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Development of Iron-making Technology

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1. Introduction

Following the rapid economic growth of Japan through the early 1970s, the petroleum crises in 1973 and 1979 caused the economies of developed countries to be sluggish. The production of the Japanese steel industry decreased as a result, and accordingly, the environment surrounding ironmaking processes changed remarkably. This article looks back at the development of ironmaking technology over the last three decades, and outlines the prospects for the future.

After the Plaza Agreement in 1985 and the consequent valuation of the yen, the Japanese steel industry began to streamline its production structure through equipment integration and the concentration of operations in fewer facilities; Nippon Steel Corporation, for instance, shut down two blast furnaces at Kamaishi Works, and one each at Sakai, Yawata, and Hirohata. Later in the 1990s, while the demand for steel decreased as a result of the break up of the bubble economy and appreciation of the yen, global warming and other environmental problems arose, and stricter waste/emission regulations were enacted.

After 2000, the global steel industry changed significantly through M&A and equipment integration; typical events included the following. (1) Iron ore shippers were reorganized into fewer companies, while over a dozen shippers existed in 2000, only three giants, namely VALE, Riotinto, and BHP-Billiton, together accounting for roughly 70% of the world supply, remain. (2) Steelmakers were also reorganized into larger companies: Arcelor was formed in 2002, JFE Steel in 2003, and Mittal Steel in 2004. (3) Steelmakers began to form networks of alliances. For example, to supply steel products of special quality to the overseas plants of Japanese car and consumer electronics makers, Nippon Steel, Arcelor, and Baosteel formed joint-venture companies, and Nippon Steel and POSCO entered into a strategic alliance agreement.

Furthermore, after 2005, steel production in Japan began to gradually increase again as the economies of the BRIC (Brazil, Russia, China, and India) and other medium-developed countries grew.

The principal ironmaking technologies that developed against the backdrop of these evolving industry conditions are described below.

After the two oil crises, all of the 42 blast furnaces operating in Japan stopped injecting heavy oil by August 1982, and pulverized coal injection (PCI), which was first introduced at the No. 1 Blast Furnace of Nippon Steel's Oita Works in June 1981, spread rapidly. By 1998, PCI was applied to all of the blast furnaces in the country, and the average coal injection amount reached 130 kg/t -not metal.

In the 1990s, the Japanese steel industry arduously developed various rationalizing and cost reducing technologies to survive the difficult economical conditions. Typical results of such development activities included the following: (1) process control systems for the principal ironmaking processes and their automation; (2) technologies for large-amount PCI, including improvements in the combustion of fine coal, intensive control of the burden distribution, clarification of the reactions and material behavior in the lower part of blast furnaces, improvements in the quality of the charging materials such as low-SiO_2 sintering, and evaluation of the phenomena inside blast furnaces; (3) use of recycled plastics in blast furnaces and coke ovens; (4) increased use of economical materials such as pisolite and noncaking or slightly caking coals; (5) labor-saving measures such as optimum operation of sintering machines and coke dry quenching (CDQ) systems, continuous unloaders, automatic operation of coke-oven machines, and short-period relining of blast furnaces; (6) extension of the campaign/service life of blast furnaces and coke ovens; (7) environmental measures such as dust recycling using rotary-hearth reducing furnaces (RHF: Rotary Hearth Furnace) and recirculation of the exhaust gas from sintering machines; (8) development of new processes such as the smelting-reduction process (DIOS: Direct Iron Ore Smelting Reduction Process) and the next-generation coke oven (SCOPE21: The Super Coke Oven for Productivity and Environmental Enhancement toward the 21st century); and (9) technology for visualizing the phenomena inside blast furnaces, such as the visual evaluation and numerical analysis system for blast furnaces (VENUS: Visual Evaluation and Numerical analysis System of Blast Furnace operation) and the accuracy enhancement of blast furnace total models.

After 2000, as the wider commercial application of the above technologies progressed, measures to increase the productivity of blast furnaces were developed, and the furnace size was increased as the economies of the BRIC countries grew. In the case of Nippon Steel, for example, in response to increased demand for pig-iron production, blast furnaces were enlarged after 2000 as they were relined: Nagoya No. 3 BF (from 3,424 to 4,300 m^3 inner volume); Kimitsu No. 3 BF (4,063 to 4,822 m^3); Muroran No. 2 BF (2,296 to 2,902 m^3); Kimitsu No. 4 BF (5,151 to 5,555 m^3); and Oita No. 2 BF (5,245 to 5,775 m^3, the world largest blast furnace as of May 2004, the time of its blow-in, see **Photo 1**). The company has, in particular, concentrated its efforts on improving furnace productivity and lowering the consumption of reducing agents.

Labor productivity nearly doubled over the last 10 years to roughly

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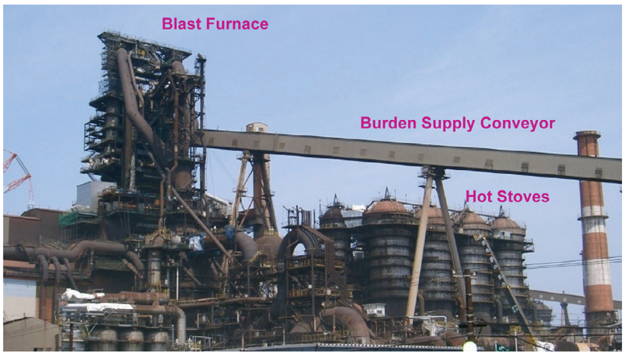

Photo 1 Oita No. 2 Blast furnace (inner volume 5,775 m^3, the world biggest BF at the time of blow-in)

1,600 t/person/year as a result of the consolidation of production facilities, the increase in equipment size, the introduction of labor-saving measures, automation, and the streamlining of facilities and operational improvements.

In response to the requirements of the time, Nippon Steel developed technologies to enhance the productivity of blast furnaces and other ironmaking facilities, better utilize raw materials of lower quality, extend equipment service life, conserve the global environment and reduce energy consumption. Typical examples of such developments are outlined in the following pages.

2. Development of Blast Furnace Technology

2.1 Development of pulverized coal injection technology

In the history of blast furnace technology in Japan, injection of reducing agents through tuyeres can be traced back to as early as 1961, when tests on the blowing of coke oven gas (COG) into a blast furnace were conducted at the Higashida area of the Yawata Works, and those on the injection of heavy oil at the Kawasaki Works of NKK (now JFE Steel). In 1962, 12 blast furnace operators in Japan together signed license agreements with Pompeii of France in order to introduce the technology for heavy oil injection,and the injection of either heavy oil or COG was applied to more than half of the 38 blast furnaces then in operation in Japan. In 1964, all of the 42 operating blast furnaces had facilities for heavy oil injection, which proved remarkably effective in improving production efficiency. Injection of various other reducing agents as substitutes for heavy oil was tested and commercially applied at different steel mills across Japan, including the injection of tar and naphtha at Hirohata; coal slurry (a mixture of heavy oil and pulverized coal) and lime slurry at Muroran; and coal-oil mixture (COM) and fine coal at different plants. In addition, the injection of reducing gas into a blast furnace through the shaft (FTG process) was tested at Hirohata (see **Table 1**) [1-9].

The first pulverized coal injection (PCI) system in Japan was that for No. 1 BF of Nippon Steel's Oita Works, which was commissioned in June 1981. This technology was tested and studied in the 1960s, mainly in U.S.A., and in the 1970s there were three types of PCI processes that were classified according to the method used for distributing the injected material to the tuyeres. Of these, the Armco type, which involved a smaller number of moving mechanisms and was designed basically for circumferentially uniform injection distribution, was selected for the Oita PCI. To apply the Armco-type PCI system, which was designed for Armco's 2000-m^3 class small blast furnaces, to the large (more than 4,000 m^3 inner volume), high-temperature and high-pressure blast furnace at Oita, it was necessary to develop various modifications in view of the potential for its wider use at other furnaces in Japan. A 1 t/h pilot plant was designed and built to confirm the design conditions for the coal processing and transfer equipment, and a plant control system was worked out. In addition, tests involving the injection of fine coal through a tuyere of No. 2 BF were conducted to collect basic information about the combustion of the coal in the raceway. All of the information thus obtained was reflected in the design and start-up operation of the first commercial PCI system in the country [10].

Table 1 History of fuel injection into blast furnaces (focusing mainly on events of Nippon Steel) [1-9]

Year	Topics
1954	Development of blast-humidity control (Higashida)
1959	Development of oxygen-enriched blasting (Hirohata)
1961	Development of COG injection (Higashida) Development of oil injection (Kawasaki)
1962	Import of oil injection technology into all Japanese steel making company Development of tar injection (Kawasaki)
1963	Development of naphtha injection (Hirohata) Application of oil injection (Tobata)
1964	Development of coal-slurry injection (Muroran)
1967	Development of oxygen atomized burner (Hirohata) Development of a mixture of oil and pulverized coal (Muroran)
1969	Development of FTG (injection of reducing gas at shaft (Hirohata) Development of lime-slurry injection (Muroran)
1971	Operation of atmospheric humidity
1972	Application of oxygen atomized burner (Kure)
1974	Application of dehumidifying equipment (Hirohata)
1979	Start of development of COM (fuel of a mixture of oil and coal)
1981	First in Japan of PCI operation (Oita No.1 BF) Establishment of oil less operation in Japan
1982	All blast furnace 40BFs in Japan start oil less operation Reducing agents 400kg/t-pig iron or less achievement (Fukuyama No.3 BF 396kg/t-pig iron)
1993	PCR200kg/t-pig iron or less achievement (Kimitsu)
1994	PCR100kg/t-pig iron or less achievement (monthly average in all Japanese BFs)
1997	CR400kg/t-pig iron or less achievement (yearly average in all Japanese BFs)
1998	PCI record 250 kg/t-pig iron super-achievement (Kakogawa No.1 BF 254kg/t-pig iron, Fukuyama No.3 BF 266kg/t-pig iron) Application of PCI to the overall blast furnaces in Japan (start-up of PCI at Mizusima No.2 BF, Fukuyama No.3 BF)

Once commissioned, PCI proved to be an effective tool for stable and high-efficiency operation of 4000-m^3 class large blast furnaces, enabling production increases and resource savings through a decrease in the reducing agent and coke ratios; it was thus quickly adopted at most blast furnaces in Japan. Later, a system for differential injection was developed to actively change the distribution of the injection amount between tuyeres, which contributed significantly to the circumferentially balanced operation of large blast furnaces.

Fig. 1 [11] shows the historical changes in the unit consumption of

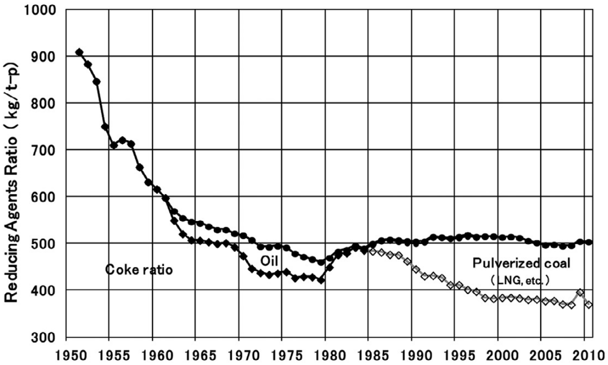

Fig. 1 Historical change in reducing agent ratio in Japan [11]

coke and auxiliary reducing agents in Japan. When oil injection was widely practiced, although furnace operation became much more stable through quick thermal control, the injection amount remained around 100 kg/t-pig iron, and as a result, the coke ratio decreased only to around 450 kg/t-pig iron on average. In contrast, the amount of PCI increased rapidly to reach a level of 130 kg/t-pig iron around 1998, lowering the coke ratio to 370 kg/t-pig iron, and at its maximum, a monthly average PCI amount of 266 kg/t-pig iron was recorded at the Fukuyama No. 3 BF of NKK (now JFE Steel) in June 1998 [12]. Meanwhile, Nippon Steel pursued a lower reducing agent ratio with high PCI, and in March 2011, hit the monthly lowest coke ratio record of 299 kg/t-pig iron with 189 kg/t-pig iron of PCI at Nagoya No. 3 BF. The measures that enabled this record are being applied to all of the company's blast furnaces.

As explained above, PCI proved effective in (1) reducing the costs of pig iron production through quick thermal control of the furnaces, consequent stabilizing furnace operation and lowering the coke ratio, and (2) extending the service life of coke ovens through a decrease in coke consumption, consequently lowering the operating ratio of the coke ovens. For this reason, steel mills actively took measures to increase the amount of PCI, especially those works where the cokemaking capacity was insufficient. Development of PCI technology advanced in response to its benefits, namely the use of noncaking coals, which are more abundant and economical than coking coals and reliable as a stable fuel for the foreseeable future, and the ease of handling of the coal; all of these reasons led to the present high-PCI operation of blast furnaces.

2.2 Development of technology to "visualize" phenomena inside blast furnaces

Measures to visualize the "inside" of blast furnaces by detecting the details of phenomena occurring inside them have enabled the optimum control of the internal furnace conditions. Complicated reactions that involve solids, liquids and gases take place inside a blast furnace and, therefore, clarifying them is of extreme importance for the control of furnace operation. On the occasions of the blow-off of the Higashida No. 5 and Kukioka No. 4 BFs of Yawata and the No. 1 BF of Hirohata from 1968 to 71, the company dissected the furnaces after cooling them with the furnace burden inside [13, 14]. Evaluation of the contents confirmed the existence and forming conditions of cohesive zones and clarified the gas flow paths, the structure of the raceways and the states of the liquids and solids in the hearth. These findings led to the recognition of an orderly structure for the cohesive zones and their importance as gas distributing structures (see **Fig. 2**). Based on these findings, and as the size of blast furnaces has increased, more importance has been attributed to the control of the burden distribution, and the need for an understanding of the gas flow distribution and its control.

Thereafter, two-dimensional numerical models to estimate internal furnace phenomena, such as the Blast Furnace Realization for the Instruction Guide by Hybrid Theory (BRIGHT), the Radial Burden Distribution Index Theoretical model (RABIT), etc., were developed, and then, sensors and detectors to more accurately detect the conditions of the cohesive zones (gas samplers for the furnace top and the upper and middle shafts, belly probes, deadman probes, vertical probes, burden profile meters, ore and coke layer thickness meters for the throat, and short probes for the lower shaft, etc.) were developed and installed in operating furnaces (see **Fig. 3**) [15-19].

Since it is very difficult to actually see the inside of the furnace, Nippon Steel has tried to work out methods for collecting numerical data on internal furnace conditions using roughly 500 thermometers located in the stave coolers and 20 or so shaft pressure sensors that detect burden packing conditions and gas flow, and displaying the

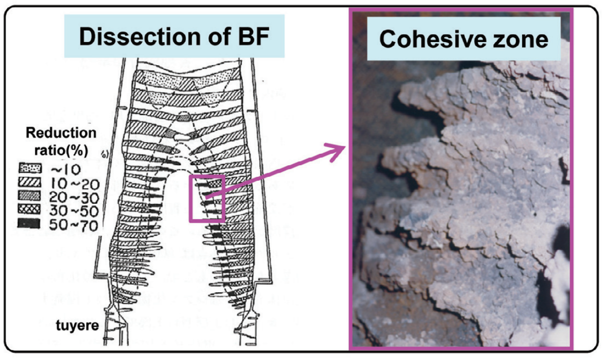

Fig. 2 Cohesive zones at furnace dissection
(left: Hirohata No. 1 BF, right: Nagoya No. 1 BF)

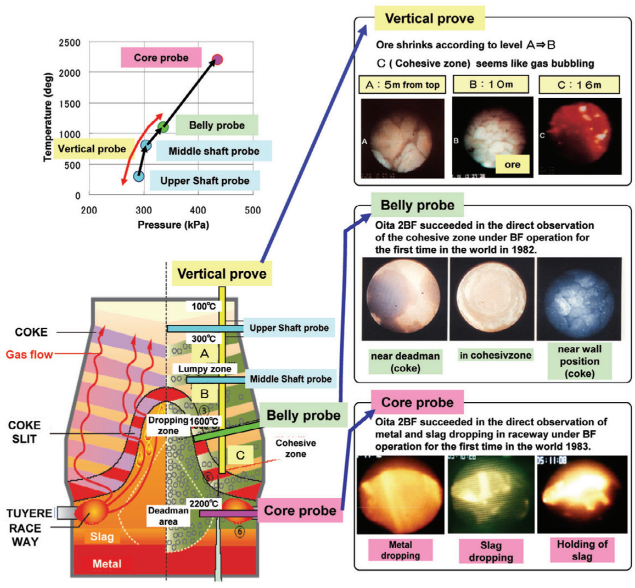

Fig. 3 Probes and sensors to directly observe blast furnace inside using fiber optics [17-19]

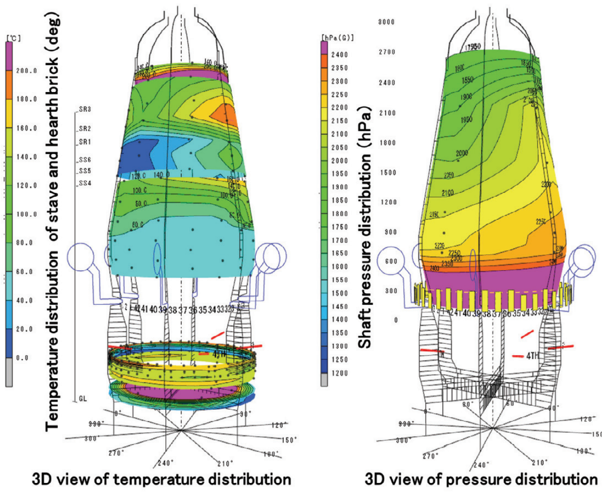

Fig. 4 Examples of display by 3D-VENUS [20]

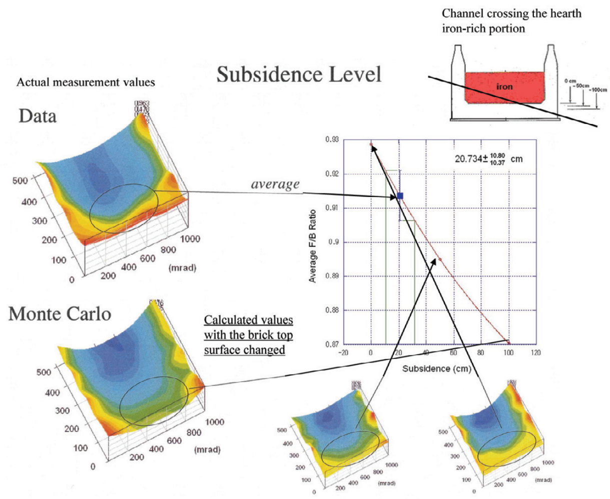

Fig. 5 Estimation of hearth brick wear [21, 22]

internal furnace conditions on monitor screens. As a result, the Two-dimensional VENUS (Visual Evaluation and Numerical analysis System of Blast Furnace operation) was developed in 2004 to display the collected data two-dimensionally. Then, in 2007, the 3D-VENUS capable of exhibiting the same data three-dimensionally, second by second, was developed and used for the operation of the Nagoya No. 1 BF and applied to the blast furnaces of the other mills, which greatly contributed to their stable operation (see **Fig. 4**) [20].

In addition to the above, Nippon Steel is developing technology to directly observe the phenomena inside blast furnaces using cosmic-ray muons jointly with the High Energy Accelerator Research Organization (KEK, now a part of the Earth Quake Research Institute at the University of Tokyo). Cosmic-ray muons are a type of elementary particle. When primary cosmic rays consisting of protons and electrons hit the aerosphere of the earth, π and k mesons form, which decay immediately into particles such as muons and neutrinos and emit gamma rays. These decay products come down to the earth's surface. Because muons penetrate matter easily, it is possible to surmise the structure of a material by measuring both the muon penetration through it and the rate of attenuation. Using this technology, Nippon Steel is seeking methods for measurement of the material density of a blast furnace hearth in order to estimate the brick wear and for measurement of the internal furnace conditions in more detail to better control furnace operation (see **Fig. 5**) [21, 22].

3. Development of Technologies for Treatment of Materials Charged to Blast Furnaces

3.1 Technology for size expansion of sintering machines

During the years of high economic growth from the 1960s to the early 70s, the size of sintering machines was increased to feed large blast furnaces with sintered ore. Enlargement was achieved mainly by increasing the area of the sintering pallets, or by increasing the pallet width and the machine length. An increase in the pallet width to 5 m, which at that time was viewed as the limit, was made possible for the first time by using insulation pieces and other countermeasures against the heat. The Kimitsu No. 3 DL (DL standing for the Dwight-Lloyd sintering machine), the first 5 m-width machine at Nippon Steel, was commissioned in 1971 as the world's largest machine at that time, with a sintering area of 500 m^2 (5 m × 100 m). Thereafter, the Oita No. 2 DL (commissioned in 1975) and the Wakamatsu DL (1976, the last sintering machine of the company) were built with sintering areas of 600 m^2 (5 m × 120 m), renewing the size record. The design and operation technologies for the company's large sintering machines were established during that period.

The most advanced technologies of the time were incorporated into those large-capacity machines, including the following: (1) High-power exhaust gas blowers capable of generating a negative pressure of −19.6 kPa were provided to cope with an ore bed thickness exceeding 500 mm. (2) Two transportation lines for sintered ore were built at the Oita No. 2 DL, the Wakamatsu DL, and the Muroran No. 6 DL to ensure high operating rates of the sintering machines, and an intermediate sinter storage bin was installed after the sinter cooler at the Muroran No. 6 DL. These measures have effectively served to maintain high operating rates for the machines up to the present. In addition, (3) there were upper design limits to the size and capacity of the conventional suction-type circular sinter coolers, and for this reason, a pressure-type circular cooler was designed and installed for the first time at the Kimitsu No. 3 DL. The compact design of the new cooler allowed efficient cooling of sintered ore in a smaller space. Furthermore, because the pressure-type cooler was more air-tight than the older type, it was possible to raise the temperature of its exhaust gas, which made it possible to eventually install a high-efficiency heat recovery system for energy conservation. (4) With respect to environmental protection, it became clear that the capacity of the conventional cyclone dust catchers was insufficient for treating the larger amounts of exhaust gas from the large sintering machines. To address this issue, electrostatic precipitators were adopted as standard equipment for the Kimitsu No. 3 DL. To improve efficiency, moving-electrode electrostatic precipitators were then introduced at the Tobata No. 3 DL of the Yawata Works in 1991; thereafter, this type of precipitator was built at many other sintering plants in Japan.

The two-layer charging system, used first at the Wakamatsu DL in 1978, is another characteristic new technology adopted during the period when size was increasing. It was the first attempt in the world to solve the problem of the downward air pull experienced in the conventional sintering method due to ignition from the upper side of the ore bed, and mitigated the thermal imbalance between the upper and lower portions of the ore bed in order to improve sintering efficiency. Assisted by these new technologies, the sinter production of Nippon Steel grew in response to increasing demands from larger and larger blast furnaces to hit a maximum total grate area of 4,582 m^2 in 1976, and the highest annual production ever of 52 Mt/y in 1980.

3.2 Energy conservation measures

As a result of the two oil crises that hit the world economy in the 1970s, ironmaking processes suffered from higher energy costs, and production decreased as a result of the world-wide decline in demand for steel products. The number of operating blast furnaces decreased, and after the blow-off of the Sakai No. 1 BF (1982), the Muroran No. 1 BF (1984), and the Kamaishi No. 2 BF (1985), the sinter production of the company fell drastically, and the Sakai No. 1 DL was shut down in 1982. At that time, while all of the blast furnaces of the company stopped injecting heavy oil into all-coke operations, and consequently, the reducing agent ratio (RAR) went up. The blast furnaces were also expected to generate more gas (BFG) as a fuel for other production facilities at the plant. For this reason, increased use of lump ore, which is lower in reducibility than sintered ore, for blast furnaces was encouraged; this preferred use of lump ore was another reason for the decline in sinter production (see **Fig. 6**).

In addition to the decrease in production, cost reduction was required for sintering plants. Lower COG unit consumption was targeted, especially through improvement in the efficiency of the ignition furnaces. This goal was promoted with such eagerness that lowering of the COG unit consumption became virtually a competition among the blast furnace operators in Japan. The most significant change at that time was the switch from conventional atmospheric ignition using high furnace temperatures in large ignition furnaces to the direct ignition at the ore bed surface using burner flames. Accordingly, large ignition furnaces were replaced with smaller ones equipped with different types of burners, such as slit burners, surface combustion burners, and line burners, according to the choice of the steelmakers. As a result, Nippon Steel's unit consumption of COG decreased drastically from a few Nm^3 to 1 Nm^3 per ton of sintered ore (see **Fig. 7**); The Hirohata No. 1 DL hit a record low COG consumption of 0.48 Nm^3/t-sinter in 1988; this value is still one of the world's best records.

The next target for improving the efficiency of sintering plants was power consumption, which was 30 to 40 kWh/t-sinter at that time. The main exhaust blower is responsible for nearly half of the power consumption of a sintering plant. Therefore, given the

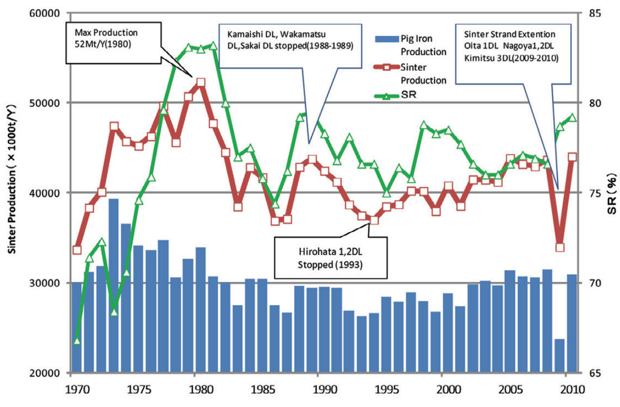

Fig. 6 Nippon Steel's sinter production

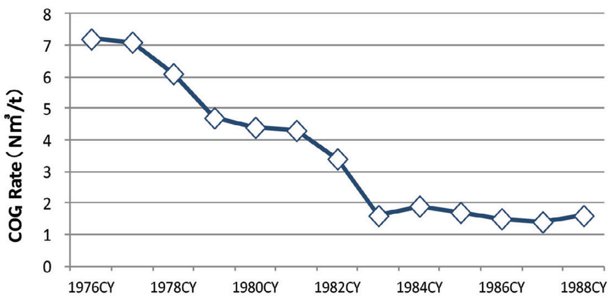

Fig. 7 Unit consumption of COG for ignition

production tonnage, the blowers at practically all of the sintering plants were replaced with ones with smaller runner diameters or those having three-dimensional blades of higher efficiency. At six of the company's 15 sintering plants, such as Yawata's Tobata No. 3 and the Kamaishi No. 1, Muroran No. 6, and Oita No. 2 DLs, where overcapacity became apparent, the runner diameter was decreased, and in addition, variable voltage variable frequency (VVVF) and other rotation control methods were introduced to greatly decrease power consumption. Most notably, at the Muroran No. 6 DL, the power consumption of the entire plant was reduced to 13.1 kWh/t-sinter in 1991 as a result of a significant decrease in the power consumption of the main blower; in addition, despite a decrease in the ore bed thickness to roughly 300 mm, the sintering yield remained unchanged.

Of the various energy-saving measures implemented for sintering machines during the period, what deserves special mention is the waste heat recovery. The sintering process consumes heat at rate of approximately 1500 MJ/t-sinter, about 400 MJ of which is lost to the air through the sinter coolers. While the temperature of the hottest part of the exhaust gas from a cooler fluctuates from 250 to 450℃ depending on the cooler type, it is mostly in the medium to low temperature range, and thus the heat can be used exergically only for limited purposes, such as preheating of the air for the ignition furnace. With a pressure-type cooler, however, the exhaust gas temperature is stable at around 400℃, and thus it is possible to use the heat in commercial scales. A hot-water type power generator was installed at the Wakamatsu DL in 1979, and then a generator using a low-boiling-point medium was built at the Kimitsu No. 3 DL in 1981, which generated as much energy as 13 MW/h, hitting the then world record for sintering plants [23]. More recently, a steam recovery system started up at the Muroran No. 6 DL (2010) and an exhaust gas re-circulating system was built at the Tobata No. 3 DL, enabling the recovery of the sensible heat of the gasses from the main blower and the cooler, in addition to greatly reducing the required amount of blown air (1992).

In the early 1980s, blast furnaces were compelled to operate at low productivity with 100% coke. As a result, given the expansion of low-temperature thermal reserve zones and to secure high permeability in the upper shaft portion, it became necessary to improve the reduction degradation index (RDI), and many works took measures to improve the RDI by using fine serpentine. Initially (1980), the serpentine was crushed using rod mills at Yawata and Oita, then (1981) a roller mill was introduced at Kimitsu [24] to obtain finer grains (1 mm or finer by more than 85%), and another at Nagoya (1982). Later, however, it became clear that the higher melting point of the bonding slag in sintered ore due to the fine serpentine had adverse effects on the sintering yield, and the use of serpentine was discontinued. More recently in 2008, Kimitsu commercially introduced a method for controlling the RDI, whereby $CaCl_2$, which does not affect sintering reactions, is added to the sintered ore outside of the sintering machine; presently, this process is the standard method for controlling RDI.

3.3 Environmental measures

While the economy of Japan grew dramatically in the 1960s and 70s, environmental problems increased. This sub-section presents the measures that the steel industry of the country took against the problems that arose from the sintering process. The concern about air pollution, whichbecame serious beginning in the second half of the 1970s, raised questions about the continued use of the sintering process. To prevent photochemical smog from occurring, tighter regulations for automobiles as moving sources of NO_x were enacted, and at the same time, stricter regulations were imposed on industrial sources of gas emissions. As a result, the upper-limit NO_x concentration for the exhaust gas from an existing sintering plant was set at 260 ppm, and that from a new plant at 220 ppm. Most of the NO_x generated in the sintering process is fuel-related NO_x originating from nitrogen in the fine coke used as the fuel; the mechanism of its generation is quite different from that of the thermal NO_x formed during combustion in reheat furnaces and the like.

Faced with these regulations and exercising all-out efforts within its R&D organizations, Nippon Steel aimed at reducing the NO_x generation from sintering plants by improving the sintering reactions, and in particular, the combustion of fine coke. The goal was to improve the granulating properties of the feed material so that the fine coke would burn at higher temperatures and thus result in a decrease in NO_x generation. More specifically, additional ore mixers were installed to improve the granulation of the ore, and coke breeze split addition systems were installed to improve the coke combustion; these measures were introduced to the Nagoya Nos. 1, 2, and 3 DLs, the Kimitsu No. 3 DL, and the Oita Nos. 1 and 2 DLs. The essence of the new method was to add fine coke between the primary and secondary ore mixers; this approach minimized excessive granulation and thus prevented the fine coke from sinking deep into the ore agglomerates, which would make its combustion difficult.

An environmental measure of special importance is the use of burnt lime. It had been commercial practice at the Kukioka DL of the Yawata Works since 1969 to help increase production. Burnt lime was found effective at decreasing NO_x generation as well as for increasing production; its use for environmental protection purposes began in 1978. With the addition of burnt lime, the granulating properties of the feed material were significantly improved, and NO_x emissionsn from Nippon Steel's sintering plants decreased dramatically [25, 26].

The above improvements in the granulating properties of the feed stock, including the use of burnt lime, still form part of the essential technology for increasing sinter production, and are typical examples of the new technology that arose from efforts to overcome adverse conditions.

To make the sintering exhaust gas cleaner yet, the dry desulfurizing and denitrating system (DDS) using activated carbon, then being developed for power plant use, was applied to the Nagoya No. 3 DL in 1987 as the first case of a non-power-plant application. The DDS is a dry method, and thus was quite different from the wet methods largely being employed for the purpose. In addition, carbon, gypsum, and sulfuric acid could easily be obtained from the by-product of the process. For this reason, its application expanded to the Nagoya Nos. 1 and 2 DLs (1999), the Oita No. 1 DL (2003), and the Kimitsu No. 3 DL (2004). All of these DDS units are still working effectively on a reliable basis as environmental control measures for the exhaust gas from sintering plants.

3.4 Measures to improve efficiency of sintering operation

Unlike in the pelletization process for iron ore, lumps of sinter cake that are discharged from a sintering machine are broken into the desired sizes, and fine ore is generated during this sizing process. For this reason, the process yield used to be below 70% in most cases. Around 1980, the people of the Oita Sintering Plant conducted a series of investigations of sinter cakes on pallets, and made it clear for the first time that the sintering yield was considerably lower in the upper and sidewall portions of the cake than in the other parts [27]. To solve the problem, the heat pattern in the thickness direction of the ore bed was improved and various other measures were taken. [28] Ultimately, grain-size segregation control in the thickness direction using a slit-bar-type feeder [29], which was developed at Hirohata, proved to be effective and was commercially applied.

This method, which is capable of controlling the carbon distribution of the feed material and its grain size distribution, proved effective also for improving the ignition of the ore bed and thus decreasing the unit consumption of COG. In appreciation of these benefits, the method was also introduced at the Nagoya, Kimitsu and Oita sintering plants. Next, a method for improving the permeability network of the ore bed was developed; this solution took the form of an intensified sifting feeder (ISF) [30] capable of classifying ore by grain size while continuously loading a large pallet area. The ISF was commercially adopted in 1987 after a series of plant tests at the Wakamatsu DL. The process proved effective for improving the sintering yield by about 4%, and was applied also to the Kimitsu No. 1 DL (1987), the Tobata No. 3 DL of Yawata (1988), the Muroran No. 6 DL (1988), and the Kimitsu No. 3 DL (2000), becoming a standard facility for the sintering machines of Nippon Steel. Presently, it is also used at many sintering plants of other steelmakers in and outside of Japan.

The ISF was awarded the Okochi Memorial Production Prize in 1989.

3.5 Technical advances in the effective use of natural resources

Australian ore accounts for the majority of the iron ore that Nippon Steel consumes. Up through the first half of the 1990s, a good part of the ore came from the Brockman layer, but fine ore of this brand contained high-melting-point gangue in high concentrations, which caused a serious problem in relation to the control of sintering reactions, particularly at the Sakai Works, where this brand accounted for most of the ore supply. As a countermeasure, the selective granulation process [31] was developed around 1990 (see Article "Developments for Saving Natural Resources and Material Recycling in Chapter 5 of this Issue); this process was put into commercial practice first at the Oita No. 2 DL in 1994, then at the Tobata No. 3 DL (1996), the Oita No. 1 DL (1997) and the Kimitsu No. 3 DL (2002) as a way to utilize high-alumina ores. This process received the Okochi Memorial Special Production Prize in 1998.

The grade of Australian iron ore has changed remarkably over the last years due to a change in the supply and demand balance. Hamersley (now Rio Tinto) has blended Marandoo ore from the Marra Mamba layer with hematite ore from the Brockman layer since 1994, and commenced shipping West Angelas ore in 2002 as the first non-blended ore brand from the Marra Mamba layer. Recently in particular, considerable amounts of high-P ore from the Brockman layer are mixed with the Marra Mamba and other low-P ores. All of

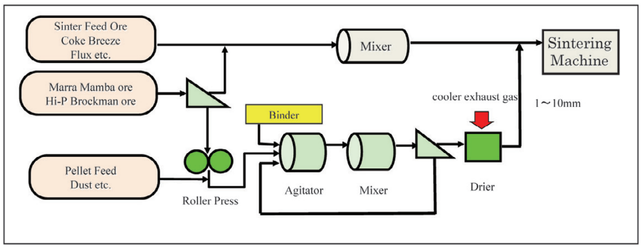

Fig. 8 Process flow of SPEx II [32)]

Photo 2 Kimitsu No. 3 DL sinter strand extension (charging side) [33)]

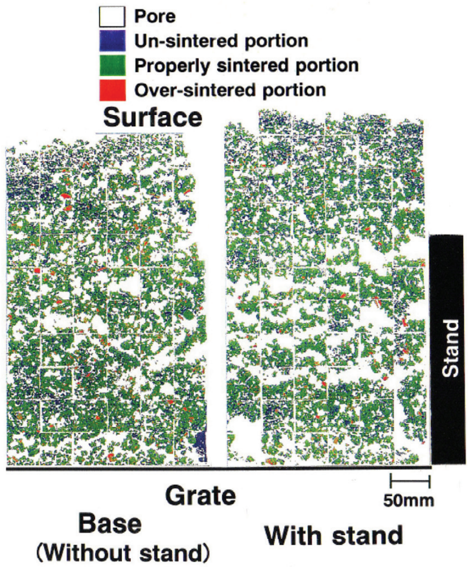

Fig. 9 Change in sinter cake structure with stand-support measured by X-ray CT in the width direction [34)]

these activities are evidence of the latest rapid changes in natural resource conditions. What was particularly feared to have an adverse affect on the operation of steel mills was the increase of limonite and fine grains in the Australian ore. Because an increase in fine ore with poor granulating properties was likely to lower the productivity of sintering plants, organic binders were introduced to improve ore granulation, and then a process was developed to form this kind of ore into resistant mini-pellets using binders. The developed process, named SPEx II (see **Fig. 8**) [32)], was put into commercial practice at Yawata in 2008 as an effective method for utilizing raw materials of low quality.

3.6 Technical advances for increasing the production of sintering plants

The sinter production of Nippon Steel hit a peak in 1980, then through production decreases following the oil crises and the blowing-off of many blast furnaces after the Plaza Agreement in 1985, the total grate area of the sintering plants of the company decreased to a minimum of 3,646 m^2 in 1993, less than 75% of that at the peak period. However, the demands for steel products returned, and for higher productivity and stable operation of blast furnaces, a higher sinter ratio (SR) was envisaged, and an increase in sinter production was required again. This requirement was particularly pressing at Nagoya and Kimitsu, where the sintering capacity fell short of meeting the demand of the blast furnaces. Although the principal measures for increasing sinter production are higher sintering speeds and improvements in yield, an increase in the sintering area by improving the permeability of the ore bed was envisaged at the beginning. First, making the best of the pallet structure, the grate areas of the Nagoya Nos. 1 and 2 DLs were increased in 1997 by expanding the suction width from 3.5 to 4.0 m; this change was then applied to all of the other sintering machines of the company except for the Muroran No. 6 DL. The lengths of many machines were then extended, and through these measures, the total grate area of the company increased by 966 m^2. At Kimitsu No. 3 DL, among others, after an increase in the pallet width to 5.5 m, the machine length was extended to 127 m in 2009, and as a result, it became the world largest sintering machine with a grate area of 700 m^2 (see **Photo 2**) [33)].

In addition to the above, new technologies were developed to enable production increases. One example is what is known as the stand-support sintering method. In the process, the sintered portion at the upper part of the ore bed is supported by side support stands called "stand grates," which are provided at both ends of the pallets to ensure the permeability of the un-sintered lower part (see **Fig. 9**) [34)]. This method brought about a production increase of about 7%, and thus, after the first commercial application at Kimitsu No. 3 DL in 1997, it was implemented at the other sintering machines of the company; the method is now used also by other steelmakers in Japan.

As for the sintering yield, there is still much room for improvement, and it is necessary to continue pursuing this important goal.

In the meantime, due to the rapid growth of demand from the Chinese steel industry, the conditions for iron ore resources have rapidly become fluid, both quantitatively and qualitatively, and for this reason, it is imperative to develop new ore agglomerating methods to cope with possible price increases and quality changes. We are already advancing such projects in earnest.

4. Development of Cokemaking Technology

4.1 Technology to cope with changes in coal resources

Nippon Steel has developed and fostered various methods for the drying of coal to make effective use of coal resources. The first commercial coal moisture control (CMC) equipment for lowering the moisture of coal to 5-6% before charging into the coke ovens was started up in 1983 [35)], and then the Dry-cleaned and Agglomerated Pre-compaction System (DAPS) to lower the coal moisture to roughly 2% began operation in 1992, both at Oita Works [36, 37)]. Using the DAPS, coal is classified in a fluidized bed dryer, and the fine coal is formed into agglomerates using a pelletizer, then mixed with the coarser coal and charged into the coke ovens (see **Fig. 10**). As a result of the drying, the coal density in the coking chambers increases, and therefore, the system is effective at improving coke strength. In addition, the agglomeration of the fine coal decreases dust emission during coal transport and charging into the ovens despite the decreased moisture, which improves the environmental performance [38].

The CMC method allows for a higher mixing ratio of abundant and economical noncaking and slightly caking coals by about 10% compared with moist coal, while the DAPS for about a 30% increase in the mixing ratio (see **Fig. 11**) [36, 38, 39]. In addition, these methods proved effective at saving energy; the CMC reduces the energy consumption for cokemaking by about 8% as compared to that with moist coal, and the DAPS by about 15% (see **Fig. 12**) [39].

Coal drying before charging was applied to other coke ovens of Nippon Steel, and presently, one of the above processes is used at virtually all of the coke ovens of the company, significantly contributing to the effective use of coal resources.

The supply and demand conditions for high-quality coking coals is expected to become tighter yet in the near future, and in view of this situation, we are developing new technologies for the use of coal resources in more efficient ways and to save energy.

4.2 Technology to extend the service life of coke ovens

The age of the oldest of Nippon Steel's operating coke ovens is 47 years, and the average age of all of its ovens is 38. Thus, measures to extend the service life of coke ovens are of vital importance for the company. To achieve this goal, it is necessary to identify the damaged parts of oven walls at an early stage, quantitatively evaluate the degree of damage and repair those parts systematically. Traditionally, however, evaluation consisted mainly of visual inspection by operators from outside of the oven and manual repair of the damaged parts.

To address this problem, Nippon Steel succeeded in devising a system called the Doctor of Coke ovens (DOC) to accurately diagnose the condition of the chamber walls in an air atmosphere at 1,200℃, and then repair the damaged portions. The system was first used in 2003 at the Oita Works (see **Photo 3**).

With the completion of the tenth DOC unit in 2011, all of the coke ovens at the five integrated steel works of the company were provided with the DOC as standard equipment. (For more details, see the Article "Development of Refractory Technology" in Chapter 2 of this Issue.)

4.3 Development of the new cokemaking process SCOPE21

The Super Coke Oven for Productivity and Environmental Enhancement toward the 21st century (SCOPE21) is the name given to a next-generation cokemaking process developed recently under a national project sponsored by the Japanese Ministry of Economy, Trade and Industry. Aiming for dramatic improvements in energy savings, the effective use of natural resources, productivity, and environmental performance, investigation and research began in 1994, and after test operation of a pilot plant built at Nippon Steel's Nagoya Works in 2002 and 2003, the first commercial SCOPE21 plant was commissioned in 2008 as the No. 5 Coke Oven at the Oita Works .

The process consists of simultaneously drying and classifying coal raw materials into fine and coarse grains, rapidly preheating them, forming the fine grains into hot briquettes, and charging the coal into the coking chambers at about 250℃; through this process, the moisture of the coal is decreased to virtually 0% (see **Fig. 13**) [40].

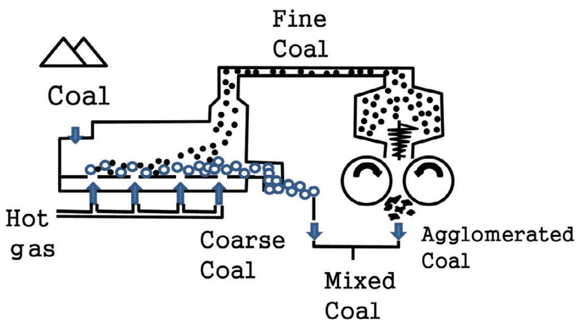

Fig. 10 Process flow of DAPS

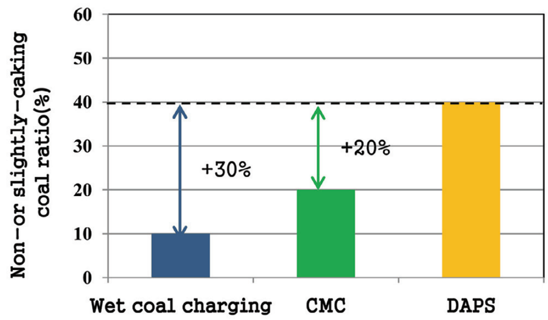

Fig. 11 Comparison of mixing ratio of non- and slightly-caking coals [39]

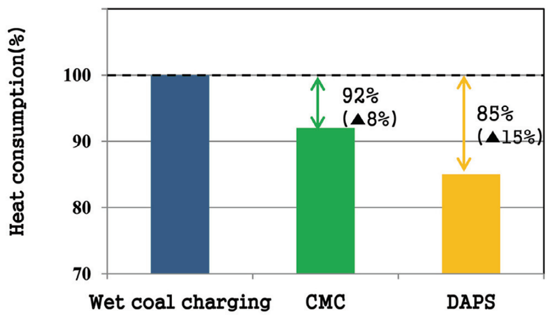

Fig. 12 Comparison of energy consumption [39]

Photo 3 Overview of DOC

The SCOPE21 process includes environmental measures, such as the transport of heated coal in air-tight containers to minimize smoke and dust emissions, and newly designed oven burners to reduce NO_x generation. The first commercial plant based on the SCOPE21 process tripled the coke oven productivity, decreased the CO_2 emissions by 400,000 t per year, and increased the use of noncaking and slightly caking coals, combining benefits in productivity enhancement, environmental protection and resource savings.

A second SCOPE21 plant is presently being constructed at the Nagoya Works, and will be commissioned in 2013.

4.4 Recycling of waste plastics as chemical raw materials

To help establish a recycling-oriented society, Nippon Steel developed a method for turning waste plastics into chemical raw materials using coke ovens, and put it into commercial operation in 2000 for the first time in the world [41-44].

Waste plastic containers and packaging from households are collected by municipalities, shredded and pelletized at pretreatment facilities, and after being mixed with coal in a ratio of about 1 to 99, charged into coke ovens and thermally decomposed into approximately 20% coke, 40% oil (tar, light oil, etc.), and 40% gas (see **Fig. 14**) [45, 46]. Of these products, the coke is charged into blast furnaces, the oils are used as raw materials for the chemical industry, and the gas is used as a clean fuel for power plants [47].

Actual recycling began at Nagoya and Kimitsu in 2000, and presently, roughly 250,000 t per year of waste plastics are recycled annually at five of the company's steel works. The amount accounts for about 30% of the plastics used in containers and packaging in all of Japan, and is the largest quantity in the world in terms of waste recycling by a single private company.

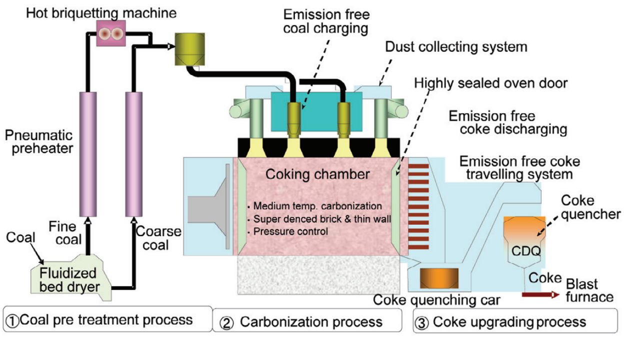

Fig. 13 Process flow of SCOPE21 [40]

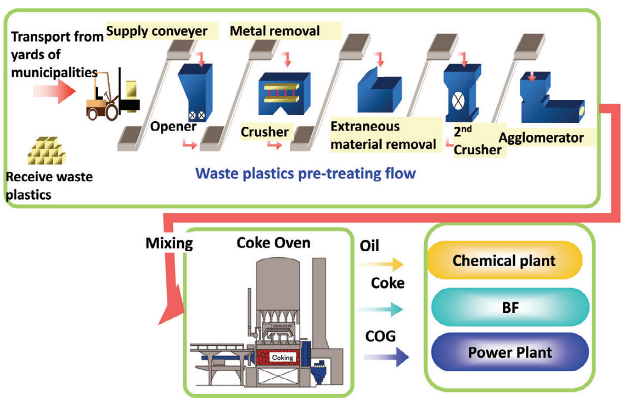

Fig. 14 Process flow of pre-treatment and recycling of waste plastics [45, 46]

5. Closing

The resource and environmental conditions surrounding the Japanese steel industry are growing increasingly difficult, and at the same time, the competition from steelmakers of nearby countries is becoming more challenging by the day. Furthermore, other problems are expected to arise: cost reductions through improvement of conventional technology will reach its limits, the aging of existing production facilities continues to advance, the procurement of natural resources become difficult with respect to bothquality and quantity. In addition, the requirements of the steel industry to actively respond to environmental regulations as measures against global warming and to construct a recycling-oriented society will become more pressing, and therefore, further streamlining will be imperative.

Nippon Steel continues its R&D activities with innovative approaches for solving these problems. Such new developments include: (1) a significant decrease in the melting reduction loads of blast furnaces by pretreatment of the raw materials at mining sites, and other measures to reform them; (2) concentration, unification and efficiency improvements at production facilities; (3) increasing the added value of by-products arising from the ironmaking process; (4) contributions to materials recycling for the entire society through coal reforming and new ironmaking processes linked with industrial venous systems; and (5) fostering and securing human resources and promotion of automation.

We are determined to solve these problems through close cooperation with both the mining and other industries and academic and research institutes in order to identify new technologies that meet the needs of this quickly changing society.

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