Advanced Technologies Towards the New Era of Energy Industries

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For more than half a century, NKK has been constructing infrastructure for energy industries such as pipelines and storage facilities for petroleum, fuel gas, city gas, and LNG. NKK has recently focused on providing solutions to potential requirements of customers and markets. This paper introduces new technologies and products developed by NKK's Energy Industries Engineering Division.

1. Introduction

NKK's engineering business for the energy industries started with pipeline construction in the late 1940's. This endeavor combined the pipe manufacturing and welding technologies that were accumulated through its long history of steel pipe production and shipbuilding. Many pipelines were constructed in Japan in response to the rapidly increasing energy demand that resulted from high economic growth. During the same period, NKK undertook the construction of a variety of pipelines and associated facilities such as trunk lines and distribution networks for city gas, long-distance pipelines for transporting indigenous natural gas, gas pipelines for thermal power generation, petroleum pipelines, and storage systems for these energy resources[1]. Through this process, NKK built up the basic technologies that constitute the backbone of engineering capability for constructing highly reliable pipelines. These capabilities include advanced corrosion prevention technology to ensure the safety of pipelines during their long service period after construction[2] and technology to evaluate earthquake resistance performance[3].

NKK developed the technology for building LNG storage tanks in the early 1970's when Japan started to import a large amount of natural gas from overseas. Utilizing its high-level welding technology, NKK successfully commercialized a stainless steel membrane type LNG storage tank and participated in the establishment of infrastructure for urban energy providers[4]. NKK also developed technology to efficiently use energy, such as cogeneration systems and district heating and cooling systems[5]. Thus, the construction of infrastructure for urban energy supply became NKK's core engineering business.

In the meantime, NKK developed a variety of new technologies for constructing energy infrastructure to shorten the period of construction and to mitigate the environmental impact of pipeline construction. One example is the arched pipeline laying method, named NK-RAPID, which allows pipelines to be laid in the ground without digging open trenches. Another example is the automatic shield tunneling method named NK-FAST (Fully Automated Slurry Transportation)[6]. NKK's energy industries engineering business is not limited to the design and construction of hardware, but also actively develops software-related technology for supporting the operation of these infrastructures. Examples include pipeline monitoring and leak detection systems, operation planning and assistance systems, inspection and maintenance systems[7], LNG tank management systems, and BOG treatment systems[8].

Further, in response to the increasingly serious global warming problem, NKK is developing environmentally friendly, highly efficient energy use technologies as represented by distributed power generation. NKK commercialized a SOFC (Solid Oxide Fuel Cell) system with the cell developed by the Siemens Westinghouse Power Corporation[9].

NKK is also developing new technologies to improve the overall efficiency of distributed energy use systems, particularly cold heat production and use systems for urban areas. These technologies include an air conditioning system using latent heat of a newly developed cooling medium, clathrate hydrate slurry, and a new cold heat production system using waste heat[10]. These development projects are being carried out under the financial support of the national government. NKK is developing technologies that facilitate the diversification of energy sources and that permit expanded use of small to medium sized, low-grade gas fields. One example is GTL (Gas-to-liquid) technology to produce and use DME (Dimethyl-ether). Another is the technology to supply and use hydrogen as an energy source, taking advantage of the fact that NKK has a steel plant located in a metropolitan area.

In order to expand these engineering businesses in the field of energy production and use, NKK considers it essential to establish the following technologies:

- Construction technology that provides low environmental impact, low cost, and high safety,
- Software technology that provides solutions to customers' requirements, and
- Energy use technology that provides high efficiency and energy saving.

This paper introduces some of the unique technologies, called "Only-One Technology", that represent the future course of NKK's engineering businesses for energy industries: (1) NK-FAST, which fully automates shield tunneling operations, (2) Win GAIA, which supports the management of pipeline operations, (3) clathrate hydrate slurry air conditioning systems, which allow highly efficient use of cold heat and provide large energy savings, and (4) SOFC systems, which are energy efficient and environmentally friendly.

2. Automatic spoil transportation system for long-distance shield tunneling operation: NK-FAST

2.1 Background of the development

The non-excavating tunneling method is increasingly employed to minimize the ground traffic interference caused by underground construction in urban areas for pipelines, sewage systems, and power transmission and communication cables. The development of a long-distance, automatic tunneling method is needed.

One technical obstacle to long-distance tunneling was how to increase the propulsion force. This issue was essentially solved by the use of a lubricating layer between the propulsion pipe and the surrounding soil. A major issue that remains to be solved is how to transport the discharged spoil efficiently over long distances.

In addition, the development of an automatic tunneling operation that does not require operators underground is desirable, not only for saving labor cost, but also for ensuring the safety of operators. Accidents such as the sudden inflow of a large amount of water due to a local heavy rainfall can be extremely hazardous for underground operators, but little progress has been made to date in this regard except for remote control of the tunneling machine.

NKK and Nippon Kokan Koji K.K. have endeavored to make improvements in the small-bore tunneling method that are very advantageous for long-distance tunneling. These include extending the tunneling distance and improving the safety by making the tunneling operation automatic. As a result, the two companies were successful in jointly developing NK-NTS, a new long-distance tunneling method that permits automatic tunneling over extremely long distances of more than 1500 m. One component technology developed for this tunneling method is the highly efficient, automatic spoil slurry transportation system named NK-FAST.

2.2 Outline of NK-FAST system

A conventional small-bore tunneling method is schematically illustrated in **Fig.1**. Mud is adjusted in accordance with the soil properties at the tunneling site and then sent from the ground level to the drilling machine, where it fills the space between the cutter and earth. The pressure of the mud prevents the ground from collapsing while the drilling operation progresses. The mud mixed with the soil that results from drilling is called spoil. The spoil is sent into the spoil tank located behind the cutter at the tip of the drilling machine. The spoil tank is connected to a vacuum pump on the ground level through the spoil transportation pipe. The spoil in the tank is transported to the ground level by the airflow caused by vacuum suction and separated in the receiver tank.

The conventional method requires a chamber-man to be positioned at the tip of the drilling machine in addition to the drilling machine operator. The chamber-man's job is to separate large rocks contained in the spoil, crush clay lumps and shove the spoil into the spoil transportation pipe. Spoil shoving requires the experience and intuition of the chamber-man who observes the air intake. Shoving too much spoil into the pipe causes clogging, which requires time consuming work to remedy. Conversely, shoving too little spoil for fear of clogging causes the spoil tank to fill up. This condition forces the drilling work to be temporarily stopped or slowed down, shortening the distance that can be drilled in a day. Remote control of the drilling machine by an operator at the ground level has already been put into practice, but the chamber-man's job has not yet been automated. As shown in **Photo 1**, this is a severe job physically and mentally that is performed in an extremely confined space at the tip of the drilling machine.

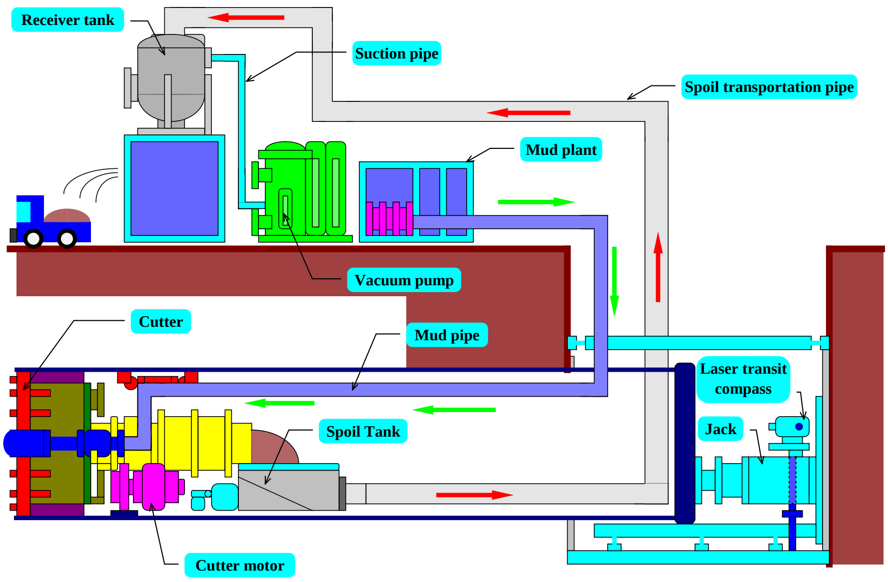

Fig.1 Schematic diagram of small-bore tunneling method

Photo 1 Chamber-man at work

The NK-FAST system automated the chamber-man's job and made spoil transportation highly efficient by controlling the fluidity in the spoil transportation pipe and by forming optimum spoil plugs. Thus, the automated spoil transportation system eliminated a severe and dangerous job that required experience and skill. It also opened the way to achieve an extremely long distance tunneling operation by extending the spoil transportation distance and increasing the transportable amount of spoil. Further, it shortened the pipeline construction period by increasing the drilling speed. The NK-FAST system is composed of four sub-systems, as schematically illustrated in **Fig.2**: spoil processing, spoil slurry transportation, remote-controlled observation, and communications.

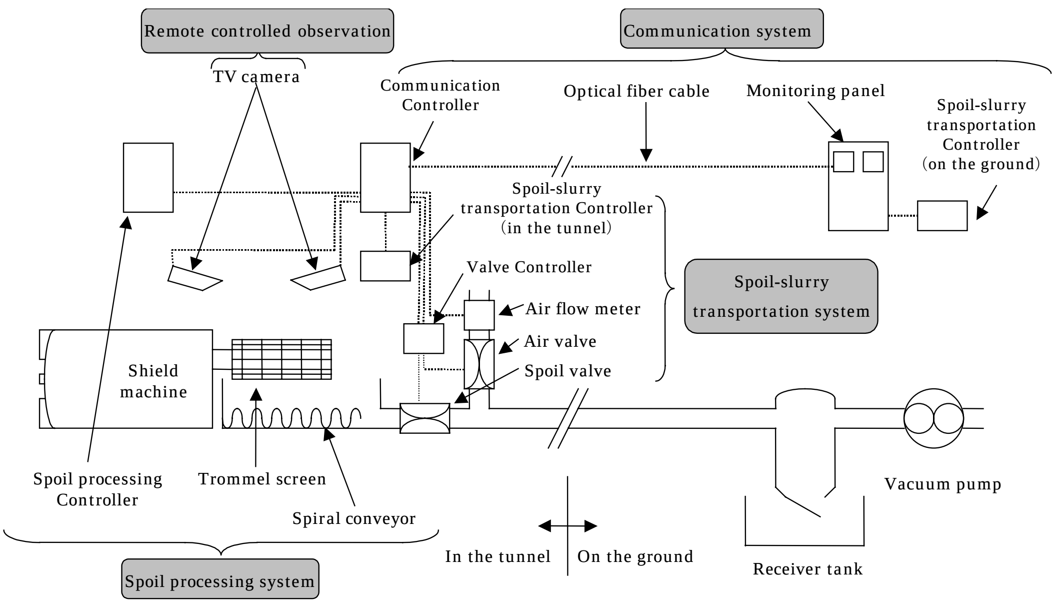

Fig.2 Schematic diagram of NK-FAST system

2.3 NK-FAST system

2.3.1 Spoil processing system

The spoil processing system automatically performs the job previously performed by the chamber-man: separation of rock, crushing of clay lumps, and shoving of spoil into the spoil transportation pipe. As shown in **Photo 2**, this system is composed of the trommel screen and spiral conveyor, both of which are remote-controlled from the ground level.

The trommel screen was newly developed specifically for the NK-FAST system. This screen not only separates rock, but also crushes clay lumps by the tensioned wires on the inner surface. The spiral conveyor moves spoil, small rock, and crushed clay lumps that pass through the trommel screen to the inlet of the spoil transportation pipe.

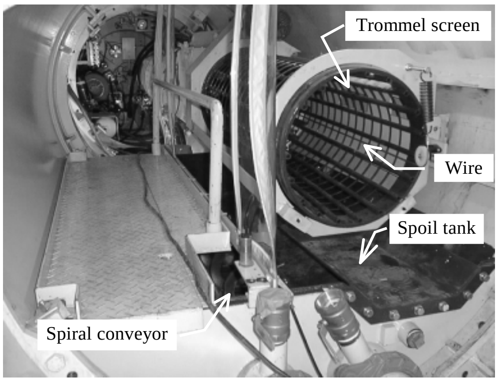

Photo 2 Spoil processing system

2.3.2 Spoil slurry transportation system

The spoil is generally highly viscous. Since the vacuum suction transportation system can only generate an effective pressure differential of about one atmospheric pressure, continuous soil transportation, where the entire length of the pipe is filled by the spoil, is not possible. No system currently exists other than plug transportation, where spoil and air are alternately transported by suction. In the conventional method, the operator uses experience and intuition while shoving the spoil little by little into the pipe along with air to form an optimum plugged condition in the pipe for transporting the spoil.

In the NK-FAST system, as shown in **Fig.2** and **Photo 3**, the spoil valve at the tip of the spoil transportation pipe, and the air valve connected to the pipe just behind the spoil valve, alternately take spoil and air into the pipe to form the plugs. The amount of spoil transported is maximized by controlling the length of time during which each valve is opened or closed and the frequency of opening and closing. The optimum plug condition is thereby achieved to prevent the clogging of the transportation pipe. In **Photo 3**, the controller panel is installed in the underground shield machine, but when it is installed on the ground level, spoil transportation is controlled remotely from there.

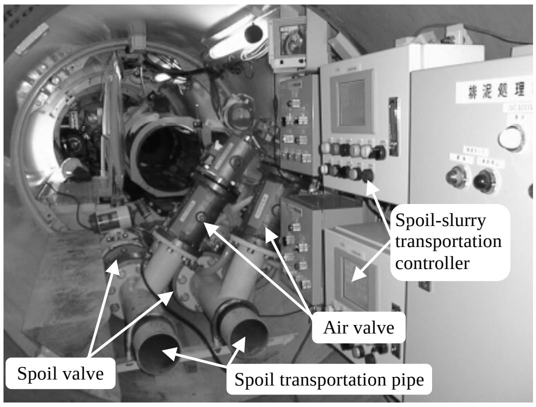

Photo 3 Plug formation equipment and controller

2.3.3 Remote-controlled observation and communication systems

As shown in **Photo 4**, multiple CCD cameras, microphones, and headphones are installed around the tip of the spoil transportation pipe to allow observation from the ground level of spoil properties, spoil processing, spoil suction into the transportation pipe, etc. A videophone connects the ground-level observation post and the inside of the shield machine.

The observation panel on the ground level is also connected to the communication control panel in the shield machine by a optical fiber cable for two-way transmission of the audio-visual, measurement, and control signals that are required to control the spoil processing and transportation systems.

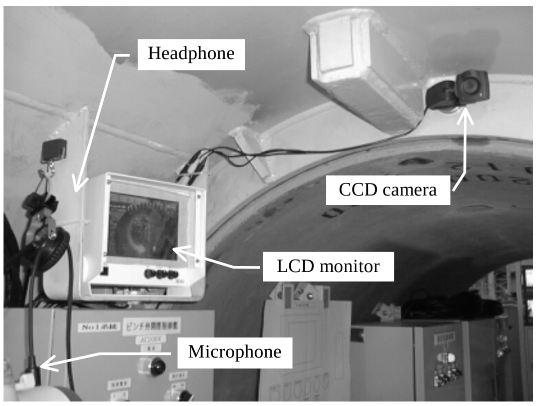

Photo 4 Remote-controlled observation system (videophone)

2.4 Application to actual pipe-laying work

2.4.1 Long-distance tunneling operation under lake bottom

This system was applied to lay a gas distribution pipeline below the bottom of the Lake Hamana-ko in Shizuoka Prefecture. The nominal diameter of the drill machine was 1200 mm, and the total length was 811 m. This was the world-first long-distance pipeline laying work performed below the bottom of a sea or lake.

Previous experience suggests that the drilling speed rapidly decreases when the drilling distance exceeds about 500 m due to decreased spoil transportation efficiency. In the case of the Lake Hamana-ko, the time required to drill a unit distance using the conventional method rapidly increased at around 450 m. However, after changing to the NK-FAST system, the time required was shortened to about two-thirds that of the conventional method.

In this case, remote control of the drilling machine was not used, and an operator was positioned at the tip of the drilling machine. However, the chamber-man, who was previously required in addition to the drilling machine operator at the tip of the drilling machine, was eliminated. For the conventional method, another underground operator was required at the starting side shaft to open and close the air suction valve to increase the efficiency of soil transportation. This air valve operator was also eliminated by the NK-FAST system.

The ground operator observed the conditions underground by using the audio-visual signals at the ground level, and good communication was maintained between the ground operator and underground operator by the videophone. Because of these aids, adequate operational instructions were quickly issued, increasing the work efficiency.

2.4.2 V-shaped steep gradient tunneling operation

A two-span tunneling operation with a V-shaped vertical cross-section was required to lay a cable under a road. The nominal diameter of the drilling machine was 1000 mm, and the total lengths of the spans were 575 m and 585 m. This drilling distance is not excessive, but one span required steep gradients of plus or minus 5 degrees to avoid underground obstacles. Thus, there was concern that the escape of the underground operator might be difficult in case of emergency. Therefore, the NK-FAST system was employed along with the remote control of the drilling machine from the ground level to avoid having any operator underground. This was the first case where the small-bore tunneling method was applied without using any underground operator.

No operators were underground at any time in either of the two spans during the tunneling operation except when underground equipment needed maintenance or adjustment. Thus, the safety of the operators was ensured. Before the drilling work was started, it was thought that the spoil transportation pipe might clog at the bottom of the V shape, but no such clogging occurred, and the spoil was smoothly transported.

2.5 Summary

The highly efficient, automatic spoil transportation system “NK-FAST” was developed in combination with the extremely long distance tunneling method “NTS”. Application to actual tunneling operations demonstrated its advantages, which include a shorter construction period and higher efficiency. In addition, operation of the system is safer because of its fully automatic underground operation, which is a first for a small-bore tunneling system.

3. Gas distribution network supply planning and operation assistance system: Win GAIA

3.1 Background of the development

The demand for natural gas as clean energy is expected to grow rapidly in the future, and wide deregulation and revisions of the related laws are being discussed toward full liberalization of the gas industry. Thus, Japan’s natural gas market is moving into an era of mega-competition, where operation will be under a completely new framework. The operation of a natural gas distribution network will be more complex due to the open access system and resultant diversification of supply sources, as well as a new gas transportation consignment system. The gas industry needs to be prepared for these institutional changes and to optimize the capital investment plan for meeting the changing market in the future. Under these circumstances, a system is required that can quantitatively monitor the current state of operation of an increasingly large and complex gas distribution network, schedule gas transportation based on appropriate excess capacity management, and assist in taking optimum countermeasures during emergencies.

3.2 Evaluation of operation of gas distribution network

A gas distribution network is a lifeline for society and must be highly reliable. The gas distribution network needs to be operated in accordance with the fluctuation of gas demand to ensure stable supply. In addition, the operation must incorporate factors such as response delays caused by the compressibility of gas, line packing by the positive use of gas compressibility, and the buffer effect for leveling demand fluctuations. These gas compressibility effects increase with the increasing size and operational complexity of a gas distribution network. However, conventional steady flow analysis cannot deal with these compressibility phenomena, and unsteady flow analysis is required. Conventional unsteady flow analysis methods are limited in that the speed of analysis is slow, and they cannot analyze large-sized network problems.

3.3 Outline of the system

In order to solve these problems, NKK developed a new system for supply planning and operation assistance of gas distribution networks. The core of the new system is a high-speed, unsteady flow analysis simulator that is several tens to several hundreds times faster than analysis by conventional systems of NKK. The system configuration is shown in **Fig.3**. The system has three major functions.

3.3.1 Off-line planning assistance function

This function is composed of components for building a gas distribution network model and for performing the planning assistance simulation. Off-line unsteady flow analysis of an existing or planned distribution network is performed considering the effect of compressibility for optimizing the operation and the capital investment plan. The high-speed core simulator permits effective case studies based on various operation scenarios for a large-scale gas distribution network, which were previously difficult to analyze. The system can be used for various studies to make the operation more effective. Examples include studies of maintenance plans and emergency countermeasures for an existing distribution network, evaluation of the possibility of starting new supply to a large-scale customer, expansion of the transportation capacity by using the buffer effect, and reduction of the peaks in the production or receiving amounts. The system can also optimize the capital investment and management plans that determine the type of equipment that needs to be expanded, along with its timing and location, in anticipation of future demand increases and supply source diversification. An image of the computer screen used in the off-line planning assistance is shown in **Fig.4**.

3.3.2 Real-time status monitoring function

Real-time unsteady flow analysis uses on-line pressure and flow rate data transmitted from various locations on an operating gas distribution network. Sophisticated operational status monitoring information is provided that cannot be obtained from a conventional, simple monitoring control system. For example, the real-time simulation function on the computer can reproduce the current transmission status of a distribution network. The current computed results are continuously compared to measured values for leak detection. When a significant discrepancy is detected between a pair of values, such as due to damage caused by third-party construction or an equipment abnormality, a warning is quickly issued and the location of the abnormality is determined.

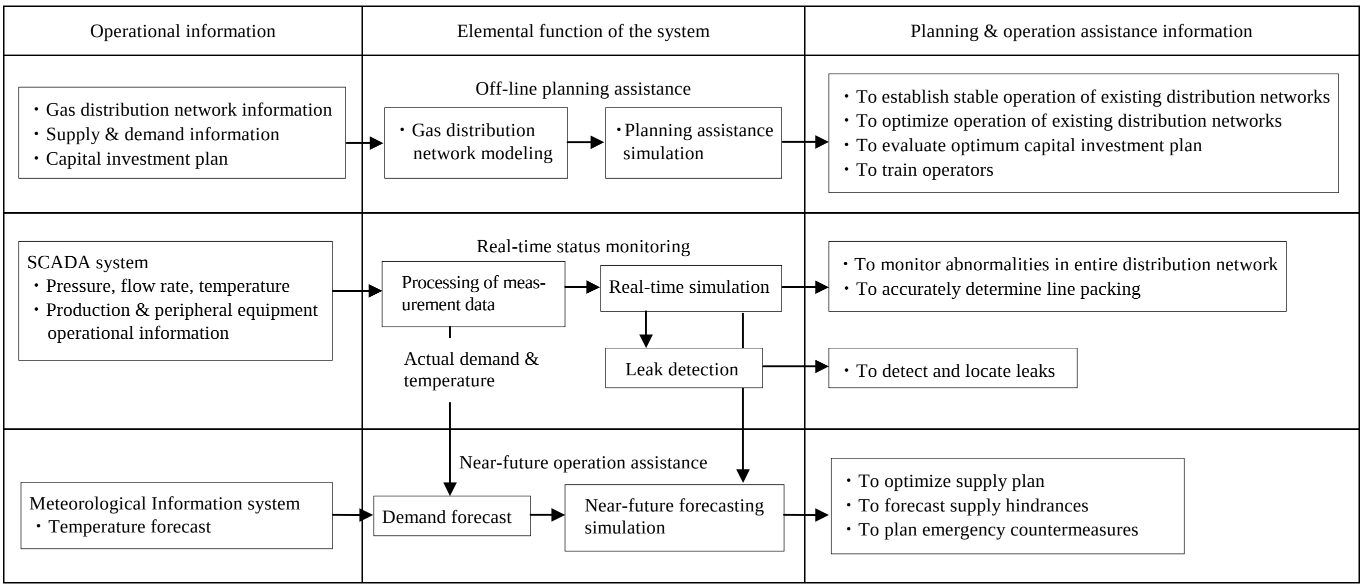

Fig.3 System configuration

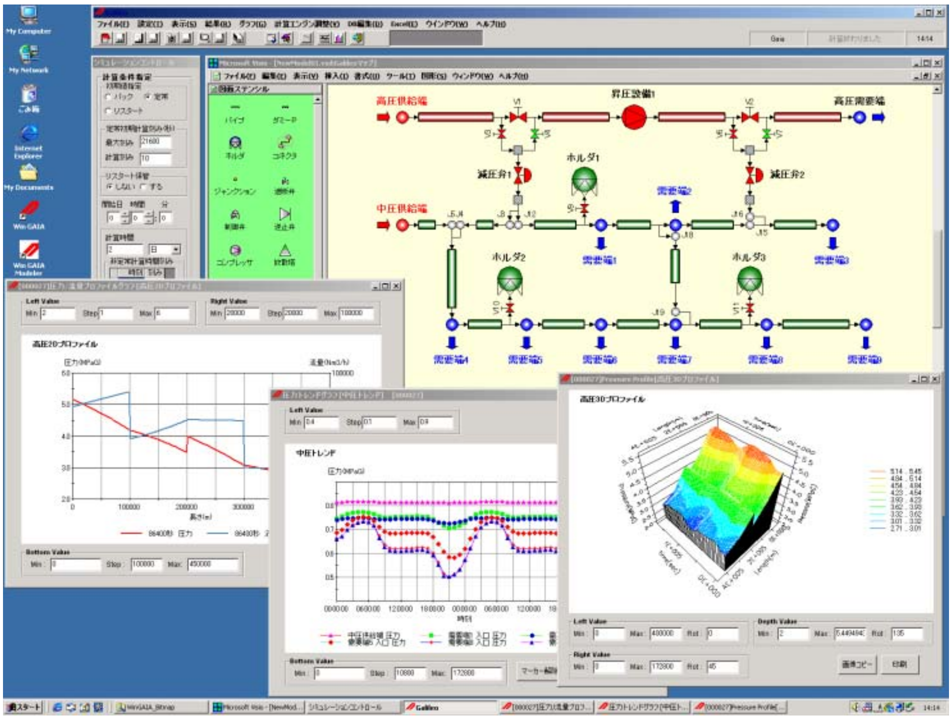

Fig.4 Screen image of Win GAIA off-line system

3.3.3 Near-future operation assistance function

The transportation status of an operating gas distribution network is markedly affected by the demand conditions. These conditions vary according to the annual season, day of the week, time of day, and ambient temperature, as well as to changes in network conditions caused by factors such as planned maintenance work. For the near-future operation assistance function, a highly accurate demand pattern is forecasted at each demand point. Near-future simulation is performed based on the latest demand forecast, network conditions, and supply operation scenarios that will be put into practice. Thus, this function optimizes the supply operation and manages excess capacity, while taking into account the response delay caused by gas compressibility.

3.4 Summary

The "Win GAIA" gas distribution network supply planning and operation assistance system developed by NKK is used in-house as an engineering tool for designing new gas distribution networks. The Win GAIA system was also furnished to outside city gas distributors and gas pipeline operators as both on-line and off-line systems, where it has gained an excellent reputation. In addition to sale of the system, NKK uses it to analyze network conditions for the request of other companies and to engineer the solution for constructing optimized gas supply systems based on the expertise accumulated within the company as NKK's solution engineering business.

4. Hydrate slurry air conditioning system

4.1 Background of the development

Power used by air conditioning accounts for a significant portion of energy consumption in the residential and commercial sectors, and is increasing year by year. In the 21st century, energy saving policies are becoming increasingly important for reducing carbon dioxide emissions and protecting the global environment. The development of revolutionary technology is desired that can produce large energy savings. In addition, the development of peak power demand leveling technology is desired because air conditioning loads are generally concentrated in the daytime.

Currently, cold-storage air conditioning systems that use water or ice as the cold-storage medium are being promoted. Cold water cold-storage systems have a lower cold-storage capacity than ice-based systems with the same size storage tanks. However, ice-storage systems consume much more electric power because the coefficient of performance of the refrigerator is less than that of cold-water-storage systems.

NKK developed a new type of cooling medium called "clathrate hydrate slurry" that is a mixture of liquid-phase clathrate hydrate and water[10]. The new cooling medium has a greater cooling capacity than water in the temperature zone of 5 to 12℃, which is generally used for room cooling. It also has excellent properties for transporting heat. Large energy savings are expected by using the newly developed clathrate hydrate slurry in air conditioning systems.

In this section, the properties of the clathrate hydrate slurry are introduced along with the air conditioning system that uses it as a cooling medium.

4.2 Features and properties of clathrate hydrate slurry

Clathrate hydrate is a medium that has latent heat. It is a chemical compound in which water particles form network structures like cages (clathrate crystals), and the space in the network structures is filled with guest particles of water-dispersible powder. Various substances can be used as the water dispersible powder for forming clathrate hydrate. Gas-phase clathrate hydrate, which uses gaseous substances such as CFC and methane as guest particles, is well known. The newly developed clathrate hydrate is a liquid-phase hydrate that uses TBAB (tetra-n-butylammonium bromide) as the water dispersible powder.

When the aqueous solution of the water dispersible powder is cooled down while being fluidized under atmospheric pressure, clathrate hydrate particles with intermediate sizes of 40 to 60 μm are formed in the aqueous solution. Thus, clathrate hydrate slurry with the fluidity as shown in **Photo 5** is obtained.

Table 1 shows features of the clathrate hydrate slurry.

Photo 5 Clathrate hydrate slurry

Table 1 Features of the clathrate hydrate slurry

(1) The slurry is stable under atmospheric pressure, contrary to gas-phase clathrate hydrate.
(2) It has latent heat in the relevant temperature zone (5 to 12℃), which gives it a coefficient of performance of refrigerator that is more advantageous than the system use ice.
(3) It can be used not only as a cold-storage medium, but also as a high-density, cold heat transportation medium in place of cold water.
(4) The same types of piping and heat exchangers are used as in cold-water systems.

The water dispersible powder used for forming the slurry is a chemical substance approved by the Law Concerning the Examination and Regulation of Manufacture, etc. of Chemical Substances. It is not subjected to more stringent laws such as the Safety and Health Law, the Poisonous and Deleterious Substance Control Law, or the Fire Services Law. **Table 2** shows the results of toxicity tests.

The aqueous solution has high thermal stability, so repeated use does not change its thermal properties.

Table 2 Toxicity test results

Acute toxicity	LD_{50} : Oral toxicity on rats ♂1414mg/kg ♀1542mg/kg
Fish toxicity	LC_{50} : Oryziatidae for 96 hrs 3340mg/kg

4.2.1 Characteristics of clathrate hydrate formation

Fig.5 shows the relation between mass concentration of the aqueous solution and the formation temperature of clathrate hydrate. This curve is called the clathrate hydrate formation line.

When the mass percentage of the water dispersible powder in the clathrate hydrate is equal to its mass concentration in the aqueous solution, the mass concentration in the aqueous solution will remain constant as the aqueous solution is cooled, even though the amount of clathrate hydrate in the slurry increases. During this process, the temperature of the clathrate hydrate slurry remains nearly constant. In experiments, the temperature of the aqueous solution remained constant at about 11.8℃ at a concentration of 40.5 wt%. The hydration number of the clathrate hydrate was estimated at about 26 from this fact. This type of clathrate hydrate is called the first clathrate hydrate.

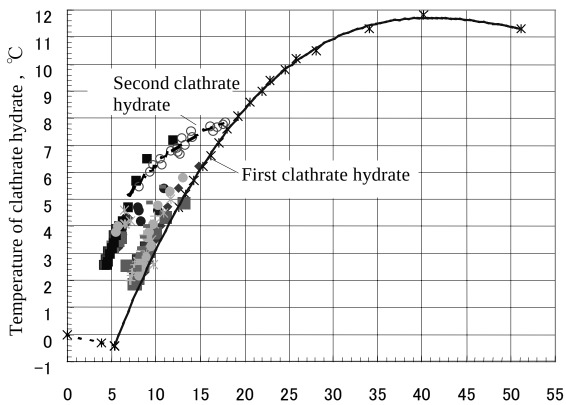

Fig.5 Mass concentration of aqueous solution vs. temperature of formation of clathrate hydrate slurry

When an aqueous solution with a concentration less than 40.5 wt% is cooled, increasing amounts of clathrate hydrate in the slurry reduce the concentration of the aqueous solution. Therefore, the temperature of formation of the clathrate hydrate decreases along the clathrate hydrate formation line. Experiments indicated that clathrate hydrate with a hydration number of about 36 is formed when the temperature of the hydrate slurry drops below about 8℃. This type of clathrate hydrate is named the second clathrate hydrate. **Fig.5** shows the two clathrate hydrate formation lines in the temperature zone below 8℃. The first clathrate hydrate is temporarily formed during the cooling process, but it is also converted to the second clathrate hydrate in the end because the latter is more stable.

Table 3 shows examples of measured values of thermo-physical properties (specific gravity, specific heat, latent heat) of the first and second clathrate hydrates. **Fig.6** shows the relation between the temperature of the clathrate hydrate slurry and the specific enthalpy for an aqueous solution concentration of 20 wt%. The value of specific enthalpy is normalized to zero at 12℃. The cooling capacity of the clathrate hydrate slurry is four times greater than that of cold water at around 5.6℃ when the temperature differential is 7℃.

Table 3 Measured values of thermo-physical properties of clathrate hydrate slurry

Properties	Measured values	
	First clathrate hydrate	Second clathrate hydrate
Specific gravity kg/L	1.08	1.03
Specific heat kJ/kgK	2.22	—
Latent heat kJ/kg	193	205

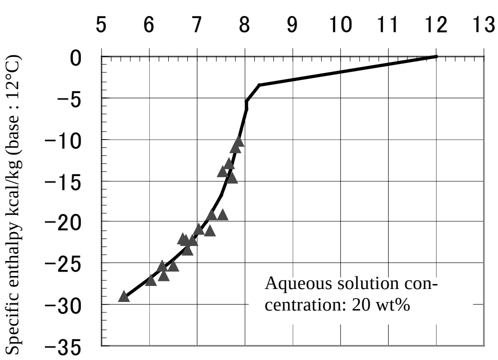

Fig.6 Temperature of clathrate hydrate slurry vs. specific enthalpy

4.2.2 Characteristics of clathrate hydrate slurry transportation

The clathrate hydrate slurry is characterized by the fact that it can be used not only as a cold-storage medium, but also as a cold heat transportation medium. The clathrate hydrate slurry is a fluid with a viscosity that is similar to soft ice cream. It can flow steadily through piping systems and heat exchangers without coagulating or clogging at valves, etc.

Fig.7 shows an example of results of experiments carried out using a full-scale cooling medium transportation system. Clathrate hydrate slurry with a cooling capacity of about 58 kJ/kg was transported to a cooling load. The flow rate and pumping power consumption were measured and compared to those using cold water to transport a similar size of cooling load. The results showed that the required flow rate and pumping power consumption for transporting the clathrate hydrate slurry were about a half and one-fourth, respectively, of those for transporting cold water. This demonstrated the pumping power saving effect of clathrate hydrate slurry in a full-scale system.

There was concern that channeling might occur at a branch line connection that would result in an uneven distribution of the solid-liquid ratio between the two lines while transporting the solid-liquid mixed phase fluid. Experiments confirmed that the clathrate hydrate particles in the slurry distribute evenly between two branching lines. Thus, its applicability to a piping system with branching points was verified.

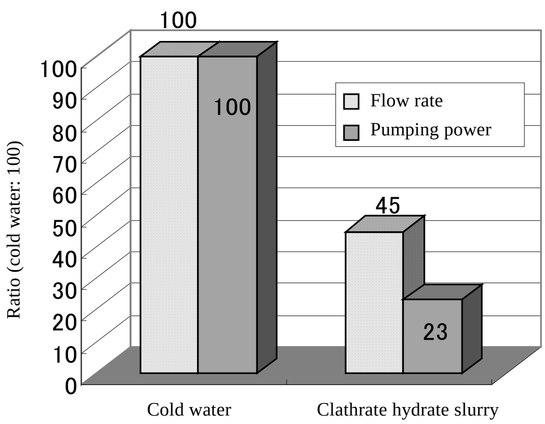

Fig.7 Comparison of required flow rate and pumping power consumption for transporting cold water and clathrate hydrate slurry

4.2.3 Characteristics of clathrate hydrate slurry heat transfer

In order to confirm its performance when used in a general-purpose cold water heat exchanger, the same general-purpose fan coil unit with a nominal flow rate of about 5 kg/min was used to study the heat exchange characteristics of the clathrate hydrate slurry. The overall heat transfer coefficient and mass flow rate were measured for both the cold water and clathrate hydrate slurry. An example of the results is shown in **Fig.8**. Even when the flow rate was below the nominal value, the clathrate hydrate slurry exhibited a higher overall heat transfer coefficient than cold water fed at the nominal flow rate. Due to this enhanced heat transfer effect, heat transfer for the clathrate hydrate slurry was nearly equal to that of cold water fed at the nominal flow rate, even when its flow rate was halved by doubling the cooling capacity. The slurry did not clog in the small-diameter copper piping and valves of the air conditioner heat exchanger and did not cause any problems in the transportation piping system either. These tests verified the applicability of clathrate hydrate slurry in cold water heat exchangers.

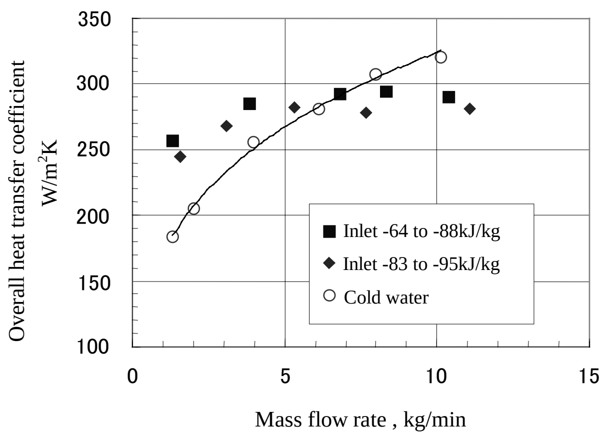

Fig.8 Characteristics of heat exchange in air conditioner

4.3 Air conditioning system using clathrate hydrate slurry

4.3.1 Configuration of clathrate hydrate slurry air conditioning system

A standard configuration for using clathrate hydrate slurry for air conditioning of a building is shown in **Fig.9**.

Except for the heat exchanger added to produce the clathrate hydrate slurry, the system is not significantly different from that of a conventional air conditioning system. Only the ice and water used as the cold storage and transportation media are replaced by clathrate hydrate slurry, and the system is operated in a manner similar to one that uses water.

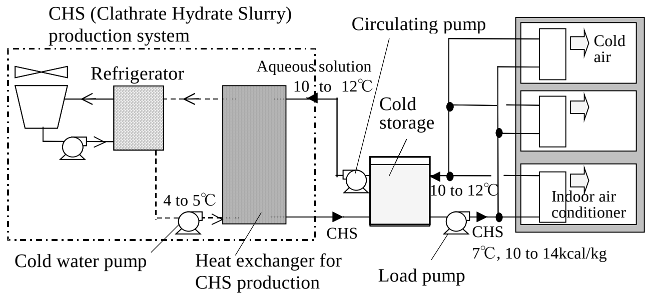

Fig.9 Clathrate hydrate slurry air conditioning system for a building

4.3.2 Estimate of power consumption by a clathrate hydrate slurry air conditioning system for an office building

The annual electric power consumption was estimated for a clathrate hydrate slurry air conditioning system in an office building with a floor area of 20000 m^2. Power consumption was also calculated for no-storage-type and ice-storage-type cold water air conditioning systems for comparison. The cooling conditions were assumed to be as follows: cooling load per unit floor area of 99 W/m^2; equivalent full-load hours of 1000 hours; peak load of 1977 kW. The loads generally used to design an air conditioning system for an office building in the Tokyo metropolitan area with both nighttime and daytime cooling loads over a year were employed as the monthly and hourly load patterns for this calculation.

The cold storage tank in the ice-storage system was assumed to have a volume of 148 m^3, while that for the hydrate-storage system was 296 m^3. The storage density was assumed to be 235 MJ/m^3 for ice storage (static type with a volumetric ice ratio of 60%) and 59 MJ/m^3 for hydrate storage. The COP (Coefficient of Performance) was assumed to be 5.0 for daytime and 5.3 for nighttime for the cold water or hydrate slurry turbine refrigerator, and 4.3 for daytime and 2.9 for ice production in the ice storage system. The partial load operation efficiency was taken into account. The secondary side was assumed to be a closed system for both the no-storage and ice-storage systems, and an open system for the hydrate-storage system. The secondary pump was assumed to have variable flow rate control.

The annual air conditioning power consumption by each system (excluding power for the air conditioner fan) is shown in **Fig.10**. This figure also shows the nighttime power consumption for cold storage. Power consumption by the hydrate-storage system is much lower than that by the no-storage system because of two factors. First, the refrigerator's partial load operation hours with low efficiency were shortened because of cold storage. The second is that power consumption for transporting the cooling medium was reduced due to direct feeding of the high cooling capacity hydrate slurry to the secondary-side of the air conditioners. The ice-storage system has a large nighttime power consumption for cold storage because its cold storage volume is twice that of the hydrate-storage system and the COP for ice production is low, resulting in only limited power savings.

Thus, the hydrate-storage system has the potential to markedly reduce the power consumption over conventional air conditioning systems.

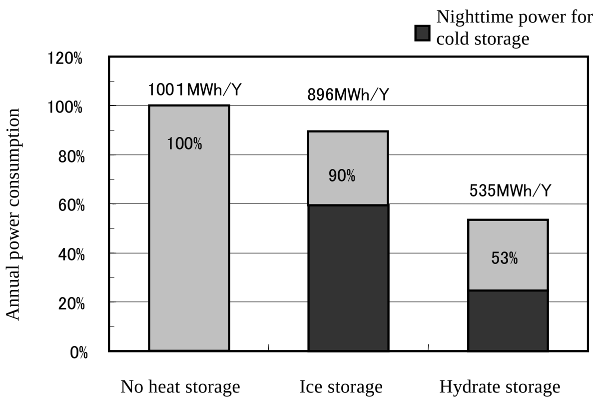

Fig.10 Relative annual electric power consumption by various air conditioning systems

4.4 Summary

Clathrate hydrate slurry can store and transport cold heat with high density and should achieve large energy savings over a conventional cold-water system by such means as large reduction of power consumption for transporting the cooling medium. Capital investment is reduced because the sizes of the cold-storage tank and transportation piping are smaller. Likewise, the amount of energy transported by an existing piping system can be increased.

The newly developed clathrate hydrate slurry will make a large contribution to reducing carbon dioxide emissions and leveling electric power loads. This slurry will be used in energy-saving, next-generation air conditioning systems to meet the increasing demand for air conditioning in the residential and commercial sectors.

NKK will continue to develop technology for optimizing the designs of the equipment and system and operational control of the clathrate hydrate slurry to enhance the commercialization of air conditioning systems that use the clathrate hydrate slurry.

This research was originally started as one of the themes in the "Eco-Energy City Project" of the Agency of Industrial Science and Technology under the former MITI and is currently being carried out under the financial support of the NEDO (New Energy and Industrial Technology Development Organization).

5. SOFC: Solid Oxide Fuel Cell

5.1 Background of the development

With the increasing awareness of the environment in recent years, fuel cells are attracting attention as the next-generation of electric power generating systems. In particular, the SOFC is expected to be the ultimate distributed power source because it has higher power generation efficiency than other types of fuel cells. NKK started developing SOFC technology in the latter half of the 1980's. In 1992, NKK joined with Westinghouse of the USA, which was later renamed as SWPC (Siemens Westinghouse Power Corporation), for developing SOFC technology. This relationship later resulted in a distributor packaging agreement.

Further, NKK formed an alliance with FCT (Fuel Cell Technology) Ltd. of Canada for developing a small-scale SOFC power generating system based on the SWPC fuel cell. In December 2001, the two companies agreed on joint commercialization of SOFC systems smaller than 50-kW. The commercial models of the SWPC 250-kW CHP (Combined Heat and Power) system and the FCT 5-kW SOFC system are outlined below.

5.2 SWPC 250-kW CHP system

This system doubled the scale of a 100-kW pilot plant that was operated for 16610 hours until November 2000 in the Netherlands. The appearance and specifications for the new system are shown in **Fig.11**. Five demonstration programs, as listed in **Table 4**, are planned with this system in the period of 2002 to 2003.

Net AC output	232-kW
Power generating efficiency (LHV)	46.2%
Thermal output	184-kW
Thermal output efficiency	36.6%
Overall efficiency	82.8%

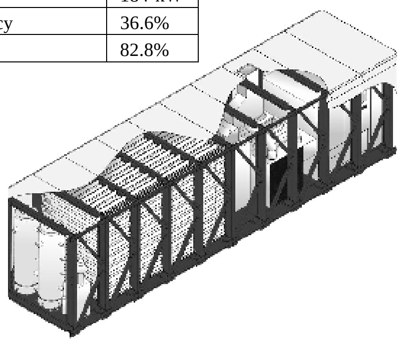

Fig.11 Appearance and specifications of SWPC 250-kW CHP system

Table 4 SWPC 250-kW CHP system demonstration programs

Client	Site	Planned startup
Kinectrics	Toronto, Canada	June 2002
BP America	Alaska, USA	June 2003
Stadtwerke Hanover	Hanover, Germany	Aug. 2003
Southern Co.	Atlanta, USA	Oct. 2003
Shell	Kollsnes, Norway	Dec. 2003

5.3 FCT 5-kW SOFC system

This is a system packaged by FCT using cell stacks manufactured by SWPS. This system was originally developed for residential use in North America. In Japan, it is too large for residential use and is thought to be more appropriate for use in small-scale restaurants and convenience stores. Its specifications are shown in **Table 5**. The process flow is schematically shown in **Fig.12**. This system has the highest efficiency in the small-scale fuel cell power generating systems currently being developed in the world.

Table 5 FCT 5-kW SOFC system specifications

No.	Item	Specification
1	Size	61×79×170 (cm)
2	Weight	300kg
3	Net output	0 to 5-kW
4	Thermal output	Max.6.4-kW
5	Power generating efficiency	46％@3-kW
6	Overall efficiency	Approx. 80%
7	Fuel	Natural gas
8	Battery	5-kW×8 hrs

Table 6 shows the calculated energy saving and emission reducing effects of this system. As shown, this system provides large energy savings and emission reductions. This system will be installed in NKK's Tsurumi Works this year to start the first SOFC demonstration test in Japan.

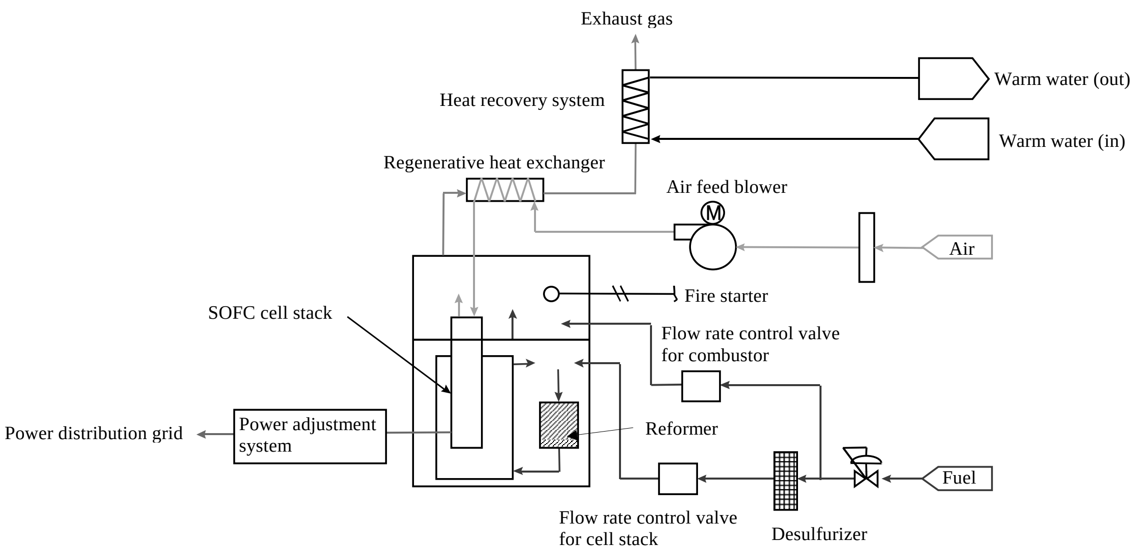

Fig.12 FCT 5-kW SOFC system process schematic

Table 6 Energy saving and emission reducing effects of FCT 5-kW SOFC system

Item	Conventional system	SOFC system	Improvement	Remark
Electric power (kWh/year)	43800	–	–	
Gas (Nm^3/year)	4306	9474	–	Efficiency 40%@5-kW
Primary energy consumption (MJ/year)	648801	436233	212569	
CO_2 emissions (kg/year)	38605	20369	18236	
NO_X emissions (kg/year)	13585	–	13585	
SO_X emissions (kg/year)	10512	0	10512	

5.4 Summary

The Ministry of Economy, Trade and Industry is promoting the use of fuel cells as a new energy source that is environmentally friendly and highly efficient, with a target of 2.2 million kW in operation by 2010. Starting with the installation of the first 5-kW SOFC system in Japan, NKK intends early commercialization.

6. Conclusions

NKK will continue to contribute to establishing a society that uses energy most efficiently in the pursuit of convenience in life. NKK will develop products related to urban energy supply infrastructure and various energy saving technologies in response to the need to save energy and diversify energy sources. NKK will closely follow market needs and continue to put new products into the marketplace in the fields of natural gas use and new energy to expand its business horizon.

All the technologies introduced in this paper should meet the needs of society for reducing environmental impact and energy consumption. NKK will continue to focus on technological development to maintain its top-level position in the environmental and energy engineering businesses.

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