM	Electrotyajmash Works (Kharkov)
FB	Fluidized Bed (table 17)
FBC	Fluidized-Bed Combustion (technology)

FGD	Flue Gas Desulfurization
FLS	Parent Company of AirPol, Inc.
FRO-12000	Trademark of Russian fabric filter
F-W	Foster Wheeler Energy Corp.
G	gaseous coals (kind of coal)
GE	General Electric Co.
GR-LNB	Gas Reburning and Low-NO_x Burner
GSA	Gas Suspension Absorption
GT	Gas Turbine
HD	High Dust
HHV	High Heating Value
HP	High Pressure
I&C	Instrumentation and Control System
IGCC	Integrated Gasification Combined Cycle
IP	Intermediate Pressure
ISO	International Standards Organization
K-A	Kansk-Achinsk coals
KhTZ	Kharkov Turbine Works (The Ukraine)
KRW	U.S. Company
KTZ	Kaluga Turbine Works
Kuzn	Kuznetsk coal field
L	Lean coals (kind of coal); Liquid (table 17)
LD	Low Dust
LHV	Low Heating Value
LIDS	Type of de-SO_x System, developed by B&W
LIFAC	Type of de-SO_x System
LF	Long-Flame coals (kind of coal)
Lig., Lign.	Lignites (kind of coal)
LIMB	Type of SO_2 and NO_x Reduction System (Limestone Injection Multistage Burner)
LMZ	Leningrad Metal Works (St. Petersburg)
LNB	Low-NO_x Burner
LNCB	Low-NO_x cell burner
LNCFS	Low-NO_x Concentric Firing System
LP	Low Pressure
MB	Moving-Bed (table 17)
MPC	Maximum Permissible Concentration
N. Caucasus	Northern Caucasus

N-W	North-West (regions of Russia)
NZL	Nevsky Works (St. Petersburg)
OMTI	Trademark of the Synthetic Fire-Resistant Oil
P.C., pc	Pulverized Coal combustion
PCFB	Pressurized Circulating Fluidized Bed (technology)
Pech	Pechora coal field
PermTPS	Permskaya Thermal Power Station
PFBC	Pressurized Fluidized-Bed Combustion
R&D	Research and Development
SCR	Selective Catalytic Reduction
SETM	Sibelektrotyajmash, (Novosibirsk)
SNCR	Selective Non-Catalytic Reduction
SNOX™	Type of combined NO_x, and SO_x Reduction System
SNRB™ SO_x-NO_x-R_{ox}-B_{ox}	Combined NO_x, SO_x and particulate Reduction System of B&W
SR ( )	Excess Air
SSG	Supercharged Steam Generator
ST	Steam Turbine
Subbitum.	subbituminous coals (kind of coal)
SZTM	Power Station Equipment Manufacturing Works (Syzran', Middle Volga)
T	Tampella and Gas Research Institute (only for table 17)
TKZ	Taganrog Boiler Manufacturing Works
™	Trademark
TMZ	The Urals Turbomotor Works (Ekaterinburg)
TPS	Thermal Power Station
TsKTI	Central Boiler/Turbine Institute (St. Petersburg)
TWR	U.S. Company
U-GAS©	Registered Trademark of the Institute of Gas Technology (gasification technology)
VA	Voest-Alpine
VNIIAM	Research Institute (Moscow)
VNIPIEnergoprom	Designing Institute (Moscow)
VTI	All-Russia Thermal Engineering Institute (Moscow)
WS, WS1, WS2	weakly sintering coals (kinds of coal)
YuTZ	Gas Turbine Manufacturing Works in Nikolaev (The Ukraine)
ZIO, ZiO	Podol'sk Boiler Manufacturing Works

Abbreviations

A,%	ash content
Al_2O_3	aluminum oxide
bar	unit of pressure
10^9	billion
BTu	British Thermal unit
°C	degrees centigrade
C	carbon; cold (table 17)
CO	carbon monoxide
CO_2	carbon dioxide
Ca	calcium
ca.	circa, approximately
$CaCO_3$	calcium carbonate, calcitic limestone
cal	calorie,unit of heat
CaO	calcium oxide, lime
$Ca(OH)_2$	calcium hydroxide, hydrated lime
CH_4	methane
CaS	calcium sulphide
Ca/S	molar ratio of calcium to sulphur
$CaSO_3$	calcium sulphite
$CaSO_4$	calcium sulphate
CaO/SO_2	molar ratio of calcium oxide to sulphur dioxide
Cl	chlorine
Cr	chromium
d	dry
daf	dry ash free
$/kW	dollars per kilowatt
$/t	dollars per ton
Fe_2O_3	ferric dioxide
g/kWh	gram per kilowatt-hour
g/m^3	gram per cubic meter
Gcal	gigacalorie, 10^9 calories
GW	gigawatt, 10^9 watts
H, (H_2)	hydrogen; hot (table 17)
H_2O	water
H_2S	hydrogen sulphide
H_2SO_4	sulphuric acid
h, hr(s)	hour(s) - unit of time

h/y	hours per year
He	helium
J	Joule
K	potassium
K_2O	potassium oxide
kcal/kg	kilocalorie per kilogram
kg/s	kilogram per second
kilo	1,000
kJ/kWh	kilojoule per kilowatt-hour
km	kilometer
kPa	kilopascale; unit of pressure
Kr	krypton
kV	kilovolt
kW	kilowatt
kWh	kilowatt-hour
kWh/y	kilowatt-hour per year
M	mixture
m, m^2, m^3	meter, square meter, cubic meter
m^3/h	cubic meter per hour
m^3/s	cubic meter per second
mega	million, 10^6
mg/m^3	milligram per cubic meter
mg/MJ	milligram per megajoule
MgO	magnesium oxide
$MgSO_3$	magnesium sulphite
$MgSO_4$	magnesium sulphate
MJ	megajoule
MJ/kg	megajoule per kilogram
10^6	million
m	micrometer, micron
mm	millimeter
MnO	manganese oxide
MPa	megapascale; unit of pressure
MW	megawatt
MWe	megawatt electric
MWt	megawatt thermal
MW/m^3	megawatt per cubic meter

N, N_2	nitrogen
NH_3	ammonia
N_2O	nitrous oxide
NO	nitrogen monoxide, nitrogen oxide
No(s)	number(s)
NO2	nitrogen dioxide
NO_x	nitrogen oxides
nom	nominal
norm.	normal conditions
Na	sodium
Na/S	molar ratio of sodium to sulphur
Ne	neon
Ni	nickel
O, O_2	oxygen
P_2O_5	lead pentoxide
Pa	pascale; unit of pressure
pH	measure of acidity, basicity; inverse of the hydrogen ion concentration
ppm	parts per million
R_{90}, R_{1000}	coal particle size less than 90 m and 1000 m respectively
rpm	revolutions per minute
S, S,%	sulphur, sulphur content
S	solid (table 17)
Sn	normatired sulphur content
s	second (unit of time)
SiO_2	silicon dioxide
SO_2	sulphur dioxide
SO_x	oxides of sulphur
SO_3	sulphur trioxide
Ta, Tb, Tc, °C	typical temperatures of ash softening
t(s)	tonne(s), unit of mass
t °C	difference of temperatures
tfe	ton of standard fuel
tfe/y	ton of standard fuel per year
t/d	ton per day
t/h	ton per hour
t/y	ton per year
Tnj, °C	temperature of the beginning of normal liquid slag removal

TiO_2	titanium dioxide
thou m^3/h (min)	thousand cubic meter per hour (minute)
thou hrs	thousand of hours
thou hrs/yr	thousand hours per year
W,%	moisture
w/o	without
Xe	xenon
Y, yr, yrs	year, years
(SR)	excess air efficiency

Types of Russian PC Boilers

E-500	type of BKS's boiler (natural circulation, steam output 500 t/h)
P-57, P-67	trademarks of ZIO's boilers
TPE-214A, TPE-216, TPP-312A, TPP-804	trademarks of TKZ's boilers

Types of Russian Large Steam Turbines

K-1200-240, K-800-240, K-300-240, K-210-130, PT-80/100-130/13	types of LMZ's steam turbines
K-500-240, K-160-130	types of KhTZ's steam turbines
T-250-240, T-185-130, T-100-130	types of TMZ's steam turbines

Types of Russian Gas Turbine Units

GTE-200, GTE-150	manufactured by LMZ
GTG-110	manufactured by Mashproject
GTE-45	manufactured by KhTZ
GTN-25	manufactured by NZL output 30.0 MW)
GTN-25, GTN-16	manufactured by TMZ

Types of CIS marine and aeroderivative GT Units

GT-15, GT-16, GT-25	manufactured by Mashproject and YuTZ
RD-29-300	manufactured by Tushino
AL-31STE	manufactured by "Saturn"

NK-37	manufactured by "Trud"

Types of Russian CCPs

CCP-450T (V94.2 GT type)	GT manufactured by Siemens-LMZ
CCP-325 (GTG-110 GT type)	GT manufactured by Mashproject
CCP-80 (NK-37)	GT manufactured by "Trud"

Marks of Russian Boiler-Turbine Steels and Alloys

12X18N12T	high-alloyed Cr-Ni austenitic steel
12X1MF	low-alloyed perlitic steel
EI607A, EI893, EI765, TsD-1, TsJ-24, EP783, EP800, EI-929, EP-220, EP-927	deformed GT alloys
EI893L, EP539LMU, TsL-2, Ts-4 (ZMI-4U), TsL5(7), ZMI-3, TsNK-7NK, JSBK-RS, JSBK-NK	casting GT alloys