DOE/MC/31392 -- 5600
(DE97002247)

Evaluation of Technology Modifications Required to Apply Clean Coal Technologies in Russian Utilities

Final Report
December 1995

Work Performed Under Contract No.: DE-FG21-94MC31392

For
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EXECUTIVE SUMMARY

The operating conditions, technology development, thermal power station (TPS) equipment, and operating and maintenance methods in Russia are very much the same as in the USA. The technical knowledge and knowhow required for designing, building, and operating an ecologically clean coal fueled TPS has been acquired at great expense over a long period of time. In many cases, the associated material and intellectual "expenditures" by Russia should be added to those expenditures in other countries. Therefore, it would be practical to use, on a mutually beneficial basis, the advanced environmental protection and energy technologies which have already been proven elsewhere, such as in the U.S.A.

Although coal is not as predominant a power industry fuel in Russia as it is the U.S.A., it plays and will continue to play in the future an important role in supplying Russian TPSs. To be competitive with natural gas, coal must be efficiently produced, transported, and fired at TPSs within permissible environmental limits.

The cheap open-cut (strip-mined) coals are located mostly in the Southern part of Central and Eastern Siberia. These regions have a high potential for further economical development. The TPSs located and constructed there largely fire local coals. The Kuznetsk bituminous and Kansk-Achinsk (K-A) brown coals are railway transported to TPSs which are thousands of km away from the coal production areas. An actual problem is processing these coals (especially high-moisture K-A coals) to reduce transportation costs.

Russia is very interested in the technologies developed in the U.S.A. under the Clean Coal Technology Demonstration Program (CCTP), other programs that improve existing and newly installed TPS equipment, and naturally, new advanced energy technologies that can find application at Russian TPSs.

In reconstruction and life extension of existing Russian TPSs the following technologies, particularly those developed under the CCTP, can be applied:

- primary (technological) NO_x reduction methods;
- selective non-catalytic reduction (SNCR) of NO_x;
- simplified wet/dry de-SO_x systems.

Russia has developed it's own version of these technologies and has already implemented them at TPSs. Accordingly, in transferring U.S.A. technologies it will be necessary to consider the competition of domestic developers and manufacturers. It may be reasonable to combine the efforts and findings of the U.S.A. and Russia, and share in supplying the equipment required to implement the technologies in question.

Implementing a comprehensive, low-cost emission reduction technology at a Russian TPS would be of interest. For example, an installation using low-NO_x burners, reburning using coal dust as a reducing agent, and non-catalytic de-NO_x sorbent injection to reduce SO_2 could serve as a prototype for wide commercial implementation.

The power units (boilers) at Russian TPSs are designed for firing with both coal (fuel oil) and natural gas. Under such conditions, NO_x emissions can be reduced by gas reburning. If coal or fuel oil is used for a short period of time (e.g., emergency fuel or in the coldest winter time), a simple dry de-SO_x system using Na-containing sorbents can be used to reduce NO_x emissions.

For cleaning flue gases of SO_2, various technologies, such as, sorbent injection into the hot duct, humidifying of gases enriched with sorbents in gas ducts, or injection of sorbent slurry into gas ducts, (Bechtel, LIMB-Coolside, E-SO_x, LIDS, LIFAC etc.) can find application in Russia.

Demonstration in Russia of wet/dry fluidized-bed DeSO_x technology and combined de-SO_x-de-NO_x-ash removal systems based on SNRB technology is desirable. Both developments are also of interest to American companies.

The results of Russian developments of the AFBC boiler are less than those in the USA, and much less than the U.S.A. development of CCPs using PFBC and IGCC.

Participation of U.S.A. companies in the development, construction and operation of plants using the above technologies, and transfer of the U.S.A. experience to Russia is desirable.

CFB technology, including operation with high-ash coals, has been mastered in various countries on a large number of boilers. Of particular note, is the completed Nucla TPS project under the DOE CCTP.

Many existing Russian TPSs have old boilers with an input of 400-420 t/h of coal and corresponding lower output which should be considered for replacement with CFB combustion technology developed in the U.S.A. by F-W, ABB-CE, Pyropower, and B&W.

An important feature of these TPSs is the close location of the equipment that allows no space for installing gas cleaning systems. New CFB boilers can be adapted to the available space occupied by existing boilers of the same or lower output. Predesign (preliminary design) work done in Russia showed the B&W technology, which requires no large external cyclones, enables the installation of CFB boilers in the existing buildings. At old TPSs difficulties may arise with the arrangement of ash collectors, such as, a high efficiency ESP.

Participation of U.S.A. companies will be required in designing the CFB boilers. Manufacture of such boilers can be arranged at Russian Works. Licensing of some components for which the U.S.A. know-how is available, or direct purchase of such components (distribution screens, instrumentation and control systems, etc.) from U.S.A. manufacturers may be needed

A question remains concerning the use in Russia of combustors designed for the DOE CCTP. According to the predesign, TRW combustors can be technically applied on Kuzn coal-fired 300-MW units, however, this application needs more information and operating experience in demo plants.

The application of CFB boilers or precombustors does not reduce the specific cost or heat consumption at a TPS. The considerable improvement to the performance will be possible by the introduction of a CCP using PFBC or integrated coal gasification.

A CCP using PFBC, like the Tidd TPS or larger, can be reasonably used in Russia to retrofit/repower an existing TPS. The small size of PFBC boiler and GT can easily be installed in the available boiler space. The steam turbine and electrical equipment can be changed a bit to increase efficiency and improve automation.

Practically all of the equipment for the first generation of PFBC plants, including the GT with an inlet temperature of about 850°C, could be manufactured in Russia. U.S.A. engineering is necessary to design the entire plant and such equipment as furnaces (supercharged boilers), associated control systems, coal feeding, the fly ash removal before the gas turbine, HP gas/air duct with valves, etc.

Predesign work has been performed in Russia for 25-30, 80 and 270-MW CCP using a PCFB boiler design. One such project is under way as part of the CCTP (Project 7-14). It is reasonable to think of collaboration with the U.S.A. companies to develop these technical ideas.

IGCC plants are most complex. In this field, the U.S.A. companies have the most experience and know-how. Also, the U.S.A. has produced the largest number of high-temperature GTs required for competitively efficient IGCC plants. It is desirable to construct in due time an IGCC plant in Russia that uses American experience and equipment. The ultimate choice of a technology, partners, and terms of a cooperative agreement needs special study. It should take into account the latest available results from the DOE CCTP.

IGCC plants will probably be employed at new TPSs of relatively high capacity. In-depth consideration of such TPS projects will be possible after the operability and performance of such plants is demonstrated in the U.S.A. or other countries. The conditions for the construction and successful mastering of similar domestic technologies are unrealistic in the present-day situation in Russia.

In view of the above, start-up of the first Russian IGCC plant in 10 years would be a good result. Of course, it does not mean that work under this project should be postponed. On the contrary, work should be started now, and it would be preferred to conduct projects in co-operation with foreign partners.

By participating in such projects, U.S.A. companies with their rich experience and advanced developments could become leaders, although there is little promise of a quick return on investment. It would be of advantage to organize the work dealing with these projects now, without hurry and large expenditures, with provision for speeding up after changes in the economical situation in Russia.

Russia possesses up-to-date machines and qualified specialists to produce efficient equipment for the power industry. The power industry equipment market is not mature due to the long-term existence of the monopoly of manufacturers. In recent years, the market has narrowed. At the same time, the production capabilities of manufacturers are more than enough to satisfy all possible demands. Now, Russian power equipment manufacturers have been certified by international organizations in many fields of their activity, and manufacturers cooperate with foreign partners and supply equipment aboard. With this in mind, co-operation is reasonable when the U.S.A. clean coal technologies are being transferred to Russia. Engineering by U.S.A. companies is required to design and construct dedicated equipment and systems. Equipment can be manufactured by Russian producers. The U.S.A. companies could supply some components and materials, e.g., special valves, catalysts, atomizers, I&C equipment, etc. Of course the profit of the U.S.A. companies will not be as large as in the case of turnkey supply of complete systems. However, such cooperation is reasonable considering the competition of Russian and Western European companies.

In some cases, the use of ideas and developments of the Russian enterprises and specialists could improve the parameters and make some technologies more attractive for U.S.A. companies in domestic and foreign (not just Russian) marketing activitities. It may be reasonable for example, to demonstrate in Russia some technologies that are new to the U.S.A., as was done with EPA in demonstrating gas reburning at the Ladyzhinskaya TPS 300-MW unit.

Application of the U.S.A. clean coal technologies in Russia will raise the efficiency of Russian coal fired TPSs, reduce the environmental impact, and facilitate creation of a market for the know-how and equipment of U.S.A. companies. It will also ensure mutually beneficial cooperation of U.S.A. and Russian enterprises.

When transferring the technologies, it is desirable that the American side would make available:

- development of key technical solutions;
- consulting and technical supervision in designing the equipment and its installation at a TPS;
- the supply of individual types of equipment, the manufacture of which is impossible or unreasonable by Russian manufacturers;
- technical supervision and management in construction, erection, adjustment and testing.

The Russian side could:

- prepare the input data for design; including siting, selection of coal and mode of operation;
- design the equipment to be manufactured in Russia and its layout at the TPS;
- conduct research to validate the design in view of the peculiarities of the fuel selected and technical selections made;

- manufacture and supply equipment;
- construct and erect;
- adjust, test, and operate.

To realize each specific project it is reasonable to form a consortium of the U.S.A. and Russian enterprises including developers of the technologies and design organizations.

In the transfer of technologies the human relations, exchange of information, education and training of specialists are extremely important. Russian specialists have adequate technical knowledge and good experience. However, they are not familiar with the judicial/ legal aspects of business, and with planning and management problems.

To familiarize Russian specialists with the U.S.A. clean coal technologies it would be desirable to prepare and conduct, in Russia, a conference to present major projects or a group of projects, and, perhaps, include an exhibition of the American companies achievements.

In the field of energy generation and environmental protection many European and transnational companies have been working in Russia. Some of them have already set up joint ventures or concluded agreements with Russian producers and consumers of power industry and pollution control equipment.

Due to this fact, potential competition of Russian and European companies shall be considered in forwarding the U.S.A. technologies to the Russian market.

For the terms of application of Clean Coal Technologies at Russian TPSs see also conclusion of this study.

1. OVERVIEW OF RUSSIAN POWER INDUSTRY

1.1. General

Russia possesses rich fuel and energy resources, however the remoteness of resources from consumers present certain problems. Thermal power stations (TPS) in Russia employ modern steam-turbine unit and operate efficiently. Construction and operation of such power stations will continue in future. Among the urgent problems are life extension and further upgrading of steam-turbine power stations, and development of combined cycle (CC) plant, the latter using first gas, and then coal [1].

The industrial and municipal electricity demands (growth) in Russia are largely met by construction of TPS. In the near future, the greater portion of electricity will be produced from natural gas and coal, mostly from natural gas.

Russian power generation is characterized by the following data (bracketed are 1990 figures when electricity generation was at the maximum level) [2].

	1994	(1990)
TPS Installed capacity, GW	210	(213.3)
Electric generation, $\times 10^9$ kWh/y	876.6	(1082.2)

Power reserve in 1994 was 15 percent on the average. Nevertheless, some regions remained energy-deficient.

Per capita electricity production was 6,190 kWh/y.

The installed capacity breakdown with reference to types of power plant, are (see also Figure 1):

	GW	%
Total	210	100
Fossil-fueled,	145.6	69.3
including		
Condensing plants,	65.6	31.2
Cogeneration plants	80.0	38.1
Nuclear power plants (NPP)	21.2	10.1
Hydro-power plants	43.2	20.6
Other	0.04	-

The following thermal efficiency data are calculated using the low heating value (LHV) of fuels; in all cases, volumes in "m^3" are for standard conditions (if not indicated otherwise); masses (weight) are in metric t; pressure and pressure drops are in Pa, kPa, bar and MPa

Fossil-fueled plant generated 602.8×10^9 kWh (68.8 percent); NPP generated 97.8×10^9 kWh (11.2 percent); and hydro-power plant generated 175.3×10^9 kWh (20.0 percent). The cogeneration plant also supplied 613.2×10^6 Gcal (713.2×10^9 kWh) of heat. Specific fuel consumption for TPS was 310.3 g/kWh with 39.64 percent average efficiency (taking account of combined heat and power generation).

For electric and heat generation 383.2×10^6 t of standard fuel (tfe) was consumed. Considering a LHV of 29.3 MJ/kg (7,000 kcal/kg) this includes the following fuel mix (see also Figure 2):

Name	10^6 tfe	%
Natural gas	244.5	63.8
Coal	98.5	25.7
Fuel oil	40.2	10.5
Total	383.2	100.0

The export of electrical energy in 1994 amounted to 21.94×10^9 kWh, which includes 1.41×10^9 to the Ukraine, 4.96×10^9 to Belorussia, 0.35×10^9 to the Caucasian republics,

7.05×10^9 to Kazakhstan, and 8.17×10^9 to Finland and other foreign countries.

The technical level of the electric power industry, and TPS in particular, is sufficiently high to provide an adequate basis for solving future technological and economical problems [3].

The electric power industry is highly centralized with over 90 percent of the generation supplied to the power grid system transmission lines at 330, 500, 750 and 1150 kV.

The length of the transmission lines of all voltages classes is about 700,000 km, and the length of lines above 110 kV is 42,800 km.

The generating capability is based on condensing TPS that employ 200-, 300-, 500-, and 800-MW unit, and cogeneration plant with 50-80, 100-, 180-, and 250-MW turbines. Unit larger than 250-300 MW are designed at supercritical (24 MPa) steam pressure. In general, 85 percent of the electricity is generated at TPS using high-pressure steam (13 MPa).

Russia is located in latitudes with severe climate. Of great importance is the heating of residential, industrial, and public premises. The required heat loads and the heat and steam requirement of industrial enterprises are traditionally supplied from centralized large boiler houses and cogeneration plant. The total capacity of such plant is about 80 GW, or more then half the capacity of all TPSs. More than 80 percent of the heat supplied to consumers comes from steam extracted from steam turbines at power stations. Considering the fact that over 60 percent of the electricity in these TPS is generated in the combined mode (it is about 34 percent of the total fossil-fuel TPS generation) with an average efficiency of 46.5 percent, and a specific fuel consumption of 265 g/kWh.

Specific fuel consumption (b_e) in the cogeneration mode is generally derived from the following expression:

$$b_{e^\cdot} = (Q_f - Q_h)/(N_e\ K)$$

Here, Q_f is fuel heat, Q_h is part of fuel consumed to produce heat, N_e is electrical output, K is coefficient matching unit of measurement. The equivalent efficiency = $123/b_e$.

The structure of fuel balances in various regions differ greatly. The larger portion of electricity in Western Siberia, the Urals, and the European part of the country is generated using natural gas. In Central and East Siberia the resources are hydro and coal, and in the

North-West and the Far East, they are nuclear power and coal, respectively. The consumption of coal was 133.4 × 10^6 t with average heating value of 16.5 MJ/kg and an ash content of 27.9 percent.

Below, are some data on coal fired condensing power unit (Figure 3):

Unit capacity, MW	800	500	300	200	150
Number of unit	2	7	27	36	17
Average load, MW	—	400	220	150	110
Efficiency, %:					
best TPS	—	36.9	36.3	35.9	35.0
worst TPS	33.2	36.2	30.1	30.4	34.0
Share of coal in the fuel consumed, %	97.0	97.7	77.5	70.0	70.5

Coal is also fired at many cogeneration plant. It share is in these cases is 20-50 percent. At numerous condensing and cogeneration plant coal is used as seasonal fuel.

The following condensing and big cogeneration units have been constructed and operated in Russia:

Unit capacity, MW	150-160	180-220	250-300	500	800
Number of units	37	89	110	7	14
including coal designed unit	27	47	31	7	5

Power units up to 200 MW and equipment for cogeneration plant using 640-670 t/h boilers are designed at subcritical parameters. Condensing units at 200-215-MW and unified cogeneration units of 180 MW are designed at 13 MPa, 540/540 °C. Cogeneration plant with smaller capacity boilers and turbines – mostly rated 60-80 and 110-115 MW – operate at 10-13 MPa, and 555 °C. Most cogeneration plant turbines extract steam for staged heating of hot water. The extraction steam pressure for that purpose ranges from 0.5-2.5 bar.

Condensing 300-, 500-, and 800-MW units and cogeneration units of 250 MW unified with 300-MW units are designed at supercritical steam parameters (24 MPa, 540/540 °C).

The total capacity of such units is about 45 GW. Their capacities and parameters are standardized. Supercritical power units with 1,000-2,650 t/h once-through boilers operate reliably and efficiently firing various fuels. The annual net efficiency of the best TPS firing gas and fuel oil is 39 percent, and in the case of coal 37 percent. The design of equipment is continuously upgraded. Four to five modifications of turbines and boilers for such units have been manufactured.

A 1,200-MW unit has been in successful operation for over 10 years with a single-shaft, 5-cylinder (stage), 3,000-rpm turbine employing welded LP rotors and a titanium last stage with 1,200-mm long bucket. This unit, firing mostly natural gas, has operated for some (many) years practically without unscheduled shutdowns at an efficiency of 39-39.5 percent and an availability factor of over 90 percent. Based on the experience with developing, constructing and operating this turbine, LMZ has designed and supplied several 1,000-MW single-shaft turbines for NPP.

For many years (up to 1992), the Russian TPS operated at heavy-duty conditions without sufficient power reserve and had rather high reliability and availability factors. Now, under a poor economical situation, substantial reserves appeared and the utilization coefficient dropped. Consequently, the duration of repair time increased and the relability of unit and TPS was somewhat reduced.

The Russian TPS have a typical low rate of equipment renewal [4]. Currently, life expiration of the equipment is 5-7 times ahead of the addition of new capacity. As of today, about 40 GW of TPS capacity has exceeded the design life. It is estimated that by the year 2000 this figure will increase to 90 GW. There are 20-30 unit of 150-160, 200 and 300 MW each that have operated approximately 200,000 hrs. Some individual 150-MW unit had been in operation over 270,000 hrs. New 800- and 1,200-MW unit have operated less than 100,000 hrs.

Many steam turbines and boilers at cogeneration plant have operated even longer than condensing unit.

Naturally, in many cases the TPS life can be extended.

Based on comprehensive research of the metal in power equipment that has seen extensive service, generalization of statistics, and durability predictions using fracture mechanics techniques, it has been established that the normal safe operation time of KhTZ 300-MW steam turbines is 170,000 hrs, and that of the LMZ steam turbines is 220,000 hrs. This is the so-called "fleet" life relating to the entire fleet of equipment.

The scope of work for inspection, repair, and replacement of key power unit component between the design life of 100,000 hrs and the fleet life does not change significantly from that required for the first 100,000 hrs.

After expiration of the fleet life one can forecast (with reference to 300-MW unit) the following scope of work to extend it's life:

- replace 50 percent of the stop and control valves on KhTZ turbines, and 10 percent on LMZ turbines;

- replace 25 percent of the rotors on KhTZ and 8 percent on LMZ turbines;

- repair of 25 percent of the rotors on KhTZ and 10 percent on LMZ turbines;

- repair of 30 percent of KhTZ and LMZ turbine cylinder casings by grinding to remove surface cracks and/or repairing deeper cracks by metal-locking or similar techniques;

- replace about half of the live steam and hot reheat pipes (or rehabilitate by heat treatment);

- replace 30 percent of boiler heating surfaces.

Accomplishing the above scopes of replacement and repair followed by careful periodic inspections can increase the equipment life 50,000 hrs beyond the fleet life. Further operation will demand replacement and repair of a large number of component and more rigid in-service inspections of the metal. In this situation, complete replacement of the turbine unit seems reasonable.

However, it should be considered that many existing TPS constructed 30-40 years ago have obsolete equipment which does not meet the modern requirement for efficiency and environmental impact. Continuation of their operation becomes unreasonable. Frequently, it is very difficult technically, or rather costly, to repower such TPS to improve the performance.

A more attractive way is replacement using new technologies. The adequate economical substantiation of constructing efficient TPS with advanced equipment is next to impossible in Russia now.

1.2. TPS Environmental Impact

TPS, especially coal fired, are large environmental polluters [5].

The sanitary standards currently existing in Russia for regulating the maximum permissible concentrations (MPC) near ground-level of the major pollutant [6] are given below.

Pollutant	MPC mg/m^3	
	maximum	daily average
Fly ash	0.30	0.10
Same, for K-A coals	0.05	0.02
SO_2	0.50	0.05
NO_x	0.60	0.06
NO_2	0.085	0.04
CO	5.0	3.0
Benz(a)pyrene	—	1×10^{-6}

For new TPS, the MPC of the ground-level contaminant have long been met in the U.S.S.R. by emission scattering through tall stacks.

Now, the State Standard has been prepared oriented to today's level of power engineering and gas cleaning equipment (up to 2001) and more stringent requirement after 2001. The norms of the Standard are given in Tables 1, 2, and 3 [7].

The strong position of local authorities and the public often force lower emissions than those specified in the Standards. Sometimes it is justified, i.e., in regions with high background industrial or transport emissions. Sometimes, implementing environment protection measures demands unjustifiable expenditures from the ecological and economical point of view.

The data on actual emissions of Russian thermal power stations in 1994 are given below.

Pollutant	Emissions, 10^6 t
SO_2	2,110
NO_x	1,210
Fly ash	1,500
Total	4,820

Coal TPS are responsible for the major part of the emissions listed above.

Specific emissions, g/kWh are strongly different for different coals.

Pollutant	Coal grade			
	Kuzn	K-A	Donetk AC	Ekib
Fly ash, slag	82.0	29.0	103.0	250.0-420.0
SO_2	3.5	2.6	21.6	9.1 -11.5
NO_x	3.7	1.5	2.8	3.4 - 3.6

Some years ago, a considerable reduction of the TPS environmental impact was felt at the state level. The development of new environmentally friendly energy technologies, conventional boilers with lower or minimum emissions, and gas cleaning equipment and systems have been under way. They were carried out in accordance with the "Ecologically Clean Power Generation" State program, including the "Ecologically Clean Coal Power Stations" section. Much of the work was being done by manufacturers of equipment and energy enterprises at their own initiative. Though at present, the rate of environmental protection work in power engineering is reduced due to the economical difficulties in this country, the development are still under way and many of them have already gained positive result.

2. ELECTRIC POWER EQUIPMENT OF RUSSIA

2.1. General

The electric power manufacturing industry of the former U.S.S.R. produced all kinds of equipment required for electric power stations: steam boilers, steam and hydro-power turbines, associated electric generators, transformers, auxiliary mechanical and electrical equipment, component and materials [1]. Brief characteristics of the thermal power station equipment used in Russia can be found in Section 1 of this report. The equipment in many respect meet the world's standards and ensures high reliability and economic efficiency. Some design data on large Russian TPSs, and a distribution of main equipment by manufacturer and rating can be found in Table 4.

The manufacture and operation of electric power equipment was based on domestic R&Ds, metal, electronics, chemicals, etc. TPSs were constructed by large specialized organizations having all the necessary equipment and facilities. At the same time, there was a certain lag of the Soviet, and later Russian, industry in the development and manufacture of GT, automatic control systems, and gas cleaning systems and equipment.

Given below are some data on Russian TPS equipment and manufacturers.

2.2. Steam Boilers and Associated Equipment

The major utility boiler manufacturers for large power unit are Taganrog Boiler Manufacturing Works (TKZ) and the Podol'sk Boiler Manufacturing Works (ZiO). The scope of their shipment for the Russian large power unit can be seen from Table 4. These two boiler works also produced many subcritical-pressure boilers with steam output up to 670 t/h. Such boilers are likewise manufactured at the Barnaul Boiler Works (BKZ). Utility boilers of smaller capacity and industrial boilers are produced at the Biysk (BIKZ) and Belgorod (BEZM) works.

The domestic works manufacture boilers of various steam output, designed at different steam parameters and adapted to fire different fuels. The boiler fleet was updated continuously due to the use of new fuels, the reduction of harmful emissions, and the export of boilers [8].

All new boilers have been designed with suspended gas-tight waterwalls. The boilers are supplied as large-size transportable assemblies to provide for high quality, rapid erection, and commissioning.

Liquid and gaseous fuel fired utility boilers are produced in the range of 160-3,950 t/h, 14-25 MPa, 560/560 °C and 545/545 °C [9,10].

Despite significant differences in capacity and steam parameters, the domestic fuel oil boilers have much in common. All of them have Π-shaped layouts and have prismatic furnaces with all-welded water walls. The boilers can operate under pressure, are equipped with a gas recirculation system, and regenerative air heaters.

The 3,950- (Figure 4) and 2,650-t/h boilers for 1,200- and 800-MW unit are suspended from the building structures, and the remaining boilers are suspended from their frame.

For gas/oil boilers with prismatic furnaces the opposed, multi-tier swirl burners are used: three-tier burners for 800- and 1,200-MW unit boilers; and two-tier for 300 MW and lower output unit boilers.

With close arrangement, only front burners are applied.

The Π-shaped, 320 t/h and larger boilers have a ledge at the back wall protecting the platens or the vertical bank of the convective superheater from direct furnace radiation.

Regenerative rotary heaters with rotor diameters from 5.4 m (429-, 320-, and 160-t/h boilers) to 14.5 m (2,650- and 3,950-t/h boilers) are used for air preheating. To protect the heater packing against corrosion, the air is preheated and ceramic packing is used in the cold layer.

Boilers for firing coals with significantly different physical-chemical properties and mineral matter behavior are manufactured in a greater number of layout and technical design [9,10].

The maximum capacity of domestic coal unit is 800 MW for which 2,650-t/h boilers had been specially designed to fire Berezovo brown coal (P-67, ZiO, Figure 5) and bituminous Kuznetsk and Donetk coals (TPP-804, TKZ). The P-57R, 1,650-t/h boiler was designed and manufactured by ZiO as 500-MW unit to fire high-ash Ekibastuz coal (Figure 6).

Brown coals, such as the strongly slagging Berezovo coal are fired in tangential furnaces. The square-section furnace used by ZiO in the P-67 boiler ensured low-temperature firing with a dry-bottom, good aerodynamics, and uniform heat flux distribution, thereby providing no-slagging operation. The tangential-fired furnaces allow for staged combustion in the plane of each burner tier where the coal-air mixture and secondary air are directed at a certain angle.

The bituminous coal fired TKZ and ZiO boilers for 800-MW and 500-MW are made with wall-mounted burners.

The solid fuel fired boilers of higher capacity are of the T-type layout.

These coal boilers are mostly of the dry-bottom design, with the exception of some 200- and 300-MW unit dedicated to fire anthracite culm and lean bituminous coals which are of the wet-bottom design. The new boiler project for these coals include both dry- and wet-bottom options.

The technical solutions laid down in the schemes and design of the component of coal boilers reflect the experience and traditions of manufacturers. So, for example, ZiO most widely applies steam-to-steam heat exchangers to control reheat temperature, whereas reheater interim stage bypassing is the practice of BKZ, and gas recirculation and water injection are used by TKZ.

Flat-flame burners are widely employed by TKZ (TPP-804 boiler for 800-MW unit, TPE-215 boiler for 200-MW unit and unified series of 400-500-t/h range boilers).

ZiO and BKZ boilers mostly use tube air heaters. Characteristics of some coal boilers are illustrated in Table 5. To decrease NO_x formation, low-NO_x burners of various designs are used. Two-stage combustion and reburning, flue gas recirculation, high concentrated coal dust supply, to mention but a few, are also applied.

Various methods and devices for cleaning the heating surfaces of slag and deposit are applied. Sliding pressure boiler operation has been mastered allowing for unit flexible operation and deep unloading in a "moderate" mode.

Both sub- and supercritical pressure boilers use low-alloyed perlitic steel (12X1MF) and high-alloyed Cr-Ni austenitic (12X18N12T) steel in addition to carbon steel. The ferrite family steels with high heat-resistance (up to 620 °C), among which the domestic example is EI-756, are also employed for some ZiO boilers, and also at foreign TPSs.

The specific metal weight vary widely for coal boilers for which moderate furnace heat release rates and water wall heat fluxes are typical.

The highest metal weight are for boilers designed for high-moisture brown coals. The metal weight for pressurized part of P-67, P-78 (1,650 t/h) and TPE-216 boilers are 3.02; 3.57 and 4.09 t/(t/h), and the total metal weights are 7.4; 8.48 and 10.0 t/(t/h); the latter boiler is suspended from it own frame.

The design gross efficiency of the currently manufactured domestic gas/oil boilers is 92.5-94.0 percent, and that of coal boilers, 90.5-92.5 percent. The actual efficiency in some cases turned out to be below the design value with the difference reaching 2 percent. The causes are increased fouling and slagging of heating surfaces, their inefficient cleaning, increased suction in the furnace and convective boiler part, increased stack gas temperature, and poorer fuel quality.

To evaluate new furnaces and firing technologies some pilot coal boilers were constructed in the 1980s.

In 1984, a 500-t/h, 14.0 MPa, 560 °C TPE-427 wet-bottom boiler was put into operation equipped with the TKTI vortex furnace to fire Kansk-Achinsk coals. The refractory, horizontal-lined furnace chamber with a diameter of 4.4 m and a width of 16 m was separated by two division walls into 3 compartment. The prismatic cooling chamber is 5.9 m deep. Six straight-flow burners are arranged over the front at an angle of 15 degrees to horizontal. The furnace volume heat release rate (0.203 MW/m^3) is considerably higher than at existing E-500 and P-67 boilers (refer to Table 5). The boiler fires Berezovo and Nazarovo field brown coals. Despite modernization of a number of component and the fuel preparation system, the boiler can only operate continuously at 60-65 percent of the nominal capacity due to superheater fouling.

The St. Petersburg Polytechnical Institute has developed low-temperature swirl combustion technology for crushed coal. The BKZ 420-t/h boiler has been redesigned to use this technology. The brown Irsha-Borodinsk coal in lumps of up to 25-mm size was used. To decrease the carbon loss, wear of water walls, and ensure design steam superheating some modernization was introduced into the boiler. As a result, the average load is 0.7-0.9 of the nominal value, carbon loss is 2 percent, furnace excess air is 1.37-1.41, and NO_x emissions - 470 mg/m^3.

Since the beginning of the 1980s, experiment have been undertaken to fire coal in different versions of fluidized-bed boilers.

These small boilers with low-temperature fluidized beds have been designed by BIKZ in cooperation with TKTI. In 1985, first 10- and then 16-t/h boilers were manufactured and reached nominal output. The carbon loss when firing Kuznetsk gas coal is 3-4 percent maximum.

Work on combined flame and bed combustion were conducted by VTI and VNIIAM. The dry bottom hopper was provided with a nozzle screen whereto the coal ranging from 2-25 mm in size was fed. The fine fraction was directed to be milled and was supplied to the furnace via the PC burners. VTI conducted the work and fired Kuznetsk and Ekibastuz coal in 210- and 160-t/h reconstructed BKZ boilers. Increased output and NO_x reduction were obtained but the work was not finished.

Positive result have been obtained by VNIIAM for flame-bed combustion of shales at the 75-t/h boiler of the "Akhtme" cogeneration plant. However, the attempt to transfer the technology to a 250-t/h boiler was confronted with certain difficulties.

The Irsha-Borodinsk brown coal fired in a 420-t/h bubbling fluidized-bed boiler (Figure 7) manufactured by BKZ in cooperation with TKTI and VTI. The furnace is of the four-section design arranged on two floors. Each section is provided with an air distributing grid which has the evaporative and superheating surfaces arranged in the bed of the granular material. The evaporative bank is located in the freeboard above the bed. Provision is also made for a separation space. The evaporative surfaces above the bed are studded to protect them against wear. The slag from the adjacent boilers is used as inert material.

According to predictions, NO_x emissions will be of the order of 350-400 mg/m^3, sulfur capture, up to 90 percent; and boiler path pressure drop, 20-29 kPa. The boiler test will start this year.

At the end of 1987, a program had been adopted in the U.S.S.R. to create CFB utility boilers, according to which BKZ in cooperation with TKTI and VTI had developed 500-t/h, 14-MPa, 565 °C, non-reheat CFB boilers. A boiler firing anthracite culm and using high-temperature cyclones [11] was designed for the Kurakhovskaya TPS, Ukraine (Figure 8).

A boiler for the Novomoskovsk TPS was designed to fire high-sulfur near-Moscow brown coal and employ cold cyclones. Similar boilers are being designed to fire Ekibastuz and Kuznetsk coals.

The anthracite culm-firing CFB boiler is made up of two furnace modules each of which has two cyclones and four ash heat exchangers. The furnace modules are combined by a single convective section. The furnace module dimensions in the upper and lower portions are 8.0 m long by 5.5 m wide and 7.4 m long by 2.5 m wide, respectively. The 1st and 2nd stages of the superheater, 1st and 2nd stages of the economizer and air heater are located in the convective path. The calculated NO_x and SO_x emissions are at 200 mg/m^3.

Much has been done in the U.S.S.R. to introduce higher supercritical steam parameters. In 1949, at the VTI Experimental cogeneration plant a pilot boiler was constructed, designed for 30 MPa, 600 °C (later 650 °C), which has been in successful operation since that time. At the Kashira TPS, the SKR-100 power unit was put into operation in 1966 employing a ZiO manufactured PK-37 boiler rated for 710 t/h, 31 MPa and 650 °C live steam, and 9.8 MPa, 565 °C reheat parameters. The steam was supplied to the high pressure steam turbine, and after being expanded there was directed to the existing K-60 turbines at 3 MPa, 400 °C. To manufacture boiler outlet component and steam pipes high-alloyed austenitic steels EP-184 and EP-17 were designed wherein the Ni content was increased to 17-18.5 percent.

The unit operated for 30,000.hrs at a boiler outlet temperature of 630-640 °C and a short-term live steam temperature rise of up to 650-655 °C. The residual life of the unit equipment is now about 100,000 hrs.

Along with traditional boilers, Russian manufacturers produce some special-purpose utility equipment. For example, the Russia's Taganrog boiler manufacturing Works (TKZ, Taganrog, Rostov district) has experience in designing and manufacturing the supercharged steam generators (SSG) for combined cycle plant. Such steam generators are located between the compressor and turbine of the GT unit. They all use compressed air and fuel to be fired at excess air rates close to that used in the conventional boilers. The released heat is utilized to generate and superheat the steam fed to the steam turbine. The combustion product are cooled down to the acceptable temperature in a heat exchanger and are expanded in a gas turbine to a pressure close to atmospheric.

A 200-MW natural gas CCP (30-MW GT, 150-MW steam turbine) with a 450-t/h supercharged steam generator (14 MPa, 545/545 °C) was constructed in Russia, and since 1973 has been in operation at the Nevinnomyssk TPS. The gas pressure in the supercharged steam generator is about 6.5 bar, and the turbine operates with inlet gas temperatures up to 770 °C. This CCP has been in operation for more than 130,000 hrs.

Later, supercharged steam generators of 600 and 655-t/h steam capacity were designed and prepared for manufacture for a 250-MW CCP (50-MW GT, 200-MW steam turbine) that would use natural gas and low-calorie gas – the air-blown coal gasification product. The layout of a SSG-650 is illustrated in Figure 9. The 250-MW CCP employs two such unit located symmetrically with respect to the GT axis (see section 6.5).

TKZ also produces HP feedwater heaters for power unit of up to 1,200 MW.

Another large boiler manufacturing works of Russia – ZiO – is located in Podol'sk (near Moscow). About 700 boilers have been produced at that works for more than 140 domestic and foreign (Poland, Rumania, Bulgaria, Germany, Greece, China, etc.) TPSs of total capacity over 64×10^6 kW, including 13×10^6 kW for export.

For CCPs ranging from 16-800 MW, heat recovery boilers of various capacity have been designed at the ZiO works. Such boilers widely employ spiral-finned pipes produced successfully at the ZiO works (8 lines for tube finning of up to 20,000 t/y capacity). The available equipment allows for tube finning of all kinds of steels ranging in diameter from 22-114 mm with rib height up to 35 mm and spacing ranging from 4-24 mm.

Since 1931, ZiO has produced equipment for refineries and allied branches of industry. Now, it annually supplies up to 700 items for column, tank equipment, heat exchangers and tube furnaces for a total volume of up to 20,000 tons. More than 40 refineries are fitted with ZiO equipment. Some items of equipment have been manufactured for foreign companies. Among them are rectification columns, stabilizers, absorbers, desorbers, evaporators of up to 3.4 m in an assembled state (for larger diameters the items are shipped to be assembled at the site), heat exchangers, tanks for various processes, product coils for furnaces, etc.

ZiO has been certified to the ASME standards with reference to boilers and pressure vessels. In 1994 the work was completed to certify ZiO in quality by ISO 9000 Standard (it is carried out by Lloyd Register). Certification by DIN is under way.

The "Belenergomash" (BEZM, Belgorod, Central Russia) can serve as an example of an enterprise producing small boilers. It's specialty is low and medium capacity boilers for TPSs, heat recovery boilers for metallurgy, chemical, wood- pulp and paper industries, and small boilers and boiler houses for residential heating. BEZM produces:

- saturated or superheated steam boilers of 35, 50, 75, 100 and 165 t/h operating on natural gas, fuel oil, bituminous and brown coals, and wood wastes;
- gas- and water-tube boilers from 0.4-15 t/h;
- gas-, water-tube and spiral hot-water boilers from 0.1-10 MW;
- equipment for small boiler houses: deaerators, chemical cleanup plant, heat exchangers;
- water- and gas-tube heat recovery boilers for cooling process gases (converter gas, dry coke quenching, etc.);
- boilers for burning black liquor (soda regeneration), hydrogen sulfide, wastes of soot production, etc.;
- hot-water boilers of up to 106 MWt in capacity; heat-recovery boilers with the spiral-finned tubes utilizing GT waste gases ;
- utility boilers of different types.

Belenergomash is also Europe's largest producer of pipes, shaped part and pipe packages for TPS and NPP. The works has bending machines both conventional and with local induction heating to manufacture bends of up to 630 mm in diameter using carbon and Cr-Mo steels, and up to 325 mm using austenitic steels; machines for tube cutting and welding, press-forging plant for stamping t-pieces and bends, and equipment for casting of shaped component.

The equipment for coal handling and pulverizing (conveyors, crushers, mills of various designs, etc.,) is produced by SZTM Works in Syzran' (Middle Volga).

HP valves (dampers, pressure-reducing unit, etc.) are issued by the ChZEM Works in Chekhov (near Moscow).

2.3. Steam Turbines

Steam turbines for large power unit are mostly manufactured by the Leningrad Metal Works (LMZ, St. Petersburg) and Kharkov Turbine Works (KhTZ, Kharkov), while the turbines for combined heat and power generation are made by the Urals Turbomotor Works (TMZ, Ekaterinburg). These works produce single shaft turbines of 30-1200 MW for driving electric generators.

Basic technical data on the largest Russian-made steam turbines are illustrated in Table 6 [12].

The condensing turbines feature the following peculiarities.

The K-160-130 turbine (KhTZ) is of a two-cylinder design with a combined HP and IP cylinder and one two-flow LP cylinder.

The K-200 turbine (LMZ) is of the three-cylinder design with separate HP and IP cylinders and two-flow 1.5 exhaust LP cylinder.

The K-300 turbine features three exhaust. The IP cylinder is combined with one LP cylinder flow which passes 1/3 of the entire steam.

The modern turbines of larger capacity are made with a single-flow HP cylinder, single or two-flow IP cylinders and one or several (up to 3) two-flow LP cylinders. The typical design of a HP cylinder with loop steam flow applied by LMZ and TMZ is shown in Figure 10, and the typical LP cylinder is illustrated in Figure 11 [13,14].

Unit of 30-185 MW are designed at 3-13 MPa and 430-555 °C without reheat and are mostly used for combined electricity and heat production at industrial enterprises and in utilities [15]. The extraction turbines have regulated steam extractions to supply steam for industrial users and to heat water for heating systems. The heating is done in 2-3 stages for better efficiency. Also, back-pressure turbines operating at pressures up to 3 MPa are available with output up to 100 MWe.

The larger turbines (180 MW) for cogeneration, and (150-200 MW) for condensing TPS are designed with reheat at 13 MPa, 540/540 °C.

The TMZ turbines dedicated for combined electricity and heat generation are made so that the nominal capacity is ensured at a nominal heat rate and a minimum steam flow to the condenser. In this case, the turbine cycle efficiency is maximum. The exception is the supercritical pressure reheat T-250 turbine. It carries it maximum electrical load of 305 MW in the condensing mode, without steam extraction.

The IP part of this T-250 extraction turbine is divided into two cylinders. Large steam pipes are connected to the top and bottom extraction point for IP cylinder No. 2. The steam is used to heat district heating water. In 100-, 180-, and 250-MW turbines steam is extracted for these purposes at 50-60 and 150-200 kPa. The maximum amount of extracted steam is 320, 490 and 600 t/h respectively. In a 250-MW turbine unit, up to 385 MWt of heat is extracted.

The process heat is extracted at 1.3-2.0 MPa.

Condensing steam turbines rated at 300 MW and more are manufactured for operation at supercritical (24 MPa) steam pressure with 540/540 °C reheat.

All Russian-made steam turbines of up to 800 MW inclusive have nozzle steam distribution. The flow path is made up by impulse stages with positive reaction in the root section and aerodynamically perfect blades, as a rule, with variable profiles along it. To increase efficiency and dampen bucket vibration, bucket are made with shrouds. This and blades machined from one piece is the latest design for IP and LP cylinders. Axi-radial seals are provided over the shrouds.

In conventional use are diaphragm-type designs of nozzles and integral-disc types of rotors that are generally supercritical, and for the LP part they mostly use shrunk-on discs. With Russian-made steam turbines there were no difficulties due to rotor stress corrosion cracking because less strong steels having a higher ductility were used.

The bucket in the heavily-loaded stages of the LMZ turbines are fastened by fork root; in the less loaded stages by T-shaped root; and in the last stages the long bucket are fastened by serration type root. Interchannel systems of moisture separation and liquid film removal in the rim gap are used in the LP cylinders.

The turbines manufactured now can operate under loads from 20-115 percent. Some characteristics of existing LMZ supercritical steam turbines are given below.

Parameters	Type of Turbine			
	K-300	K-500	K-800	K-1200
Maximum output, MW	330	540	870	1400
Specific heat consumption, kJ/kWh	7704	7641	7683	7616
Specific weight, kg/kW	2.3	1.9	1.5	1.47
Nonscheduled outage, %	1.5	-	0.7	0.6
Number of unit in operation	55	5	15	1

The efficiency of the HP, IP and LP cylinders of supercritical turbines now in operation are 84-86 percent, 91-92 percent and 82.5 percent, respectively. More efficient turbines have been designed (first with increased efficiency of the LP cylinder) with a specific heat consumption of 7300-7500 kJ/kWh.

The Russian-made steam turbines are reliable in operation. Availability factors of 200-1,200-MW steam turbines are 97-99 percent, and the time between overhauls is 4-5 years with operation of up to 6,000 - 7,000 hrs/y. The time between failure is 10,000 hrs.

To ensure the strength and reliability of the component and increase the efficiency of the turbine flow pass, state-of- the-art computer codes (in recent years 3D codes) are used. The Works, Research Institutes and Universities have test facilities and experimental turbines (at LMZ a full-scale LP cylinder with 960 and 1,200-mm long last stage blades) to investigate the flow path and component of steam turbines.

Some unique technical achievement [13] are:

- 50-MW control stage of LMZ steam turbines made-up of bucket that use design damping were welded in packages by an electron-beam welding technique

- LP cylinder last stage bucket 1,200 mm long made of titanium alloy (the annular area of the stage is 11.3 m^2, circumferential velocity over the periphery is 658 m/s) which have been in successful operation since 1983;

- LMZ turbines for PPNs are using one-piece forged LP turbine rotors weighing 80 t without boring at 3,000 rpm

Russia has successful experiences in the operation of 300- and 800-MW turbine unit without deaerators using direct-contact LP heaters where feedwater deaeration is provided, which is sufficient with a neutral-oxygen water chemistry regime.

The turbine extractions for industrial and heating applications are controlled by adjustable diaphragms.

The turbine manufacturers produce for their turbines' condensers with copper-nickel, titanium alloys, and stainless steel tubes. They produce water heaters for heating systems; condensate and feedwater heaters, both surface-types with tubes made of various materials and direct-contact; deaerators; evaporators; oil coolers and heat exchangers for district-heating systems; and auxiliary heat exchangers.

Synthetic fire-resistant OMTI oil has found application in LMZ turbine lubrication and control systems. Some turbines of 300 and 800 MW have been in operation some tens of thousands hrs using OMTI in the lubrication systems. It is also used on all LMZ 1,000-MW turbines at NPP.

For Russian manufacturers wide standardization of technical solutions is typical in the design and manufacture of steam turbines. Identical blade profiles, nozzle blades and bucket, especially of last stages, valves, seals, bearings and other component and systems are used.

Steam turbines of smaller capacity, up to 25-30 MW, are manufactured by the Kaluga Turbine Works (KTZ, Kaluga) to drive electric generators and feed pumps, and by the Nevsky Works (NZL, St. Petersburg) to drive electric generators and compressors.

High-speed steam back-pressure turbines of about 12 MW and condensing turbines of 11-12 and 17 MW are produced for driving feed pumps. Similar turbines of 6.5 MW are manufactured to drive air blowers (fans) of 800 and 1,200-MW unit boilers.

2.4. Gas-Turbine Unit

The former U.S.S.R. and later Russia has long-term experience in GT operation at TPS and main gas pipelines. In the national economy GT unit developed and constructed by power machine manufacturers, and also aircraft and marine derivatives are used.

The land GT are mostly applied in Russia to pump natural gas at main pipe lines. Currently the total capacity of GT unit used for this purpose amount to about 40 GW with unit capacity ranging from 4-25 MW. The most upgraded unit operate at a turbine inlet temperature of 1,060-1,100 °C and an efficiency of 32-35 percent. However, the majority of these unit belong to the first generation with uncooled bucket and vanes, and they operate at a turbine inlet temperature of 760-920 °C.

Such GT are supplied in packages of works manufacture. As a rule, prior to shipment, GT are tested at the works rig under load or at nominal gas temperature. Most of GT operate in severe climatic conditions, and in low-population areas lacking the required infrastructure, transport communications, and transmission lines. Some of the gas pipeline GT' parameters can be found in Table 7.

GT units are made with a free running power turbine and can be used for electric generator driving applications via reducing gear.

For power generating GT characteristics, refer to the same Table 7.

Large heavy-duty GT unit dedicated for electric power generation were manufactured by LMZ (St. Petersburg) and KhTZ (Kharkov); heavy-duty GT unit for the gas industry were manufactured by NZL (St. Petersburg) and TMZ (Ekaterinburg, Urals). For the layout of a GT rated of 150 MW see Figure 12.

The big suppliers of 10- to 12-MW GT unit for electric generation and the gas industry are "Mashproject" and YuTZ in Nikolaev (Ukraine). Currently the Works (industry) produce(s) GT unit for the next generation of 2.5-25 MW turbines with better characteristics, particularly for the power industry. "Mashproject" has worked out, using it advanced technology, a single-shaft state-of-the-art GT rated at 110 MW [16]. This GT will be manufactured in cooperation with the Russian "Rybinskije motory" Works (Rybinsk, Upper Volga). The first GT of this type will be produced this year.

A large number of aircraft-derivative GT of 6.3 and 16 MW have been manufactured for the main gas pipelines by the "Trud" Aircraft engine enterprise in Samara (on the Volga River). Operation of the latest model, NK-36ST, has started at the gas pipeline. The Utility version [17] of this GT unit, NK-37 (Figure 13), is being tested on-load at the pilot plant. Some GT units of this kind have been ordered to be used in 80-MW CCP (2 GT + ST) which are now under construction. The design and supply of this CCP is performed by the Kirov Works (St. Petersburg).

In recent years, the activity of aircraft engine developers and manufacturers in marketing land (fixed) GT unit in Russia has increased. Based on their GT engines they have developed efficient utility and mechanical driving GT unit rated from 1.5-25 MW. Operation of such GT will be started in the near future. The data for the most promising unit are illustrated in Table 8.

Various gas-turbine manufacturers already have agreement or are conducting negotiations with leading Western firms (LMZ-Siemens, NZL and Saturn-ABB, Kirov Works and Rybinskije Motory-GE, etc.).

Some project using combined cycle unit have been developed in Russia with various types of GT. The data for the most efficient project is presented in Table 9.

The technologies of Russian aircraft engine manufacturers are at the top level. Yet, the heavy-duty GT manufacturers have fallen behind the leading Western firms in parameters and in the number of GT produced, in particular, for power generation. However, Russian manufacturers have designed many samples of high-efficient equipment for their GT.[18,19].

About 20 types of efficient air paths have been perfected for axial compressors ranging by flow from 30-700 kg/s, pressure ratio from 2 to 13, and adiabatic efficiency of 85-90 percent. In many cases, the compressor flow paths are provided by using the group stages of previously developed and operationally proven machines [19].

The development of high-temperature component for turbines are based on experimental investigations, mathematical modelling, and computer programs that allow for the calculation of thermal stress and the evaluation of the durability of component over all of the blades.

The vanes with deflector cooling systems have a long operating history with GTN-16 (TMZ) and GTN-25 (NZL) GT unit.

The first stage bucket with original internal cooling (Figure 14,c) had been used for the GTN-25 (TMZ) turbine some 10 years ago. When using 2.5 percent of the air taken past the compressor, the metal temperature of the bucket was reduced by 250 C at low (70 °C) temperature gradient.

For sufficiently long bucket of large GT unit, use is also made of channel and loop-type cooling systems that are capable of reducing the maximum bucket metal temperature to

800-825 °C with a turbine inlet temperature of 1,100 °C and cooling air flow of 1.7-3 percent.

The properties of Ni-based alloys used for blade manufacture of heavy-duty GT are shown in Table 10 [20]. The mechanical properties have been determined at 20 °C after ageing at 750 °C for 3,000-5,000 hrs. The creep-rupture strength is based on a service life of 20,000 hrs.

The most experience available now with a blade operating at up to 700-750 °C is with the alloy EI-893. At many GT unit, the blades made of this alloy have been in operation for over 60,000 hrs. To increase operability, the blades are protected against corrosion by coatings.

For the GT unit manufactured now, the forged bucket are made of EI-929VD, EP-800VD, and EP-957ID alloys. The cast blades are made of EP-539-LMU, TcNK-7 and ZMI-3 alloys.

Some years ago, casting with directional solidification had been mastered for manufacturing the bucket for GTN-25 unit (NZL) which have been in operation for some tens of thousands of hours. The directional solidification has markedly improved ductility and the creep-rupture strength of bucket [20]. The technology has been adapted to manufacture large cooled bucket.

Various types of combustors are in use for the Russian-made heavy-duty GT unit, viz., silo, can-type and annular. For all of these combustors stable and efficient firing of natural gas, and liquid fuel was obtained in various operating conditions and modes whenever required. The component of the combustors exhibited a long service life.

In designing the existing GT, little attention had been paid to NO_x emissions. Now, the combustors of existing GT have been modified to reduce NO_x emissions. For the new GT unit, low-NO_x combustors have been designed that satisfy the modern standards ($NO_x <$ 50 mg/m^3) without water/steam injection when using natural gas.

The work on direct coal combustion in GT was conducted in the U.S.S.R. as far back as the 60s. Then some 3- and 12-MW GT unit firing gases derived from underground coal gasification were constructed and put into operation. The gas used was similar in composition and properties to the coal-derived gas obtained by the air-blown Lurgi gasification method. Combustion of that gas caused no problems.

Intermediate air coolers, tubular and plate air heaters, heat-recovery boilers and water heaters for heating systems have been designed, tested and operated for long periods with different GT units

3. THE POWER INDUSTRY DEVELOPMENT FORECAST FOR RUSSIA

The essential goals of the Russian energy strategy are to promote social and economic revival of the country and increase the GNP, income, life standard and it quality, and reduce the man-made load on the environment [21].

The priority lies in increasing energy efficiency and conservation.

In 10-15 years a more effective use of natural gas and a larger share for it in domestic consumption are scheduled. The quality of coals will be improved by producing smaller amount of high-ash, high-sulfur coals through washing and benefication.

The development of the regions is planned in a way that will ensure their self-sufficiency in electricity, heat, and wherever possible in fuel, while preserving the United Power Grid of Russia.

If economically justified, smaller sources of electrical energy and heat will be provided as close as possible to the consumer. It will be based on economically efficient and ecologically clean technologies, particularly for coal TPS.

Some forecast made just after the collapse of the U.S.S.R. and at the start of the transmission of Russia to a market economy can be seen in Table 11. The forecast are based on the economical demands of the main regions of Russia and are still reasonable. Of course, the forecast could not take into account the depth and consequences of the economical crisis in today's Russia. However, with an optimistic view to the future and hope in the revival of the Russian economy, the figures of Table 11 are of present interest but are not attainable by the year 2010, as supposed, but by some later year.

One can see from Table 11 that for the addition of considerable new capacity, mostly fossil-fueled TPSs, is required to solve the social and economic problems, while increasing the standard and quality of life.

Coal is and will remain, in the near future, the basic fuel in Siberia and the Far East. It is also a very important fuel in the Urals and in the European part of the country. Coal consumption for power generation should double and constitute over 200×10^6 tfe/y in the future.

The prospect for the evolution of the Russian power industry are now uncertain. In recent years, due to economic difficulties and because of the transition to free market conditions, the consumption of electric energy was reduced and is going to decrease further. By 1995, electric generation is predicted at 850×10^9 kWh which is 3 percent lower compared to 1994.

The revival of the Russian economy is predicted in a long period of time. By various estimates, electric generation will reach the 1990 level in the years 2000-2010. In the near future, no high-investment construction of large TPS is planned. In 1994, only 25 hydro-power and steam turbines were put in operation for a total capacity of 2.4 GW, including an 800-MW natural gas fired unit at the Nizne-Vartovsk TPS in the Tumen region.

Currently in Russia, mostly in the Eastern and Central regions of Southern Siberia and the Far East, there are some coal-fired TPSs under construction located near brown coal open-cast deposit. Some of them, for example, the Gusinoozersk and the Kharanorsk condensing TPS are in energy-deficient areas. Both TPSs have been designed to employ 215-MW unit. At the Gusinoozersk TPS, 6 such unit are in operation and two unit are scheduled to be started. At the Kharanorsk TPS, the first unit is being prepared for start-up and 6 unit will be commissioned in all.

At the Berezovo TPS N.1, two 800-MW unit are in operation but the construction is not completed yet. The equipment for unit No. 3 is at the site. The Berezovo coal seam, where coal is the cheapest in Russia, can supply 4 unit now, and after further development can supply two additional TPS of 6.4 GW each.

Several cogeneration plant are under construction or being prepared for construction. They will be equipped with 320-670-t/h boilers and 80- to 185-MW turbines.

The main attention is being paid to the radical reconstruction of the existing TPSs and the preparation for using up-to-date technologies. The worn-out and obsolete equipment, which have an overall capacity of about 90 GW, will be put out of operation.

The analysis of energy use in Russia made by several independent Western and Russian organizations indicates that:

- even without the decommissioning of some NPP and

- provided that existing TPS will expire their service life there will be a considerable power deficit in Russia, if new capacities are not put into operation. The deficit are as follows:

Calendar year	2000	2010
Power deficit, GW	24-56	149-174

About 80 percent of the deficit is attributed to the European regions and Urals which have insufficient fuel resources.

The deficit can be partially covered by a life extension of the existing equipment together with the replacement of the worn-out component. This approach is economically justifiable mostly for cogeneration plant. It could be implemented for equipment with a total capacity of 10-15 GW by the year 2000 and another 10-15 GW by 2010. With reference what can be done by 2010, it will cover only 20 percent of the overall demand. The remaining deficit will be covered by construction of new power unit instead of decommissioning at existing TPS (in the same main building or at the same site). New construction will include both cogeneration and condensing TPSs. TPS retrofitting/repowering will be implemented along with increasing the efficiency (in particular, by increasing the share of combined heat and electricity generation) and decreasing the environmental impact.

Further growth of electric generation will depend on the rates of restoration of the country's economy. If they will be decelerated, and the energy saving be realized at a large scale and efficiently, a small number of relatively low-capacity new condensing plant will suffice, together with cogeneration plant, including those of low and medium capacity.

At higher rates of energy use, construction of some large condensing K-A and Kuzn coal-fired TPS in Siberia, the Urals, and maybe in the Volga River region will be needed. For such TPS, the use of 300- to 500-MW unit is under consideration.

Along with cogeneration plant, a significant fraction of the heat required for consumers will be generated in the boiler houses (district heating plant). The steam capacity of the boilers installed there will be from 1-2 to 160 t/h, while that of hot-water boilers, up to 200 Gcal/h (230 MW). Now, many of them are of low efficiency and operate with considerable SO_2, NO_x and fly ash emissions. The boiler houses could also be the places, where clean coal technologies could be applied.

The Energy Strategy is based on the fact that the coal industry will play the important role supplying the country with fuel, electricity and heat.

The strategy is to terminate the drop of coal production, stabilizing it at 250-270 $\times$ 10^6 t/y level, continue the restructuring of the coal industry with the greater share of the open-cut coal production and the closing of unprofitable enterprises by the year 2000. In so doing, the following options of coal production evolution are considered.

Coal annual production	Calendar year				
	1990	1993	1995	2000	2010
Maximum: 10^6 t	396	306	270	290	340
10^6 tfe	257	196	172	185	210
GJ	7530	5740	5040	5420	6150
Minimum; 10^6 t	—	—	260	250	300
10^6 tfe	—	—	166	160	190
GJ	—	—	4860	4690	5670

In the European part of the country the coal production will tend in general to decrease, while that in the Kuzn and K-A fields will increase to supply the regions of Siberia and the Urals where these coals will be fired at TPS. The remaining regions will, to a greater extent, use local coals. The brown coal production is supposed to be increased in the Eastern region of the country in the Irkutk district, Zabaikalie, Primorsk and Khabarovsk regions from about 50 $\times$ 10^6 t/y (17 $\times$ 10^6 tfe/y) produced at present to 90 $\times$ 10^6 t/y (30 $\times$ 10^6 tfe/y).

The problems of transporting the cheap K-A and Kuzn coals to industrialized regions of the Urals and the East of the European part of the country are rather acute. It is clear that the handling of a greater portion of coal to raise it heat value prior to transportation will be required along with possible development of special transport means and systems.

Economical estimates provide evidence about competitiveness of Kuzn and K-A coals as fuel for TPS in the Urals, Volga River region and, may be, in the areas to the East from Moscow. For interregional transportation, mostly Kuzn coal or processed, for example, briquetted, K-A coal will be involved. The demands in solid fuel for the Eastern Siberia and Far East will be covered by local production and shipment of K-A coals. The Peach coals will be used in the Northern regions, and the coals from the Eastern Donbas, in the South of the European part of Russia.

The Energy Strategy of Russia plans to distinguish the central and local energy control functions.

The Federal Governmental Bodies will control the activity of Federal power systems and the nuclear power industry, manage the strategic energy resources, establish the standards and norms of safety and efficiency of energy object, supervise their observance, license economic activity of utilities and regulate the activity of natural monopolies by legislative and normative act and by holding their shares.

The local (regional) authorities will set up functioning of the enterprises that are not part of the Federal power systems, issue licenses for construction of new and expansion of the existing TPS and specify additional environmental requirement for them.

Together with the Federal bodies, they will license the activity of the enterprises belonging to the Federal power systems and responsible for reliable electricity and heat supply to the consumers, and also check the execution of the licenses granted.

The regional authorities will have the right required to provide for stable energy supply to the territories under their jurisdiction, state control of electricity and heat tariffs, establishing the energy market at their territories, including participation of independent producers.

The Energy Strategy of Russia declares the equal opportunities for domestic and foreign organizations and companies in the course of mutually beneficial cooperation and welcomes any forms of participation for foreign capital in the power industry of Russia.

4. CLEAN COAL TECHNOLOGY DEMONSTRATION PROGRAM (CCTP) OF U.S. DEPARTMENT OF ENERGY

4.1. General

In the U.S., the clean coal technology program (CCTP) has been underway since 1985 aimed at:

- environmental protection by elaboration and industrial-scale use of economically effective and environmentally low-impact technologies for coal-based electricity generation;
- ensuring the reliable and safe power supply to the country through the development of processes and equipment for direct, or with some conversion, efficient use of coal instead of oil and natural gas;
- increasing the competitiveness of American industry in the external market through the development and industrial application of the above technologies and equipment.

Within this program R&D and demo project are being developed. The scale of the latter is so selected that the result obtained are sufficient to assess all aspect of designing, constructing, and operating industrial plant [22,23,24].

The program for ecologically clean technologies for coal utilization is financed by the government in cooperation with commercial firms, and other institutions. The program builds demo plant using selected technologies that show the most promise for advancement to the market during the next decade. The capacity of such plant shall be sufficient to get evidence (data) on their commercial potential.

Traditionally, DOE undertakes long-term R&D programs for TPSs that have high risk and the potential to be effective. Since the fulfillment of the program at commercial scale was a high risk, DOE undertook full or almost full financing.

The clean coal technology program is realized on the basis of agreement between the government and commercial firms bearing at least 50 percent financing. The patent right to inventions are the property of all sponsors.

The program was based on five independent competitive solicitations.

The project were selected from the offers by commercial firms that were based on technologies that the given companies thought to be most promising.

The execution of the project is supervised by the Pittburgh and Morgantown Energy Technologies Centers.

Currently 47 project selected in 5 competitions are underway in accordance with the Clean Coal Technology Program that was started in 1985. The total cost of the project is over $\$6.5 \times 10^9$, including $\$2.7 \times 10^9$ out of the Federal budget.

At the initial stages the program was mostly oriented to project that would decrease SO_x and NO_x emissions responsible for acid rains. Various devices and systems to decrease these emissions are being developed within the framework of 19 project at a total cost of $\$688 \times 10^6$. Among them are project of NO_x reduction (Table 12) at power plant with an overall capacity of 1,700 MW, SO_2 reduction at power plant of 770 MW (Table 13) and combined NO_x and SO_2 reduction (Table 14) at power plant with an overall capacity of 765 MW. The technologies have been designed to be adaptable to newly constructed and existing TPSs. With reference to the majority of the project, test result and operating experience are available. Some of the project have already been completed and some of them are being implemented for commercial use. The total data on the efficiency of various gas cleaning technologies can be found in Table 15.

Later, as CCTP progressed, greater attention was being paid to the development of advanced AFBC and PFBC technologies, CCPs with integrated coal gasification (IGCC), and other technologies (Table 16) that offered higher efficiencies, reduced CO_2 and rather low SO_2 and NO_x emissions, and also better performance. 15 project, at a total cost of $\$4.7 \times 10^9$, belong to this group. The project are being realized at new TPS with a total capacity of 1200 MW and existing TPS of total capacity of 800 MW.

The operating result for the majority of the power plant will be available in the second half of the 1990s.

CCTP also includes 5 project for processing coal to clean fuels at a total cost of $\$467 \times 10^6$ and 6 project for industrial power plant that offer increased efficiency and better ecological parameters at a total cost of $\$1.118 \times 10^9$. Also included is an integral facility for coke-free iron production and electricity generation with a CCP firing coal-derived gas at a total cost of $\$825 \times 10^6$.

4.2. Project for Reducing Emissions from Conventional Boilers

To reduce NO_x emissions, low-NO_x burners and staged combustion with overfire air are used. These technical solutions ensure NO_x reduction by 40-60 percent for a small capital investment (< \$10/kW), some loss in efficiency (< 0,2 percent), and an operating cost penalty. The implementation of these measures do not require much time as shown in Table 12. (Project 7-46 and 7-48 in Table 12, and 7-66, Table 14 are examples of this technology. The project numbers correspond to pages in the 1993 Program Technology Update where these project are described).

Similar technology is a low-NO_x cell burner retrofit (developed) demonstrated by B&W on one of it own boilers (Project 7-42, Table 12). According to the project description the lower burner fires all fuel while the upper burner is used to supply the secondary air.

More complex but more effective measures are associated with reburning. The technology proves to be simpler and more efficient (60-70 percent of NO_x reduction) when natural gas is used as reduction fuel (Project 7-44, 7-70, Table 12). Micronized coal reburning (Project 7-52, Table 12) and cyclone boiler reburning (Project 7-40, Table 12) are more difficult to realize and are less efficient. NO_x emissions in this case are reduced by 50-60 percent. Application of reburning technology needs a \$17-65/kW capital investment, reduces unit efficiency by about 0.25 percent, and increases operating cost by about 0.1 cent/kWh (Table 15).

CCTP includes some project using SCR technology for the control of NO_x emissions (Project 7-50, 7-64, 7-68, Tables 12 and 14) and SNCR technology (Project 7-76, 7-72, Table 14).

In non-catalytic systems that use urea 50-70 percent of the NO_x are reduced with a capital cost of \$5-20/kW and a cost of generation increased by 0.11-0.13 cent/kWh (Table 15).

The ammonia-based catalytic system can reduce 80-90 percent of NO_x at a capital cost of \$80-90/kW (combined with SO_2 control, \$250/kW).

In implementing SCR systems, the technologies of both foreign (Project 7-50, 7-64) and domestic (Project 7-68, Table 14) companies were applied.

The data on various NO_x control technologies are shown in Table 15.

Wet and wet/dry flue gas cleaning systems have been used for many years to reduce SO_x emissions at U.S. TPSs. Limestone and lime are employed as sorbent with the final product (usually a mixture of $CaSO_3$ and $CaSO_4$), after additional oxidizing (neutralization) and mixing with ash, being dumped to disposal areas.

Under the CCTP some simplified SO_x cleaning systems are being designed. Among them Project 7-66, 7-76, 7-70 are technologies that inject limestone and various grades of lime into the upper part of the furnace, and humidify the sorbent-containing flue gases in the gas duct to enhance sulfur capture.

To this group belong technologies of sorbent (lime) solution or slurry injection into the gas duct. In some cases the slurry is injected such that it is dispersed along the duct, as it is done in Project 7-56, Table 13. Besides the CCTP project, U.S.A. companies have developed many other simplified SO_x control systems: E-SO_x featured by using the entrance of the ESP as the location of the wet/dry reactor; LIDS, which inject a slurry of ash enriched with unused sorbent into the gas duct, etc.

Implementation of such systems requires relatively small capital investment ($30-100/kW). At considerable sorbent consumption rates their efficiency is 50-70 percent maximum, while the cost of removed sulfur turns out to be rather high ($350-700/t). The by-product of FGD are not commercial grade.

Realization of wet/dry sulfur removal in special reactors (Project 7-54, 7-58, Table 13) enables increased efficiency of up to 80-90 percent and better sorbent utilization, but, of course, at a higher cost of the system.

Under Project 7-54 the technology of wet/dry SO_x removal in a CFB with high particle concentration (from 460-1830 kg/m^3) has been developed . The concept is based on increased surface contact between the lime slurry and acid gases on the particle surface which becomes commensurable with the contact surface typical for wet SO_x control systems. In this case, heat and mass transfer are enhanced, injection of slurry is simplified, and – because of recirculation – lime utilization increases up to about 80 percent. Reaction in the CFB needs less time; 2-3 seconds at a gas velocity of 6-6.5 m/s as compared to 10-12 seconds at

1.2-2 m/s in conventional wet/dry reactors. It is important that the cleaning action of the fluidized particles in the reactor causes no deposit, and the temperatures can be lower than those in conventional wet/dry reactors. The cost of such a wet/dry sulfur removal system can be about 25 percent less, and the total expenditures – despite more expensive sorbent – 15 percent less than in the case of wet limestone FGD.

More efficient sulfur removal systems are required when using high sulfur coals where even 90 percent SO_2 removal efficiency may be insufficient to meet environmental control requirement. The CCTP project include 2 advanced wet limestone FGD technologies of 95 percent efficiency (Project 7-60 and 7-62, Table 13). They are based on improved processes that employ cheap natural limestone as sorbent in minimum amount, operate close to the stoichiometric value, and produce commercial-grade gypsum. For these reasons, despite the complex nature, the high investment cost ($180-250/kW), and decreasing of unit efficiency by about 1.5 percent, the cost of 1 t of removed sulfur is competitive, and with high sulfur coals may be the cheapest technology.

Under Project 7-60, a wet limestone advanced FGD system with a scrubber suitable to clean gases from several boilers has been designed and installed at the Bailly TPS. It employs an advanced single-stage process based on an increased rate of straight-flow washing and better oxidation in the same scrubber to produce commercial-grade gypsum. It also employs an effluent evaporation system.

A jet-bubbling reactor has been designed for FGD at the Yates Plant Unit No. 1, a 100-MW unit firing high sulfur bituminous coal (Project 7-62).

The reactor with a 12.8-m diameter and height is made of fiberglass-reinforced plastic. The flue gas bubbling through the limestone slurry is accompanied by SO_2 absorption, neutralization, gypsum crystallization and washing from the particulate. Air is also bubbled through the slurry oxidizing $CaSO_3$ to $CaSO_4$. Fiberglass-reinforced plastic is used to manufacture the wet flue gas duct, a 115-m high stack, and 8.54-m diameter by 7.63-m high limestone slurry tank. Fiberglass plastic undergoes no corrosion/erosion, which is the case with the same element manufactured from stainless steel. Therefore, no preheating of wet cleaned gases is required to prevent condensation in the gas duct located downstream. Only 2 stages of the separator (mist eliminator) are installed past the absorber to remove water droplet entrained from the latter. Aerodynamic separation of the condensed moisture is provided in the stack throat.

Several integrated NO_x/SO_2 emission control technologies are being designed in CCTP project.

Project 7-76 most completely utilized simplified technologies of NO_x/SO_2 emission control. The base is a 100-MW unit boiler using down-fired burners with over-fire air port in the bottom of the furnace. The boiler fires low-sulfur (S = 0.4 percent) bituminous coal. To reduce NO_x formation low-NO_x burners and two-stage combustion is applied. For further NO_x reduction urea is injected at the furnace outlet. Sulfur is captured by Ca- and Na-based sorbent injected before economizer (540 °C) and air preheater (315 °C).

The SNOX technology (Project 7-64, Table 14) is well known. It has been used for several years at a commercial 300-MW unit in Denmark. Flue gases are catalytically deeply cleaned of NO_x/SO_2 along with the production of saleable sulfuric acid. No data is available on the system's operational characteristics, cost, or the intention of Denmark electric utilities to apply this technology at any other TPS under construction in that country.

The efficiency and prospects for application of SO_2/NO_x, and, sometimes, ash emission control systems that are undoubtedly technically interesting, under Project 7-68, 7-72 and 7-74 (Table 14) are difficult to assess because only predesign data are available. They indicate only technical feasibility and the terms of implementation of the processes and the determination of the major equipment profile.

4.3. Advanced Power Technologies Project

The CCTP includes two project that use circulating fluidized-bed boiler unit.

At Nucla Station (Project 7-16) a 420-t/h CFB boiler with hot cyclones for fly ash separation has been constructed, tested in detail, and is now in operation. The boiler has been designed to fire 3 types of Western coals with sulfur content of 0.4 -0.8, 1.5, and 0.5 percent. Limestone is in-bed injected for sulfur capture.

The final atmospheric fluidized-bed boiler project under the CCTP is Project 7-18 with a goal to design the largest U.S. boiler, a 227-MW unit capable of delivering 175 t/h of 4.3 MPa process steam. The experience known to date has been accounted for in the project. The sulfur capture is scheduled at 92 percent. In addition to using state-of-the-art combustion measures, ammonia/urea will be injected into the gas duct running from the furnace to cyclones to reduce half of the in-furnace formed NO_x. Much attention has been paid to maintaining optimal boiler modes. The start of test is scheduled for the beginning of 1998.

Under Project 7-32 a system of coal combustion in a slagging cyclone has been designed. Two cyclones with a total capacity of 50 MW are planned to be installed at the Healy station in Alaska. The cyclone is in fact a horizontal water-cooled cylinder slightly inclined in the direction of the gas exit. It employs staged fuel and air feed and pulverized limestone injection to capture SO_2. Further SO_2 capture will be in the wet/dry cleaning system. The CaO-containing fly ash removed in the baghouse is used to prepare the sprayed slurry.

As fuel, a mixture of 50 percent run-of-mine and 50 percent waste coal with high ash content and lower heating value is fired. To facilitate removal of the liquid slag, air fed to the cyclone is preheated by firing 25-40 percent of the coal in the precombustor. Seventy to eighty percent of the fly ash is removed as molten slag. The hot gas containing the incomplete combustion product is directed to the furnace, and additional air is fed to the furnace for complete combustion. In such a system, SO_2 emissions are reduced by more than 90 percent, maximum NO_x emissions are 86 mg/MJ (220 mg/m^3), and maximum particulate emissions are 6.5 mg/MJ (16.5 mg/m^3).

The slagging horizontal cyclone combustor included in Project 7-98 is close in concept to the above design. It specific features are ceramic lining and wall cooling by secondary air, which enables the use of compact cyclones to retrofit various types of boilers while leaving their steam/water path unchanged. The design capacity of the cyclones is 6.74 MWt.

Formation of NO_x in the cyclone combustors is reduced by oxygen-deficient combustion; for SO_2 capture limestone is injected. The molten ash and the sorbent that captures the major amount of the coal sulfur are separated on the cyclone walls. Injection of additional amount of sorbent into the boiler duct increases the sulfur capture efficiency.

Under the CCTP, seven project that demonstrate IGCC plant are being developed. Some data on these project can be found in Tables 16 and 17. The total cost is about $\$3 \times 10^9$, including about $\$1 \times 10^9$ from the Federal budget.

Project 7-28 and 7-30 are based on the technology of coal-water slurry, entrained-flow, oxygen-blown gasification which has been commercially demonstrated.

At the Wabash River TPS (Project 7-30) a two-stage gasification of the slurry prepared from a 2.3 to 5.9 percent S bituminous coal will be realized. The coal consumption will be

2,315 t/d (96.5 t/h). In the first stage, gasification occurs creating molten ash which is removed as liquid slag from the gasifier lower part. No ash melting occurs in the second stage. The raw gas is cooled in heat exchangers and cleaned in the conventional low-temperature system where particulate, NH_3, and sulfur compounds are removed. Ceramic filters capture the fly ash and return it to the gasifier. The cleaned mean-calorie (medium Btu) gas is preheated with steam generated in the raw gas cooling system, and then fired in the GT combustor. Superheated HP steam is generated in the heat-recovery boiler downstream of the GT. Also, HP steam produced in the raw fuel gas cooling system is superheated there. Both steam streams are expanded in the steam turbine available at the existing TPS site.

This single-train gasification system will be the largest in the U.S.A.

The designed sulfur cleaning efficiency will be 98 percent, NO_x reduction will amount to 90 percent, and SO_2 emissions will be < 86 mg/MJ, NO_x < 43 mg/MJ.

The Polk Power Station (Project 7-28) will use single-stage gasification of Illinois 6 and Pittburgh 8 bituminous coals having a sulfur content ranging from 2.5-3.5 percent. Two parallel desulfurization systems will be employed in the project: conventional low-temperature and high-temperature in a moving bed of zinc titanate sorbent. To decrease NO_x formation, the cleaned syngas will be mixed with nitrogen from the air separation plant. The design sulfur removal efficiency will be 96 percent (98 percent, for industrial plant), NO_x will be reduced by 90 percent; and the emissions of SO_2 will be 90 mg/MJ, NO_x 116 mg/MJ.

The third CCP project (Project 7-20) using entrained-flow gasification is underway at the Springfield TPS. There, at 23 t/h (550 t/d) dry dust of Illinois 6 coal will be gasified in a two-stage air-blown gasifier with liquid slag removal at the first stage. The raw coal-derived gas temperature will be 1000 °C before being reduced to 540 °C in the gas cooler. At this temperature, the gas will be cleaned of coke particles; first in a cyclone, and then in a fines filter. The particles will be returned to the gasifier, and the gas will be directed to the desulfurization system with a zinc titanate moving bed. The sulfur removal efficiency will be 99 percent, and the NO_x will be reduced by 90 percent. The SO_2 and NO_x emissions will be less than 43 mg/MJ.

Fluidized-bed air-blown gasification of bituminous coals is underway according to Project 7-24 and 7-26.

At the Piñon Pine Station (Project 7-24), 812 t/d (34 t/h) of the Utah 0.5-0.9 percent S crushed coal will be gasified. The limestone is also in-bed injected to capture the sulfur and to prevent the conversion of fuel nitrogen to NH_3. The temperature of the raw coal-derived gas at the gasifier outlet is 925 °C. The fly ash is separated in a cyclone and returned into the gasifier. The gas is cooled to 595 °C and sulfur is additionally removed in an oxide metal bed. When sulfur is captured in the fluidized bed, CaS is formed which forms after oxidation, together with the fuel ash, agglomerated particles suitable to be disposed. The coal-derived gas is fine cleaned of particulate mater in ceramic filters. To reduce NO_x formation steam is added to the cleaned coal-derived gas.

The design sulfur cleaning efficiency is 94 percent, and NO_x emissions will be reduced by 90 percent. The emissions of SO_2 and NO_x will be 30 mg/MJ.

Test are planned using West Virginia bituminous coal with S = 2-3 percent.

An industrial CCP using the above gasification technology will be 43.7 percent efficient and ensure 98-99 percent cleaning of sulfur when high-sulfur coals are gasified. The emissions of SO_2 will be below 19.5 mg/MJ and those of NO_x below 23 mg/MJ.

At the Toms Creek Station (Project 7-26) a fluidized-bed system that will gasifiy 390-t/d (16.5-t/h) of coal will be realized. Using a calcium base sorbent, 90 percent of the coal sulfur is captured in the bed. The raw coal-derived gas will leave the gasifier at an outlet temperature of 980-1040 °C and be cleaned of the fly ash in two stage cyclones. The gas is cooled to 540 °C and the remaining sulfur is removed in a zinc titanate fluidized-bed reactor. Particulates are removed by a ceramic filter. Sulfur removal efficiency is 99 percent, with emissions of 24 mg/MJ SO_2 and 39 mg/MJ NO_x. The efficiency of the industrial 270-MW CCP will be 44 percent.

Another gasification technology is being designed under Project 7-22 for the Camden TPS. Gasification of high-sulfur (S = 3 percent) bituminous coal from West Virginia will be done in an oxygen-blown, moving-bed reactor with liquid slag removal. The gasifier output will be 1,685 t/d (67.5 t/h). The lump coal will be used and the fines will be briquetted.

The raw gas will be washed to reduce it's temperature and remove tars, oils, ammonia and particulate. Combustibles will be returned to the gasifier. Conventional low-temperature cleaning will remove 99 percent of the S. The cold-gas gasification efficiency will be 89 percent and the carbon conversion will be 99 percent.

The clean syngas is mixed with nitrogen from the air separation plant and is preheated prior to being fed to the GT.

SO_2 and NO_x emissions will be less then 43 and 65 mg/MJ respectively (NO_x reduction will be 90 percent).

Part of the syngas, after additional cleaning and saturation with steam, will be used to feed a 2.5-MW electrochemical generator, based on the molten carbonate fuel cell, that will be integrated into the CCP circuit.

One more gasification project, Project 7-96, will be realized within CCTP. There the 2,910 t/d (121 t/h) plant for direct reduction of iron ore without using coke will be integrated with the CCP circuit of 150 MWe. The process system includes an iron ore reduction furnace and the melter gasifier arranged below it. The capacity of gasifier is 2,550 t of coal/d (106 t/h). It's purpose is gasifying coal and melting iron. A reducing gas is generated in the gasifier and the heat required for iron melting is released. The excess of coal-derived reduction gas exiting the furnace is cooled, cleaned, and compressed before firing in a GT.

Reduction of emissions by more than 85 percent is achieved through the capture of ore and coal sulfur in the reducing furnace with limestone injection under effective control of the process. Since no coke is required for iron production there is no environmental pollution resulting from it's production.

The combined process energy efficiency is 35 percent higher, compared with alternative processes, due to the better utilization of the coal's sensible heat, volatiles, and integration with CCP for production of electricity.

It is expected that the final SO_2 and NO_x cleaning efficiency will be above 90 percent and at least 97 percent, respectively; SO_2 emissions will be 10.5 mg/MJ, and NO_x emissions will be 5.2 mg/MJ.

The general requirement for IGCC is the possible use of various kinds of coal. The gasification modules are being designed to provide flexibility when the CCP unit capacity is changed.

Project of CCP with various coal gasification and combustible gas cleaning technologies are at different stages of commercialization.

Testing demo IGCC plants will start in 1995-1996. Oxygen-blown gasification systems with low-temperature gas cleaning are at a higher stage of development (Project 7-28, 7-30, 7-22) than other technologies under development. The specific cost of such systems will be $1500-2000/kW with LHV coal combustion efficiency at 40-42 percent.

It is thought that the development and use of high-temperature gas cleaning systems will enable a future increase in the IGCC efficiency to 47 percent and create (the opportunity for) large commercial-size unit.

Along with higher efficiency typical for CCP with coal combustion in PFBC it is possible to exclude special de-SO_x systems by adding limestone or dolomite to the coal. At moderate combustion temperature in the bed a small amount of NO_x is formed. The by-product in this case is dry ash which can be utilized. A CCP using first generation bubbling PFBC has been realized at the Tidd Station in the U.S. (Project 7-14) and has operated for a long time. The 110-MW, 9 MPa, 495 °C steam unit was redesigned by replacing the conventional boiler with a PFBC boiler fed with 1.3 MPa air from a 16-MW GT. The PFBC temperature is 860 °C, and the gas turbine inlet temperature is 830 °C. The steam turbine integrated with CCP operates at a reduced load of 55.9 MW. The CCP net capacity is 70.5 MW at 34.5 percent efficiency.

According to the DOE CCTP, the same technology is being designed for the New Haven Station (Project 7-8), a 340-MW (net) PFBC. A GT of 75 MW and a steam turbine with reheat are used there. The PFBC furnace pressure is increased to 1.6 MPa, the bed temperature is 870 °C, and the CCP efficiency is 42.2 percent. The design SO_2 capture and NO_x reduction are 95 percent and 80 percent respectively.

Also under the CCTP, a 70-MW CCP using a PCFB is being designed (Project 7-10) with a bed temperature and pressure of 870 °C and 1.2 MPa. The gas will be cleaned in a cyclone and a ceramic filter. The steam generated in the PCFB boiler will be expanded in an existing steam turbine. After redesigning, CCP efficiency will be 34.5 percent. Considering the parameters of the steam turbine, the efficiency will be increased by 15 percent.

With a 90 percent sulfur capture, SO_2 emissions will be 300 mg/MJ. Fly ash emissions will be 13 mg/MJ, and NO_x emissions will be reduced by 70 percent. The CCP start-up is scheduled for 1996. The project development (preliminary design) has been made for a 45 percent efficient commercial CCP with a PCFB boiler and additional topping combustor.

Work is under way to design a second generation CCP with PFBC. To this end, the following is planned:

(1) replacement of the GT with a U.S.-made unit;

(2) incorporation of a pyrolyzer and gas hot filter;

(3) increasing the GT inlet temperature.

The pyrolyzer ensures partial coal gasification producing a 925 °C combustible gas. The remaining carbon is removed as coke (char) and is fired in the PFBC combustor at 870 °C. The gases after the pyrolyzer and PFBC combustor are cleaned in high temperature filters. The GT inlet temperature is increased due to firing the combustible gas formed in the pyrolyzer in the top (topping) combustor.

The design validating test will be carried out at the Wilsonville, Alabama plant to be started in 1995. The test modules of the plant will be used to investigate heat transfer and refine the conditions for removing the total heat released in the PCFB. The bubbling-bed system is supposed to be used in the pyrolyzer. The demo plant employs a 4-MW GT. The top (topping) combustor is designed for an outlet temperature of 1290 °C. Before the GT, the gases will be air cooled to 1080 °C.

The plant is intended to play an important role in speeding up and simplifying the development and test of integrated GT clean coal technologies. After construction is completed, it will employ 5 modules. Apart from the advanced PFB combustor and GT, the system will use gasification in a transport reactor, several hot gas cleaning rigs, a fuel cell, and the associated gas treatment systems.

Within the framework of CCTP (Project 7-12), a 95-MW equivalent capacity, demo, CCP using a second generation PFBC is being designed and will be constructed at the Calvert City Station. It will employ a 38-MW GT, model W251B12, a 35-MW steam turbine, and produce 141 t/h of process steam.

In the GT with external, indirect coal combustion, the compressed air is preheated in the boiler to be further expanded in the GT. Coal combustion and flue gas cleaning are made close to atmospheric pressure as in conventional utility boilers.

Predesign works dealt with this technology for 280-320-MW CCP proved a possible efficiency of 49.5-51 percent with a simple GT operating at a firing temperature of 1260-1370 °C, and steam parameters of 16.4 MPa, 593/593 °C. In the boiler path in ceramic heat exchangers the air is heated up to 1090 °C. Further temperature rise is obtained by fuel combustion in the additional combustor. The boiler furnace in the active burning zone is screened by wall superheaters.

Under the CCTP (Project 7-36) an externally fired combined-cycle demo system with a ceramic heat exchanger and hot-air operated GT will be constructed at Warren Station in Pennsylvania.

Work has been conducted in the U.S. on direct P.C. or coal-water slurry (CWS) combustion in the GT combustors for a long time. Some result are illustrated in Table 18. In all project, two-stage external combustion systems were used. At the first stage under fuel rich conditions carbon was gasified accompanied by the formation of low-calorie combustible gas which was cleaned between the first and second stages of fly ash, and – in the Allison and Westinghouse technologies – sulfur that was captured by sorbent injected at the first stage. According to the Solar technology, sorbent was injected at the second stage. In all cases at the second stage high amount of excess fresh air was added for full burnup of combustibles contained in the gas. Shown in the third column of Table 18 are the result of test conducted by the Allison with a full-size 4-MW GT. In large utility CCP with a coal-fired GT predesign, a net efficiency of 42 percent was calculated. Despite the promising result of the research, no construction of a demo plant is now planned.

4.4. Result Obtained in CCTP Project

Many project using low-NO_x burners and reburning are either close to completion or are already completed with good result.

Under Project 7-46 with wall-fired burners and over-fire air at a nominal 500-MWe load, NO_x emissions were reduced to 172 mg/MJ (440 mg/m^3). The emissions were found to vary insignificantly when the load dropped to 200 MW. When compared to the initial level of 546 mg/MJ (1400 mg/m^3), NO_x emissions were reduced by 68 percent, including 43 percent due to burner retrofit and 25 percent because of staged combustion (over-fire). The test were conducted with bituminous coal of 28.6 MJ/kg (LHV) and 30.0 MJ/kg (HHV). The coal contained 10 percent ash, 33 percent volatiles, 72 percent carbon, 1.7 percent sulfur and 1.4 percent nitrogen.

The amount of combustibles in the fly ash at 500-MW load increased from 5.5-8.0 percent despite considerably more fine coal dust.

	Mesh 200 undersize,%	Mesh 50 oversize,%
Initial state	63	2.8
Advanced burners and over-fire air	74	0.6

This fact caused boiler efficiency to decrease by 0.25 percent. By increasing excess air, carbon loss can be decreased to the initial level. In this case, however, NO_x emissions increase to 228 mg/MJ (589 mg/m^3).

Under project 7-42 cell burners were redesigned (see above). When firing different bituminous coals with S = 1.1 percent, the average NO_x concentration at boiler full load was found to drop from 500 mg/MJ (1280 mg/m^3) to 205-240 mg/MJ (530-615 mg/m^3), 55 percent on average. The fly ash combustibles content was 1.1 percent and the carbon loss was 0.2 percent. The unit efficiency was not changed and no boiler corrosion rate change was observed.

Reduction of NO_x formation by 37-48 percent at full-load was attained under Project 7-48 when testing a low-NO_x burner in a tangential-fired furnace with various combinations of burner rows, an additional air feed just above the row and separately above the burner area. The test were carried out firing various Eastern bituminous coals with S = 2.5-3.0 percent.

The reconstruction and testing of boilers with the new low-NO_x burners and reburning, using natural gas as a reducing fuel was made at 3 coal TPS employing different firing systems (Project 7-44, Table 12).

Basic result of test can be seen from the Table below:

Quantity	Location of test, furnace specifics		
	Hanneping, tangential-fired	Lake Side, cyclone	Denver, wall-fired burners
Unit output, MWe	71	33	172
NO_x initial emission,			
mg/MJ	320	435	310
mg/m^3	820	1115	795
NO_x attained level,			
mg/MJ	105	150	110
mg/m^3	270	330	285
NO_x reduction, %	67	66	64
Share of natural gas, %	18	22.5 (20-26)	12.6 (5-19)
Reduction of boiler efficiency, %	0.3-1.1	0.59	0.45
Over-fire air, %	—	28.7	19.3

Reburning, using coal dust as a reducing fuel, was implemented on a 100-MW unit cyclone boiler (Project 7-40) with the result that follow.

Quantity	Coal Grade	
	Lamar bituminous, S = 1.8%	Powder River Basin subbituminous coal, S = 0.6%
NO_x initial emissions,		
mg/MJ	505	445
mg/m^3	1290	1140
NO_x attained level,		
mg/MJ	230	165
mg/m^3	590	420
NO_x reduction, %	55	63
Carbon loss, %	1.5	0.3
Increase of carbon loss, %	0.1	0.0

In Project 7-56, 50 percent SO_2 capture was attained on 73.5-MW unit boiler firing bituminous coal with S = 1.5-2.5 percent when sorbent – slurry of hydrated calcite and pressurized hydrated dolomite limes – were sprayed in the gas duct.

The evaporation of droplet and the absorption of SO_2 were completed in 2 s. No deposit were observed in the duct. The system operated reliably and it is easily automated.

When testing a simplified wet/dry SO_2 control system under Project 7-66, LIMB-Coolside, 61 percent of SO_2 capture was reached in LIMB system on a 105-MW unit firing 3.8 percent S coal using lignolime as sorbent. In the Coolside process using hydrated lime at a Ca/S = 2.0 and a Na/Ca = 0.2, 70 percent SO_2 capture was reached at 11 °C of the approach-to-saturation temperature.

In SO_2 control system testing with LIFAC technology (Project 7-58) 20-30 percent SO_2 was captured using limestone injection into the top of a 60-MW boiler furnace. Another 40-55 percent SO_2 was captured in the activation reactor where flue gas containing CaO – the limestone calcination product – was humidified with injected water. Thus, the overall SO_2 cleaning efficiency reached 80-85 percent. To recover the flume opacity above the stack, the leaving gas temperature, which was reduced since SO_2 control installation, was increased to

93 °C by mixing the leaving gas with a small amount of hot gas.

Using technological methods in Project 7-76, NO_x emissions were reduced from 665 mg/MJ (1700 mg/m^3) to 240 mg/MJ (615 mg/m^3), i.e., by 63-69 percent without increased carbon losses. With in-furnace urea injection, NO_x emissions were further decreased to 128 mg/MJ (330 mg/m^3), that is another 40 percent with an $NH_3/NO_x = 0.85$. The overall NO_x reduction was greater than 80 percent. Urea injection causes N_2O formation in the amount of 20-35 percent of the total reduced NO_x. With the injection of pretreated urea to yield NH_3 only 3-10 percent N_2O was formed.

With in-duct injection of dry calcium hydroxide (Ca/S = 1.75-2.0) followed by gas humidification to 16.5 °C of the approach-to-saturation temperature not more than 25 percent S was captured. Even in this case hard to remove deposit were formed in the fabric filter.

Injection of dry sodium sesquicarbonate and bicarbonate before the air heater in the ratio of Na/S = 1.2-1.5 enables an 80-89 percent SO_2 capture to be obtained. Despite formation of 20-35 ppm of NO_2 a colored plume above the stack was not observed.

As for Project 7-54, good result were reported in testing wet/dry SO_2 removal in a CFB reactor with a high concentration of particles.

The reactor with an equivalent capacity of 10 MWe was constructed on the gas duct bypass of the 150-MW unit boiler. In demonstration test on 2.7 percent S (in some periods up to 3.5 percent S) and 0.12 percent Cl coal the system operated with an average SO_2 reduction of 90-91 percent at a molar ratio of $Ca(OH)_2/SO_2 = 1.40 - 1.45$ and an approach-to-saturation temperature of 10 °C. Previously the system operated normally without deposit formation at an approach-to-saturation temperature of 2.8 °C using coal with low Cl content, and at 10.0-12.8 °C of the approach-to-saturation temperature with Cl content no more than 0.3 percent. With such approach-to-saturation temperature values and $Ca(OH)_2/SO_2 = 1.4$, SO_2 capture was 98-100 percent in preliminary test. The effect of operating conditions on SO_2 reduction can be seen below.

Approach-to-saturation temperature, °C	4.4	10.0	10.0
Coal Cl content, %	0.004	0.04	0.12
SO_2 removal efficiency, %:			
at $Ca(OH)_2/SO_2 = 1.0$	79.5(72-92)	70(67-77)	84(78-95)
at $Ca(OH)_2/SO_2 = 1.3$	94.0(88-99)	85(78-92)	93(90-95)

The advanced wet SO_2 control systems have been in operation for years (Project 7-60, 7-62).

The average system efficiency at the Baily TPS 500-MW unit (Project 7-60) firing bituminous coal with 2.0-4.5 percent S content was 94 percent. During special test over 98 percent efficiency was attained. With regular unit operation SO_2 emissions were 165 mg/MJ (420 mg/m^3). Auxiliary power requirement were 5.3 MW (< 0.9 percent), and the gas path pressure drop was about 800 Pa. The SO_2 control system operated reliably. The 2-year average availability factor of the whole complex was close to unity (99.996 percent). During that period, 121,300 t of SO_2 was removed, 198,800 t of limestone was consumed, and 356, 000 t of 97.2 percent quality gypsum was produced.

The average water flow rate was 355 m^3/h with an average effluent discharged at 18.4 m^3/h. Waste waters contained 4,560 ppm chlorides, < 2,500 ppm sulfates, 19 ppm fluorides, 14.1 g/m^3 dissolved solids and had a pH = 8-9.

The SO_2 control system using a bubbling reactor (Project 7-62) was put into operation in March 1993. It enabled 98.7 percent S capture, collected 90 percent of particles > 1 micron and up to 50 percent, of particles < 1 micron that were left after cleaning by a 99 percent efficiency ESP, and utilization of over 97 percent of the limestone when operating at low pH value. The SO_2 removal system final product is saleable gypsum produced at rate of 7 t/h. The power consumed by the SO_2 control system constitutes about 1.5 percent of the unit output with a possible reduction by process optimization. No liquid deposition from the flume above the stack was observed even at 100 percent air humidity. During the first 5,000 operating hours the system availability was 98 percent.

The 35-MW equivalent capacity system of flue gas cleaning was installed as a bypass (slipstream) on a boiler firing coal with S = 3.4 percent. The system used a baghouse to remove particulate matter and SNOX technology to catalytically remove SO_2 and NO_x. The flue gas cleaning efficiency of SO_2, NO_x, and particulate matter was 96 percent, 94 percent and 99.9 percent respectively. The system produced 25.5 t/d of 93 percent sulfuric acid with no solid wastes. The majority (99 percent) of flue gas toxics were removed in the SNOX process itelf, with or without the baghouse The system has been in operation for 5,700 hrs.

When testing a 5-MW equivalent capacity SNRB system (Project 7-68) the following result were obtained using real combustion gases of bituminous coal with S = 3.4 percent.

Sorbent	Ratio	Temperature, °C	Sulfur Capture,%
Commercial hydrated lime	Ca/S = 2.0	430-470	80
Sugar hydrated lime	Ca/S = 2.0	430-470	90
Sodium bicarbonate	Na/S = 1.0	220	80

At 430-470 °C, 90 percent NO_x reduction was attained with zeolite catalyst and ammonia injection providing an NH_3/NO_x = 0.9. Particulate removal by the baghouse was 99.89 percent.

Out of the advanced electric power generation technologies, the PFB coal combustion CCP project is the most mature (Project 7-14, Table 16).

The CCP test began at the end of 1990. Since that time comprehensive investigations have been conducted. Problems were detected and eliminated with preparation, feed, and distribution of the coal-water paste used as fuel; uniform in-bed coal combustion without impermissible ash agglomeration; ensuring nominal steam capacity by increasing the surface of in-bed tube bundles; and cleaning combustion product of fly ash in cyclones and removal of separated ash. The modifications and repairs to restore operability after damages took time. Ultimately the CCP total operating time by mid-1994 was 7,880 hrs.

When assessing CCP availability one should take into account that the plant had been designed without backup systems and component which were the practice with industrial (commercial) unit. It is also important to note that CCP availability increased constantly with operational and test experience.

CCP featured good ecological characteristics. At full load and a 3.2 m high bed a 90 percent S capture was obtained at a Ca/S = 1.15-1.35, and 95 percent S capture at a

Ca/S = 1.5-1.8. NO_x emissions were 65-77 mg/MJ.

Considering the experience obtained in mastering similar plant in Sweden and Spain, the PFBC technology can be considered ready for commercial application.

Project 7-16 is less complicated and also relates to the same group. The Nucla Station CFB boiler designed under this project was tested during 15,700 hrs firing various coals with S = 0.4-0.8 and 1.4-1.8 percent. At bed temperature of 880 °C, the following result were obtained:

Ca/S Ratio	1.5	4.0
Sulfur Capture, %	70.0	95.0

NO_x emissions were < 145 mg/MJ (375 mg/m^3) with 77 mg/MJ (200 mg/m^3) on the average, and coal burnup was between 96.9-98.9 percent. The presence of combustibles in the fly ash was evidence of incomplete combustion: only a small fraction of it is attributed to combustibles in the bottom ash and the flue gas CO. The boiler efficiency was 85.6-88.6 percent.

The new development for power generation are advanced cyclone combustors enabling radical reduction of SO_2 and NO_x. Such a cyclone (Project 7-98) operated on an industrial boiler under heat loads from 5.57-1.76 MW. It was tested during 900 hrs firing 8 various bituminous coals containing 19-37 percent volatiles and 1.0-3.3 percent sulfur. When limestone was used in the cyclone as sorbent in the ratio of Ca/S = 2.0, up to 58 percent S capture was observed. It increased reaching 80 percent with sorbent addition in the boiler furnace. NO_x emissions were 160-184 ppm (130-150 mg/MJ, 330-380 mg/m^3). Removed from the cyclone combustor as liquid slag were 55-90 percent of the ash and sorbent. The inert slag is a waste product. The combustion efficiency was > 99 percent.