NIPPON STEEL TECHNICAL REPORT No. 94 July 2006

UDC 669 . 162 . 2

Development of Ironmaking Technology

Masaaki NAITO*1

Abstract

The Japanese steel industry has a long history of introducing new and innovative technologies in the field of ironmaking. The new technologies introduced during the past ten years include technologies to use cheaper and lower-grade raw materials, measures to prolong the service life of blast furnaces and coke ovens, promotion of energy saving, use of wastes and solutions to environmental problems. This report outlines the condition of production and technological trends and technical development themes in ironmaking technologies.

1. Introduction

At the beginning of this special edition of nearly 20 years of the Nippon Steel Technical Report on ironmaking technology (then called Seitetsu Kenkyu), I would like to outline the trend of ironmaking technology in Japan and the world over the past 20 years.

After the guidance toward the appreciation of the yen based on the Plaza Accord in 1985, Japanese steelmakers focused their efforts on rationalization of production structure through measures such as closures of old facilities and priority production on high-efficiency facilities; for example, Nippon Steel Corporation shut down two blast furnaces at Kamaishi, and one each at Sakai, Yawata and Hirohata Works. Thereafter, in the 1990s, the demands for steel products fell after the collapse of the Japanese bubble economy and the valuation of the yen, and then, environmental issues such as global worming and the increasing amount of industrial and household wastes came up as major problems.

After the turn of the century, the restructuring of the steel and related industries and closures of old facilities advanced all over the world. The major events that changed the structure of the world steel industry include the following: (1) the restructuring of iron ore shippers (more than 12 shippers as of 2000 were reorganized into only three, namely Rio Tinto, CVRD and BHP-Billiton, who now account for no less than roughly 70% of the world iron-ore supply), (2) the formation of large steelmakers through mergers and acquisitions (the formations of Arcelor in 2002, JFE Steel in 2003, and Mittal in 2004), and (3) alliances between steelmakers (such as those between NSC, Arcelor, POSCO and Baoshan Iron & Steel in view of the construction of overseas plants of Japanese carmakers and appliance manufacturers and their local procurement of steel materials). More recently, owing to the rapid economic growth of China, the world steel production increased significantly (see **Fig. 1**), and the consequent price run-up and quality deterioration of the raw materials due to their short supply became serious concerns.

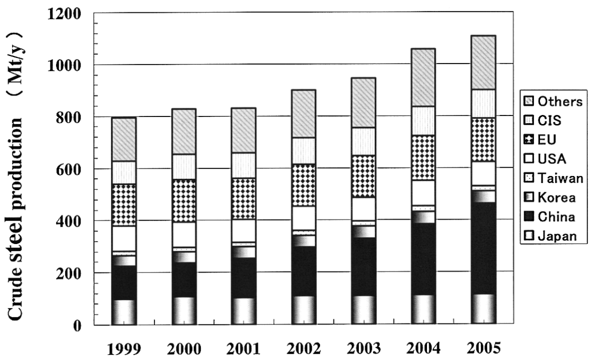


Fig. 1 Crude steel production in the world

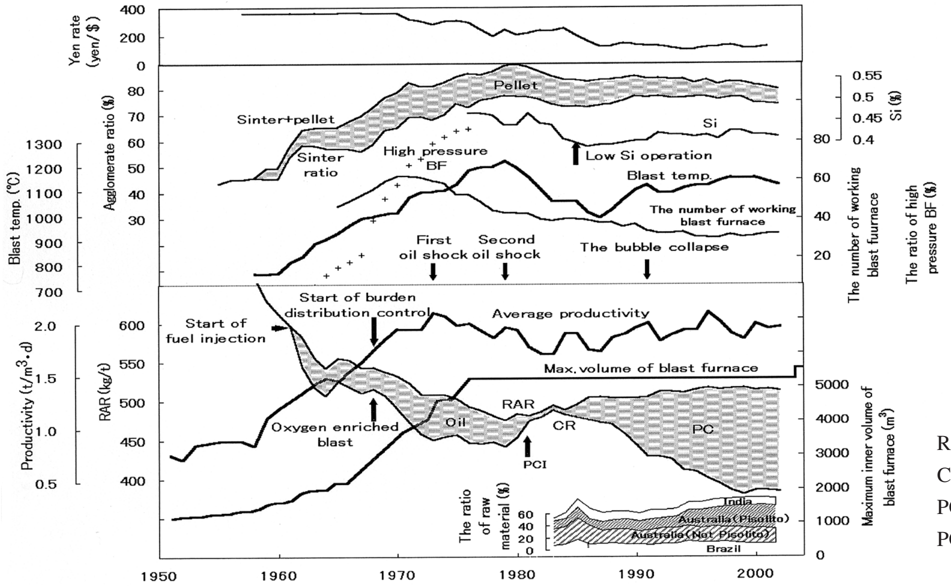
This paper outlines the changes in ironmaking technologies in the above period. The details of the development of individual technologies are described in the other papers of this edition.

2. Historical Overview of Ironmaking Technology

2.1 Trend in ironmaking technology

Fig. 2 shows the principal changes that occurred in the blast furnace operation technology over the last half century. After the World War II, the Japanese steel industry grew to be the most advanced steelmaking arena of the world, so to speak, by actively introducing many of the latest technologies from the Western countries, improving them,

*1 Environment & Process Technology Center



RAR: reducing agent rate
CR: coke rate
PCI: pulverized coal injection
PC: pulverized coal

Fig. 2 Trend of BF operation

and making the most of the advantages of coastal steel works of being able to import high-quality raw materials in great quantities from any sources in the world. During the 1960s and 70s, the steelmakers of the country fiercely competed against each other in terms of the reducing agent rate (RAR); Nippon Steel's Kimitsu No. 4 BF attained a low-RAR record of 406 kg/t in November 1980 [1] and NKK's (presently JFE) Fukuyama No. 3 BF another of 396 kg/t in November 1981 [2]. The measures taken to achieve these near-the-limit records include the increase in the furnace size, top pressure and blast temperature, intensive size control of the burden, improvement in the quality of sinter, burden distribution control and injection of heavy oil or other fuels.

However, the heavy oil injection through tuyeres, which was first introduced in 1961, lost its cost advantage after the oil shocks in 1973 and 79, and by August 1982, all the 42 operating blast furnaces of Japan discontinued the oil injection. To minimize the overall energy cost of a steelworks, the trend of blast furnace operation at that time was to aim at a high reducing agent rate to increase the generation of blast furnace gas. Another trend then was to develop furnace operation technology to increase the use of low-price raw materials to reduce the pig iron cost, and the injection of pulverized coal was introduced. The pulverized coal injection (PCI), which was introduced to Nippon Steel Oita No. 1 BF[3] in June 1981 for the first time in the country, quickly became popular, and by 1998, all the operating blast furnaces of Japan had PCI facilities, and the average PCI rate reached 130 kg/t. The highest records of PCI operation include 254 kg/t of Kobe Steel's Kakogawa No. 1 BF[4] and 266 kg/t of JFE's Fukuyama No. 3 BF[5] attained in 1998.

As **Fig. 3** shows, the situation surrounding the steel industry in

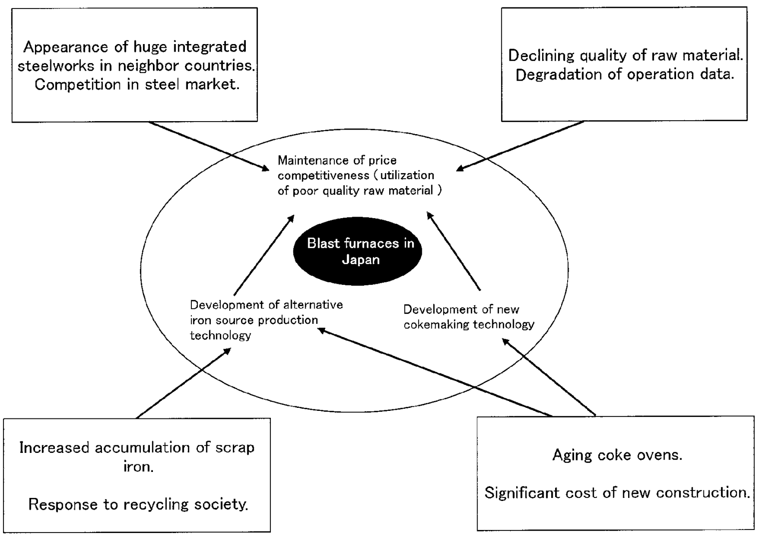


Fig. 3 Environment surrounding the steel industry in Japan in the 1990s

the 1990s was a difficult one. What is more, the high valuation of the yen and the economical instability in the wake of the collapse of the bubble economy made the situation more difficult. As countermeasures, the following rationalization and cost reduction technologies were strenuously developed and applied to the commercial production activities:

(1) Introduction of control systems to each of ironmaking processes and the automation of their operation,
(2) PCI in large quantities (improvement in the combustion properties of pulverized coal, burden distribution control, clarification of phenomena in the lower part of a blast furnace (including the behavior of particulate substances), quality control of sinter and coke such as a sintering method for lowering SiO_2 content and blast furnace evaluation technology, etc.),
(3) Use of plastics as the alternative energy source for blast furnaces and coke ovens,
(4) Use of economical raw materials (use of pisolite and slightly caking coal in large quantities, etc.),
(5) Labor saving (operation optimization of sintering machines and coke-dry-quenching (CDQ) equipment, continuous unloaders, automation of coke oven operation and reduction of the work period of blast furnace relining, etc.),
(6) Extension of equipment service life (blast furnaces and coke ovens),
(7) Environmental conservation (dust treatment using a rotary-hearth reduction furnace (RHF), circulation of sintering exhaust gas, etc.),
(8) Innovative processes (production technologies of substitutional iron sources, the Smelting-reduction Process (DIOS), next-generation coke ovens (SCOPE21), etc.), and
(9) Visualization of phenomena within a blast furnace (development of the visual evaluation and numerical analysis system of a blast furnace (Venus), improvement in the prediction accuracy of a blast furnace total model, etc.).

After the turn of the century, while the commercial application of the above technologies has been expanded, the research and development in the ironmaking field have focused mainly on the productivity increase of blast furnaces in response to the rapid economic growth and increasing demands for steel products in China. **Fig. 4** shows the number of operating blast furnaces in Japan and their average inner volume; the size of the Japanese blast furnaces has been expanded again since 2000 on the occasions of their relining to respond to the latest needs for production increase: for example, Nagoya No. 3 BF was enlarged from 3,424 to 4,300 m^3, Kimitsu No. 3 BF from 4,063 to 4,822 m^3, Muroran No. 2 BF from 2,296 to 2,902 m^3, Kimitsu No. 4 BF from 5,151 to 5,555 m^3 and Oita No. 2 BF from 5,245 to 5,775 m^3 (at present, the largest blast furnace in the world).

Fig. 5 shows the past changes in the productivity and RAR of the blast furnaces in Japan. In this background, Nippon Steel has concentrated efforts on increasing the productivity of each of its blast furnaces and decreasing the consumption rate of reducing agents.

The labor productivity of Japan's ironmaking nearly doubled in the last ten years to approximately 1,600 t/head/year (see **Fig. 6**). This is largely due to the size expansion, closures of old, small furnaces, introduction of labor saving facilities, automation and rationalization of furnace equipment and improvement in furnace operation.

Most recently, the company has been developing technologies to enhance the productivity of blast furnaces and other ironmaking facilities, cope with the deteriorating quality of raw materials, conserve the global environment and energy resources. The outlines of typical cases of the above technical development are described below.

2.2 Technology for use of economical raw materials

Raw materials and fuels for blast furnaces accounts for as much as approximately 70% of the total production cost of pig iron. In the

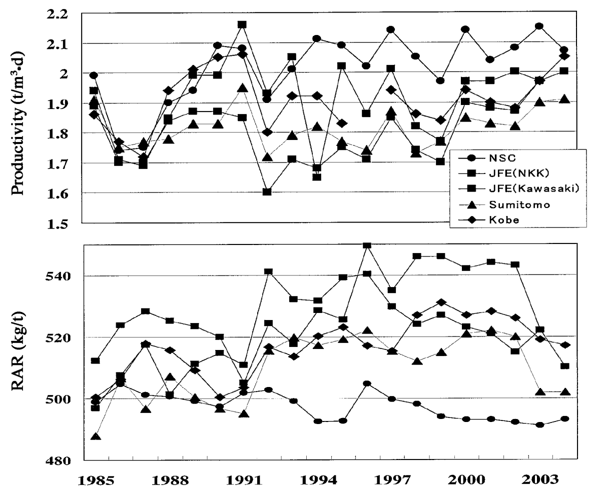


Fig. 5 Transition of average RAR and productivity in each company of Japan

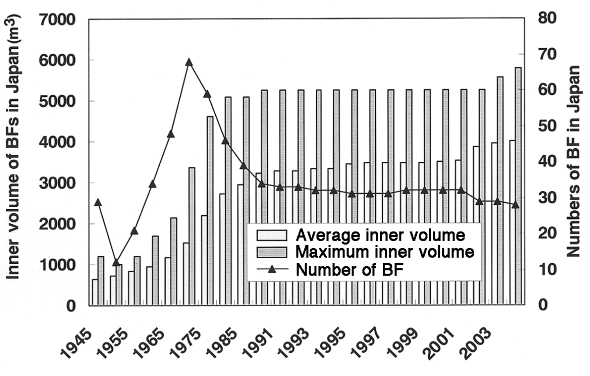


Fig. 4 Numbers and average inner volume of blast furnaces in Japan

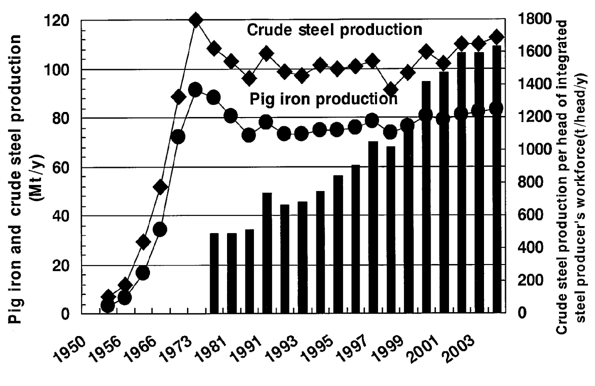


Fig. 6 Pig iron production and crude steel production per head of integrated steel producer's workforce

early 1990s, the prices of the raw materials and fuels went up significantly, and the measures for increasing the use of low-quality and economical raw materials were studied as important subjects of technical development.

2.2.1 Development of technology for use of economical iron ores for sintering process

In consideration of transportation costs, the main supply source of iron ore has shifted from Brazil to Australia (see **Tables 1** and **2**), and the percentage of goethite ores, which are economical among the Australian ores, has increased year by year (see **Fig. 7**). While the Robe River ore have been a main source of the Australian goethite ores, the import of the Yandi ore started in 1992 and that of the Marra Mamba ore in 2002. The goethite ores contain much combined water: the Robe River ore, among others, has a high content of gangue, and the gangue contains much alumina and combined water, the Marra Mamba ore has a high percentage of fine, and for these reasons, the sintering properties of these brands are poor leading to a low strength of sinter. Nippon Steel pursued methods for rendering alumina harmless to increase the use of the Robe River ore, and has established a process to seal alumina through selective granulation[6].

Other measures for improving the tumbler strength (TI) and shatter strength (SI) of sinter in cold have been taken to increase the mixing ratio of the goethite ores; these measures include (1) the increase in the productivity of a sintering machine through measures such as intensified sifting feeder (ISF[7]), air classification[8]), etc.) and stand-support sintering[9]), (2) production of low-SiO_2 sinter through decrease in auxiliary materials and (3) the reform of pseudo-particle structure through intensive granulation. Thanks to the development of these new technologies, the ratio of the goethite ores in all the Australian ores increased to approximately 60% in 2004. In view of the shipment of the blended ore of the high-P Brockman ore and Marra Mamba ore, which is slated to start from 2007, Nippon Steel is focusing the development of sintering technology on granulation methods.

Table 1 Changes in the percentage of sources of Japan's iron-ore imports

(%)

	1991	2001	2002	2003
Australia	47	56	60	64
South America	29	24	22	19
India	15	13	12	9
Others	9	7	6	8

Table 2 Amounts and grades of typical iron-ore reserves in Australia

	Low P-Brockman	Robe	Yandi	Marra Mamba	High P-Brockman
Reserve (Mt)	2070	3000	5200	6900	9000
T. Fe (%)	63.5	56.9	58.2	61.1	62.7
Al_2O_3 (%)	2.1	2.8	1.4	2.3	2.0
–0.15 mm (%)	12.7	3.6	2.8	21.0	19.0
Combined water (%)	2.8	8.0	10.2	6.3	4.1

(2004 fy)

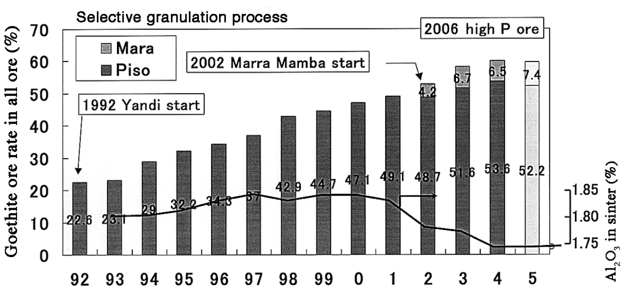


Fig. 7 Transition of high goethite ores ratio

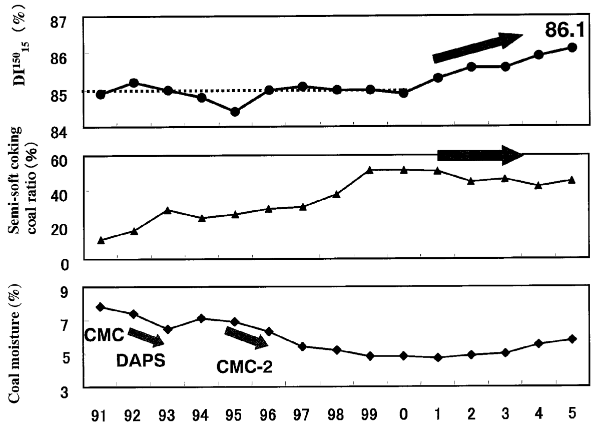


Fig. 8 Transition of semi-soft coking coal ratio

2.2.2 Development of technology for use of semi-soft caking coals for cokemaking process

With respect to reducing agents, in addition to the injection of pulverized coal into blast furnaces, Nippon Steel has increased the use of semi-soft caking coal, which are more economical than coking coals, for coke production. Technologies for enhancing coke strength are essential for increasing the mixing ratios of such coal brands, and therefore, besides introducing the coke dry quenching (CDQ) process[10]), the company developed methods for coal moisture control (CMC)[11]) and Dry-cleaned and Agglomerated Pre-compaction System (DAPS)[12]). Thanks to these new technologies, the moisture of coal charged into coke ovens fell from 8-odd % in the early 1990s to less than 5% in 1999, and the mixing ratio of the semi-soft caking coal surpassed 50% while keeping the coke strength unchanged (see **Fig. 8**).

In response to the demands for production increase of blast furnaces, however, increasing the coke strength ($DI^{150}{}_{15}$) has become a priority issue, and the mixing ratio of the semi-soft caking coal has been controlled to a little below 50% over the last years. With respect to the increase in the coke strength and the mixing ratio of the semi-soft caking coal, on the other hand, Nippon Steel continued studying coal blending technologies such as the coking pressure control method and a new coal evaluation method using the high-temperature, in-situ NMR imaging method[13]).

2.3 Technologies for blast furnaces operation with PCI and at high productivity and low coke rate

2.3.1 Development of technologies for high-PCR blast furnaces operation

The injection of pulverized coal (PCI) into a blast furnace is effective not only in cost reduction but also in decreasing the opera-

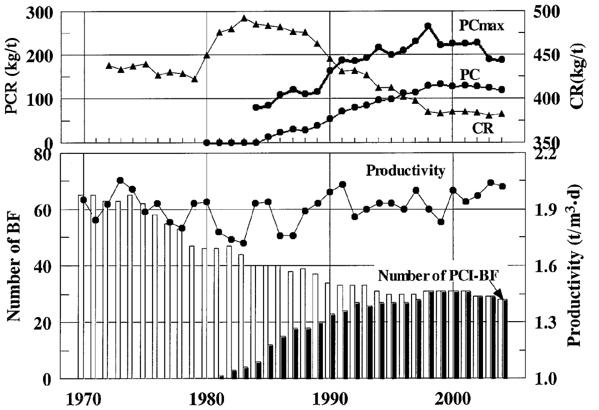


Fig. 9 Transition of average pulverized coal rate (PCR), CR, productivity and number of BF in Japan

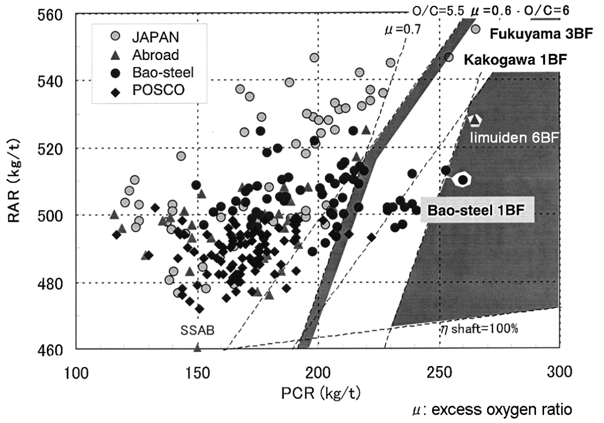


Fig. 10 Relationship between RAR and PCR

tion load of coke ovens, thus extending their service lives and, consequently, decreasing the number of ovens to construct.

The PCI was first introduced to Nippon Steel's Oita No. 1 BF[3] in 1981, and was applied to the blast furnaces of the other steelmakers of Japan (see **Fig. 9**). In the early stages of PCI, the combustibility of pulverized coal constituted the main issue of technical studies, but as the amount of injection increased, the deterioration of permeability and the increase in the heat loss in the lower part of a furnace and the inactivation of the deadman became appreciable.

The measures studied in the process of increasing the pulverized coal rate (PCR) related to the problems such as the following: (a) the decrease in central gas flow resulting from a higher ore/coke rate, an inevitable consequence to a high PCR, and the increase in peripheral flow; (b) the increase in the gas temperature at the furnace top resulting from the decrease in heat flow rate and consequent deterioration of the furnace permeability; (c) the decrease in the coke-slit thickness and increase in the permeability resistance in the cohesive zone resulting from a lower coke rate; (d) the inactivation of the deadman resulting from the accumulation of unburned char and fine coke on the surface of the deadman due to the deterioration of combustibility of the pulverized coal; (e) the decrease in the furnace temperature due to the dripping of high-FeO slag that results from the deterioration of the reducibility and high-temperature properties of ore layers; and (f) the deterioration of the slag fluidity resulting from the dripping of high-Al_2O_3 slag due to use of low-SiO_2 sinter.

To solve these problems, technologies such as the following were applied to commercial furnace operation: (i) optimum burden distribution control at high-ore/coke operation (techniques for controlling center and peripheral gas flow such as the center coke charging method developed by Kobe Steel[14] and installation of armor plates at the furnace throat developed by Nippon Steel[15]); (ii) control of the combustibility of pulverized coal (studies of the relationship between excessive oxygen rate and combustibility, optimization of the injection position and the shape of injection lances); (iii) improvement in the high-temperature reducing properties of ore layers at high-ore/coke operation (studies into methods for improving the high-temperature reducing properties such as control of heat flow rate, decreasing the thicknesses of coke and ore bases, increasing the use of small-lump coke and decreasing the amount of slag)[16]; and (iv) suppressing the accumulation of fine coke and coal in the lower furnace portion (clarification of the mechanisms of coke disintegration and measures for its suppression, and studies of blast blowing conditions including the optimization of the packing structure, behavior of powder and particulate materials in and around the raceway and the blast velocity). **Fig. 10** shows the relationship between the reducing agent rate (RAR) and PCR, and **Table 3** the operation data of the blast furnaces with high PCRs.

Nippon Steel tested injection of 200 kg/t of pulverized coal in 1994 at Kimitsu No. 4 BF, and at Muroran No. 2 BF, achieved a productivity of 2.14 t/m^3/day and a PCR of 191.4 kg/t in 1998 using high-Al_2O_3 sinter. On the other hand, high-PCR operation above 200 kg/t was practiced at Kobe Steel's Kakogawa No. 1 BF, JFE's Fukuyama No. 3 BF, Baoshan's No. 1 BF and POSCO's Pohang No. 3 BF. The blast furnaces of Baoshan and POSCO, among these, have attained an excessive oxygen rate of 0.6 and an ore/coke rate of 6.0, which had been considered beyond practical limits (see Fig. 10). Although the productivity and RAR were varied, all the above blast furnaces aimed at suppressing the degradation of coke into fine powder at the lower furnace portion and improving the high-temperature properties of sinter layers to achieve the high-PCR operation. All the above blast furnaces used high-strength coke (in terms of drum index, DI) and low-SiO_2, and low-Al_2O_3 sinter excellent in high-temperature reducing properties[16].

Nippon Steel also aimed at increasing the PCR of large blast furnaces to enhance the productivity or lower the coke rate. Over the last years, the company has focused efforts on increasing the injection amount of pulverized, low-volatile coal, which has a high calorific value, improving the circumferential distribution of the PC injection and its combustibility , revision of blast blowing conditions at tuyere tips for use of high-strength coke, and the study of furnace profile.

2.3.2 Technologies for blast furnace operation at low reducing agent rate

The theoretical studies related to the decrease in the RAR have been conducted using Rist's model and the like, and covered the aspects such as (1) improving shaft efficiency (improving the reducibility of sinter, controlling burden distribution, etc.), (2) lowering the reduction equilibrium temperature (W point) of wustite (technology for use of high-reactivity coke[17]), (3) increasing the heat input in front of tuyere tips (increasing the temperature and decreasing the blast moisture, etc.), (4) decreasing the heat loss due to tapping of hot metal (decreasing the Si content of hot metal and the tempera-

Table 3 BF operation data with the high PCR in the world

		Kakogawa 1BF	Fukuyama 3BF	Muroran 2BF	Ijmuiden 7BF	Bao steel 1BF	POSCO 3BF
Charging device		Bell	Bell	PW[*1]	Bell	Bell	PW[*1]
		1998. 3	1998. 6	1998. 12	1999. 1	1999. 9	2002. 1
Inner volume	m^3	4550	3223	2296	-	4063	3795
Working volume	m^3	3750	2774	1963	3790	-	-
Productivity	$t/m^3 \cdot d$	1.88	1.84	2.18	-	2.20	2.28
RAR	kg/t	545.4	554.5	505.4	523	510.0	493.0
CR	kg/t	291	289	314	307	250.0	271.0
PCR	kg/t	254.4	265.5	191.4	216	260.6	222.3
Lance type		Double	Double / Oxygen	Single	Single		
Ore/Coke	-	5.43	5.46	5.17	-	(6.48)	(5.98)
Blast temp.	℃	1233	1220	1262	1258	1251	1138
Blast moisture	g/Nm^3	17	32	16.8	8	14	6
O_2 enrichment	%	4.1	4.8	2.8	8.3	3.2	
Top gas temp.	℃	210	251	-	146	239	2.8
Gas utilization CO (η_{co})[*2]	%	49.6	46.5	49.5	47.7	51.0	
Sinter ratio (SR)	%	43.0	76.7	87.6	44.1	72.8	83.1
Pellet ratio (PR)	%	35.0	15.5	0	52.5	11.5	4.9
TI (SI)		73 (89.6)	66.3	74.7	TI>5mm: 81.1	75.6	(93.5)
Reduced degradation index (RDI)	%	23.9	47.5	38.8	-	35.1	39
Reduced index (RI)	%	66.9	71.5	66.4	-	69.5	
Sinter SiO_2	%	5.60	4.21	5.10	3.75	4.56	
Sinter CaO/SiO_2	-	2.11	2.07	1.77	2.65	1.83	
Sinter Al_2O_3	%	1.73	1.61	1.89	Al_2O_3+TiO_2: 1.63	1.49	1.5
Sinter FeO	%	7.40	5.22	5.83	14.64	7.47	6.47
Coke strength after reaction	%	-	-	62	62.2	-	67.7
Coke ash	%	11.3	11.9	11.5	9.8	11.3	11.4
Coke size	mm	49.7	49.75 (65)	44.2		50.8	52.1
DI^{150}_{15}	%	84.8	(DI^{30}: 92.4)	85.7		87.7	88.1
Pig temp.	℃	1496	1501	1514	-	1501	1516
Pig Si	%	0.48	0.34	0.66	0.43	0.3	0.4
Pig S	%	0.021	0.027	0.015	0.029	0.021	0.017
Slag rate	kg/t	265	266	309	199	255	277
Slag Al_2O_3	%	15.2	13.8	15.9	18.1	14.3	14.3
Slag CaO/SiO_2	-	1.25	1.28	1.26	1.15	1.21	1.25

[*1] PW: Paulw Wurts, [*2] $\eta_{co} = CO_2 / (CO + CO_2)$

tures of hot metal and slag), and (5) decreasing the heat loss through the furnace shell.

Fig. 11 and **Table 4** show the past records of low-RAR operation. The typical records of low-RAR operation are, by the use or otherwise of different auxiliary reducing agents, 396 kg/t of JFE's Fukuyama No. 3 BF (inner volume 3,223 m^3)[18] in 1981 with a tar injection rate of 42.1 kg/t and a coke rate of 354 kg/t, 440 kg/t of Nippon Steel's Muroran No. 2 BF (inner volume 2296 m^3) in 1981 as an all coke operation , 455 kg/t of Nippon Steel's Oita No. 2 BF (inner volume 5245 m^3)[19] in 1994 with a PCR of 98 kg/t and a CR of 357 kg/t, 493 kg/t of POSCO's Pohang No. 3 BF (inner volume 3795 m^3) in 2002 with a PCR of 222.3 kg/t and a CR of 271 kg/t (the latter two are with PCI)[17].

Any one or more of the technologies mentioned above were applied to attain these records: for example, in the low-RAR operation of Nippon Steel's Oita No. 2 BF, the increased use of small-size lump coke, the decrease in the ore layer thickness (improvement in

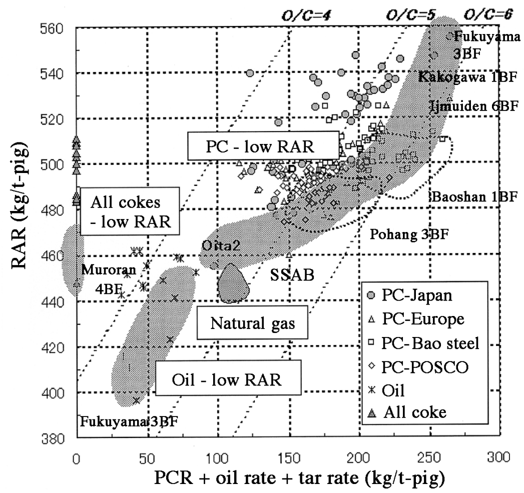


Fig. 11 Blast furnace operation results with low RAR

Table 4 Low RAR operation data in the BF

		Fukuyama 3BF 1981. 11	Muroran 4BF 1981. 7	Oita 2BF 1994. 3	Pohang 3BF 2002. 1
Inner volume	m^3	3223	2290	5245	3795
Productivity	$t/m^3 \cdot d$	2.37	1.84	2.19	2.28
RAR	kg/t	396	448	454.7	493
CR	kg/t	354	448	356.3	271
Tar, PCR	kg/t	Tar 42.1	0	PC 98.4	PC 222.3
Ore/Coke	-	* 4.5	3.59	4.52	* 5.98
Blast temp.	℃	1353	1202	1268	1138
Blast moisture	g/Nm^3	5.6	23	20	6
O_2 enrichment	%	0	0	0.5	
Top gas temp.	℃	73	113	109	208
η co	%	54.8	51.5	53.3	
SR + PR	%	96.6 + 0	93.9 + 4.6	78.5 + 7	83.1 + 4.9
RI (RDI)	%	68.9 (36.9)	(31.3)	68.1 (35.8)	(39)
TI		60.3	70.8	75.7	
Sinter SiO_2 (FeO)	%	5.01 (4.64)	5.51 (5.55)	5.03 (5.53)	(6.47)
Sinter Al_2O_3	%	1.8	2.13	1.61	1.5
Coke ash	%	9	10.6	10.7	11.4
Coke size	mm	52.3		47	52.1
DI^{150}_{15}	%	DI^{30}: 92.9	DI^{30}: 95.4	85.7	88.1
Pig temp.	℃	1481	1518	1522	1516
Slag rate	kg/t	274	315	287	277
Slag CaO/SiO_2 (Al_2O_3)	-	1.28 (14)	1.22 (14.9)	1.23 (13.5)	1.25 (14.3)
		Tar injection	All coke	PC injection	

* Estimated

the high-temperature reduction properties), the decrease in the blast moisture and improvement in the reducibility of sinter were commercially applied[19].

Technologies for improving the high-temperature properties of sinter, controlling the temperature of the thermal reserve zone (control of reduction equilibrium temperature), and producing and using pre-reduced ore are being developed in the research and development laboratories of ironmaking technology.

With respect to the temperature control of the thermal reserve zone, Nippon Steel has commenced development of technologies for producing and using high-reactivity coke ahead of other steelmakers, conducted test production and use of high-reactivity coke using China's Shenhua coal at Muroran No. 2 BF, and confirmed its effects[20]. More recently, the company is developing the technology for decreasing the temperature of the thermal reserve zone by using carbon composite iron ore[21].

With respect to the production and use of pre-reduced ore, Nippon Steel has proposed a two-stage reduction system. This is a technology that can increase the productivity and lower the RAR of a blast furnace by producing pre-reduced ore for use in Japanese blast furnaces, for instance, using iron ores with low sintering ability as the raw materials at an overseas location where natural gas is economically available. It is expected also to decrease CO_2 emission in a global scale.

2.3.3 Development of blast furnace simulation models[22-24]

Mathematical models capable of simulating a blast furnace as an integrated system have been developed as a tool to clarify the phenomena in the furnace inside and analyze the process. A blast furnace is a very complicated, moving-layer type, counter-flow reaction furnace where various kinds of reactions take place between gas, solid, liquid and power. Iron ore charged from the top of the furnace at room temperature undergoes a series of complicated processes: it softens and coheres through heating and reduction, and finally melts and drips down as molten metal. A mathematical model is expected to form a virtual blast furnace inside a computer and thus play a role as an off-line simulator. In the 1980s, the Japanese steelmakers worked out practically applicable, two-dimensional total models of blast furnaces, and as the capacity of computers increased, they developed three-dimensional steady-state and non-steady-state models. Furthermore, as the technology for high-PCR operation advanced, four-phase models that dealt with gas, solid, liquid and power, and then five-phase models that dealt with slag and hot metal as two different liquid phases in addition to the other three, were developed to analyze the behavior of fine coke and unburned pulverized coal in the lower portion of a blast furnace. The basic framework of the mathematical models for blast furnaces has been substantially established with the development of these four- and five-phase models (see **Fig. 12**).

In this technical field, Nippon Steel studied measures for improving the analysis accuracy of sub-models based on the two-dimensional, steady-state total model of a blast furnace (BRIGHT model) developed by Sugiyama et al.[25] in the early 1980s. More specifically, the functions and accuracy of the operation prediction model were enhanced (N-BRIGHT model) using the following newly developed models as the sub-models: the burden distribution control model development by Matsuzaki et al.[26], and the sinter reduction

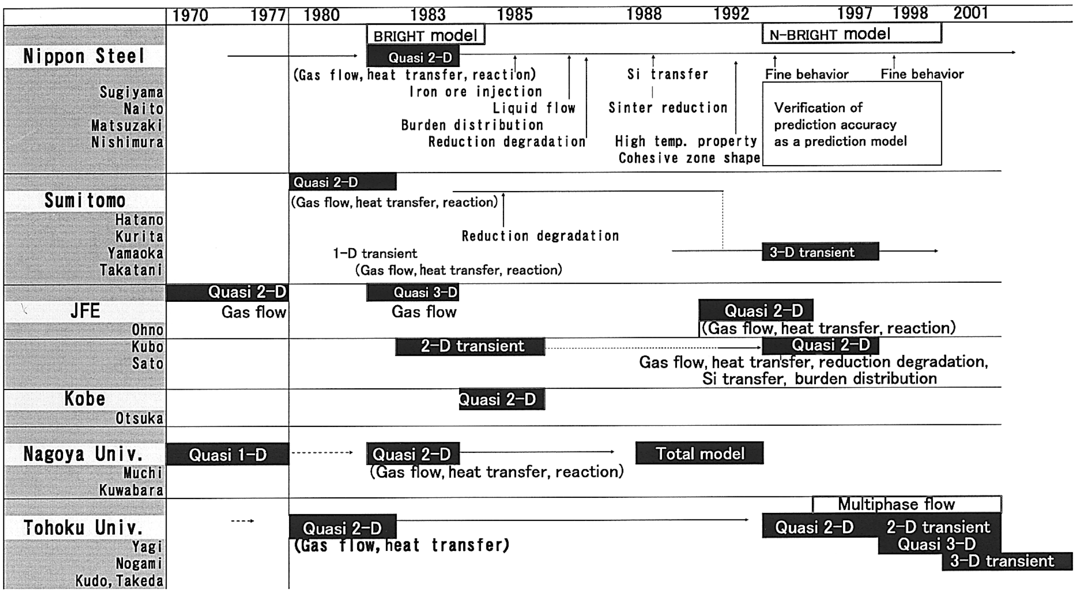


Fig. 12 Development of mathematical model of blast furnace

model, the sinter reduction and degradation model, model for evaluating the high-temperature properties of sinter and that for determining cohesive zone shape developed by Naito et al.[27]. Then, owing to the rapid expansion of the capacity of personal computers since the late 1990s, it is now possible to analyze blast furnace processes using the N-BRIGHT model on PCs and display the analysis results graphically (see **Fig. 13**). To analyze other furnace inside phenomena, a pulverized coal combustion model, non-steady-state, lower-furnace model, hearth liquid metal flow model have been developed, and more recently, 2-D and 3-D burden distribution models are being developed using discrete element models (see **Fig. 14**).

With the advance in the processing capacity of computers, general-purpose LAN came to be used for the instrumentations of blast furnaces, and it became possible to process a greater amount of data. Presently, the N-BRIGHT model is used for the on-line analysis of Kimitsu Nos. 3 and 4 BFs. Besides the above simulation models, Nippon Steel has developed an operation evaluation system called Venus to visualize the phenomena inside a blast furnace based on information from sensors; this system is ready for actual use for daily operation control of blast furnaces.

2.4 Development of technologies for extending service lives of blast furnace and coke oven

2.4.1 Extension of service life of blast furnace

Various technologies have been developed to extend the campaign life of a blast furnace, reduce the huge cost of relining and minimize the production decrease during a relining period. As a result, the pig iron production per cubic meter inner volume of a blast furnace throughout a campaign has increased to more than 11,000 metric tons.

The factors essential for extending a furnace campaign life are

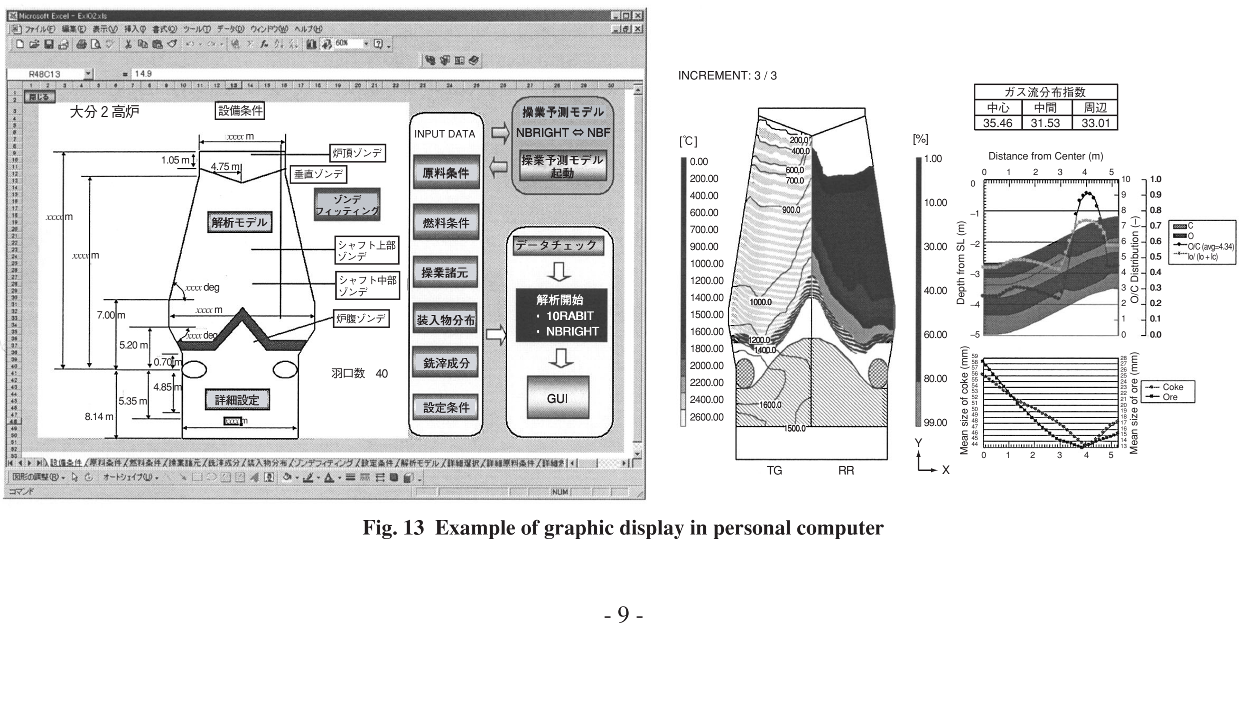


Fig. 13 Example of graphic display in personal computer

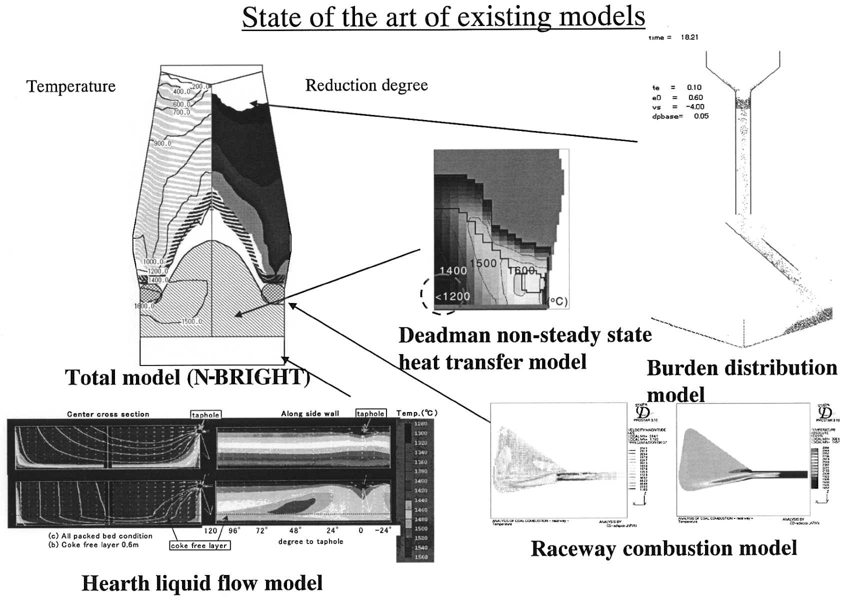


Fig. 14 Simulation model for analysis of blast furnace

(1) adequate furnace design at the construction, (2) careful operation control during a campaign and (3) repairing measures in the later period of a campaign. **Fig. 15** shows the change of the campaign lives of Japan large blast furnaces and the causes of blowout; in most cases excluding scheduled blowout, blast furnaces were blown out owing to causes in the shaft and bottom portions.

A comparison of the causes of blowout in the 10-year period from 1986 with those in the preceding period shows that the number of blowouts due to damage in the bosh and belly decreased, and that due to the wear of hearth wall increased[28].

In the throat, shaft and bottom, which determine the campaign life of a blast furnace, stave-type, water-cooled armor plates with a detachable inner face portion were introduced to the upper shaft, and the cooling capacity of staves and cooling plates from the lower shaft to the belly was improved, and the refractory for these portions was also improved to enhance durability. Fourth-generation staves and copper staves were introduced especially to the furnace portions where the heat loads are high.

Since the 1990s, the corrosion resistance of hearth wall has become the most important factor for extending the campaign life. Accordingly, the thermal conductivity of carbon bricks was enhanced, their pores were made smaller to prevent the penetration of hot metal, refrigerators were introduced to lower the temperature of cooling water, and copper staves came to be used for the furnace bottom wall. All these measures have significantly contributed to the extension of the furnace campaign life.

2.4.2 Extension of service life of coke oven

Many coke oven batteries were constructed in Japan during the era of rapid economic growth in the 1970s, and the average age of all the Japanese coke ovens is now 33 years, some being more than 40 years old (see **Fig. 16**). **Fig. 17** shows a prospect of the coke production capacity of Japan on an assumption that the service life of a

	1975 - 1985	1986 - 2000	2001-
Throat, shaft, belly, bosh	43	22	-
Bottom	11	3	-
Hearth side wall	29	47	4 (+5)
Other equipment	0	6	-
Scheduled stop	36	22	3

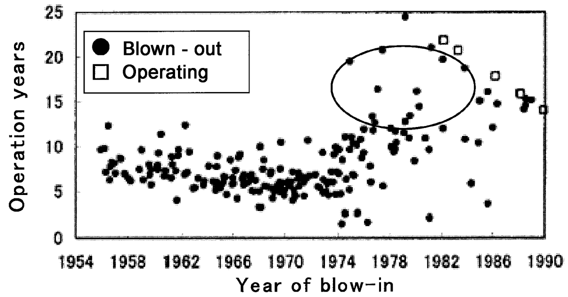


Fig. 15 Causes of blown-out blast furnace and furnace longevity transition of domestic blast furnaces

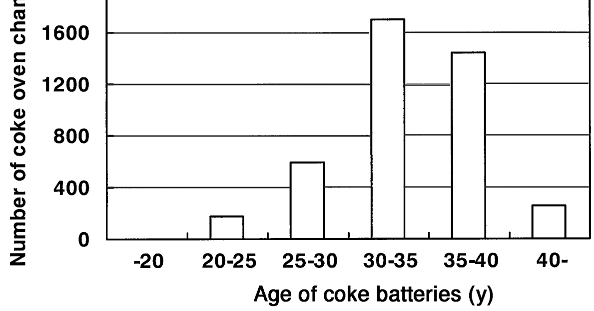


Fig. 16 Age of coke batteries in Japan

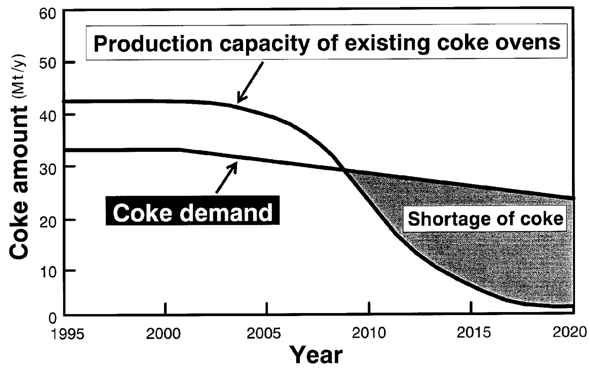


Fig. 17 Production capacity of existing coke ovens

coke oven is 40 years; the graph shows that some measures have to be taken urgently against the short supply of coke expected to take place shortly. In consideration of the aging of coke ovens and the huge costs of their new construction, various techniques were developed to extend the service lives of coke ovens, aiming at a service life of 50 years.

In this respect, Nippon Steel clarified the mechanisms of carbon deposition on the coking chamber walls, taken measures to prevent the deposition, developed facilities for diagnosing the condition of coking chamber walls and repairing them.

2.5 Technologies for resource recycling and energy conservation

To construct a recycling-oriented society and realize zero-emission steel works, the Japanese steel industry has actively promoted (1) energy saving to prevent the aggravation of global warming, (2) recycling of wastes (recycling of steel, nearly 100% use of dust, slag and steel scrap arising from steelmaking processes and recycling of outside wastes such as waste plastics, used tires and home appliances) and (3) development of environment-friendly products and processes (steel products having long service lives, high functionality and free of hazardous materials, eco-plants such as melting/gasification furnaces for waste treatment, etc.).

2.5.1 Resource recycling utilizing ironmaking processes

In the fiscal year beginning from April 2004, 17.6 million metric tons of by-products (not including steel scrap) arose from Nippon Steel's steel works; they were slag (accounting for roughly 70%), dust and sludge. The slag from blast furnaces is used mainly as the raw material for cement production, roadbed material and aggregate for concrete in place of sand, and its recycling rate is 100%.

To recycle the dust and sludge internally and to sell them to outside as the material for zinc refining, Nippon Steel constructed a rotary hearth furnace (RHF) each at Kimitsu[29] and Hirohata Works in 2000 for the first time among the blast furnace manufacturers of the world. The dust and sludge containing iron and carbon are formed into pellets or briquettes, rid of zinc through heating and reducing in the RHF, and the product metallic iron is charged into blast furnaces or electric arc furnaces as a raw material.

The Japanese blast furnace operators are active also in recycling outside waste plastics utilizing their ironmaking facilities. While JFE and Kobe Steel inject waste plastics into blast furnaces, Nippon Steel developed the Coke-Oven from Waste Plastics to Chemical Raw Materials Method[30] whereby waste plastics are charged into coke ovens. The recycling facilities started operation at Nagoya and Kimitsu Works in 2000, at Yawata and Muroran Works in 2002 and at Oita Works in 2004, and the total treatment capacity has increased to more than 200,000 metric tons per year (see **Fig. 18**).

Besides the above, Nippon Steel has developed and commercialized a direct melting system, which is capable of treating a wide variety of wastes (combustible, non-combustible, bulky and recyclable wastes, sludge, incineration residues and excavated wastes) and counts more than 20 supply references of operating units in Japan, processed shredder dust using the direct melting system[31], and is developing a multi-function melting furnace for combined treatment of outside steel scrap and dust[32]. In the field of ironmaking, the company has developed and is developing the process technologies shown in **Fig. 19**.

2.5.2 Challenge to energy saving technologies

Fig. 20 shows the trend of energy consumption of the Japanese steel industry since 1990. The industry has been concentrating efforts to attain a target for 2010 to decrease energy consumption from that in 1990 by 11.5% (including 1.5% through recycling of waste plastics, etc.) on the assumption of a national crude steel production of 100 million metric tons per annum. At a meeting on January 22, 2004 of the Advisory Committee for Natural Resources and Energy, a consultative panel for the Minister of Economy, Trade and Industry, Mr. Akio Mimura, the president of Nippon Steel and chairman of

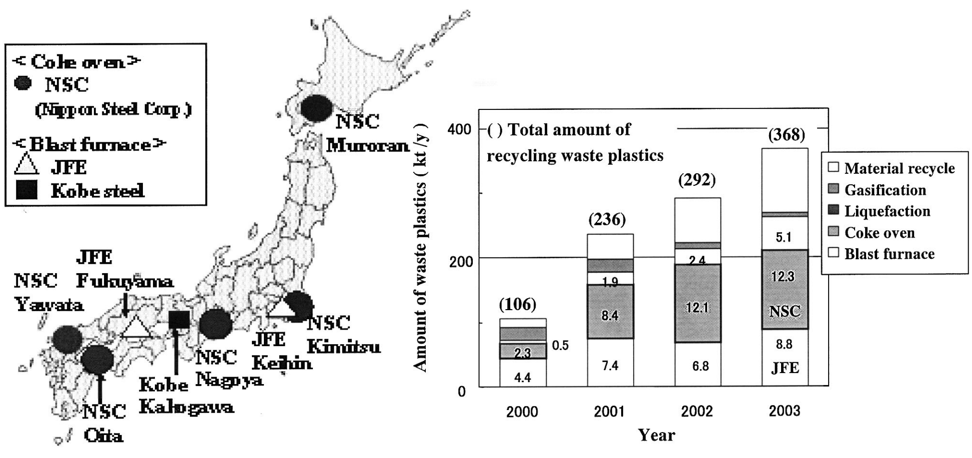


Fig. 18 Ironworks where waste plastics are processed and amount of recycling waste plastics in Japan

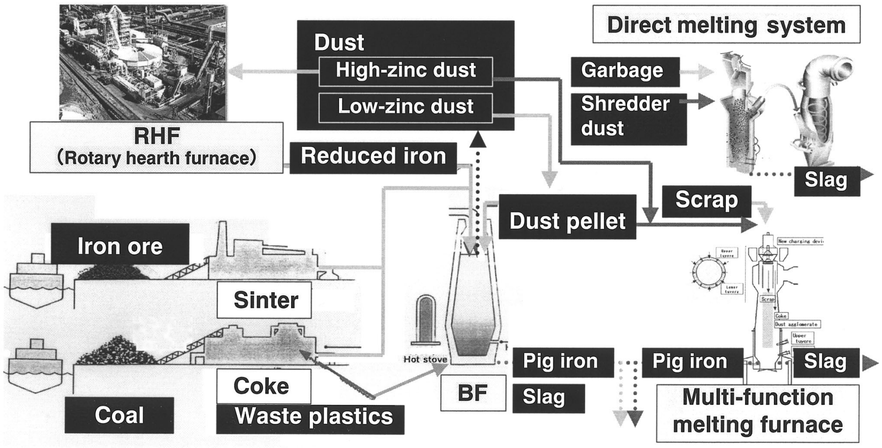


Fig. 19 Ironmaking process including environmental recycle system

(%)

	PCI	TRT*	Hot stove waste heat recovery	Waste heat recovery in sinter	CDQ	CMC or DAPS
1991 cy	78	91	98	56	57	28
2001 cy	100	100	98	72	76	61

*TRT: Top pressure recovery turbine

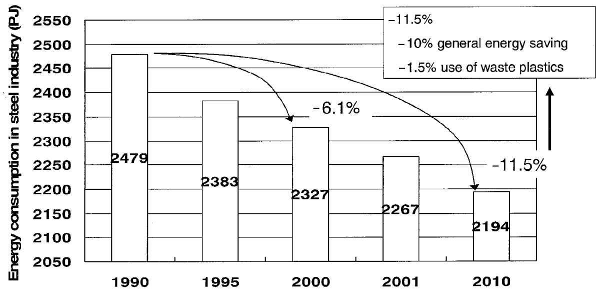


Fig. 20 Trends of energy consumption in the Japanese steel industry since 1990 and the target for 2010

the Japan Iron and Steel Federation, delivered a lecture titled "Energy Prospect for 2030" to explain energy conservation technologies of the industry (see **Fig. 21**). In accordance with the road map presented therein, the ironmaking organization of Nippon Steel is actively promoting wider commercial application of energy conservation technologies, increasing the recycling amount of waste plastics and dust (the target for the whole steel industry is 1 million metric tons per year, Nippon Steel being responsible for 300,000 metric tons) and decreasing the RAR of its blast furnaces.

A joint research project involving the steel industry and universities called "the studies on innovative refining reactions of blast furnaces aiming at halving energy consumption and minimizing environmental loads" was carried out from 1999 to 2004 under Government auspices and the leadership of Mr. K. Ishii, the then Professor of Hokkaido University. Under the framework of the project, Nippon Steel was a member of the group for examining the composition and designing the structure of high-strength ore agglomerate excellent in reducibility and melting properties. As such, through the study on optimization of the gangue composition and pore structure of the

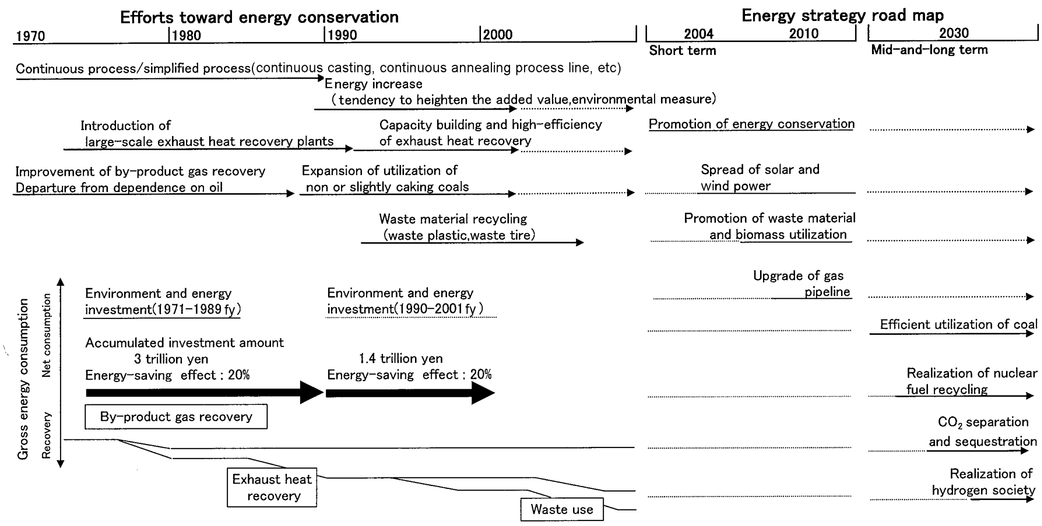


Fig. 21 Efforts toward energy conservation (energy strategy road map)

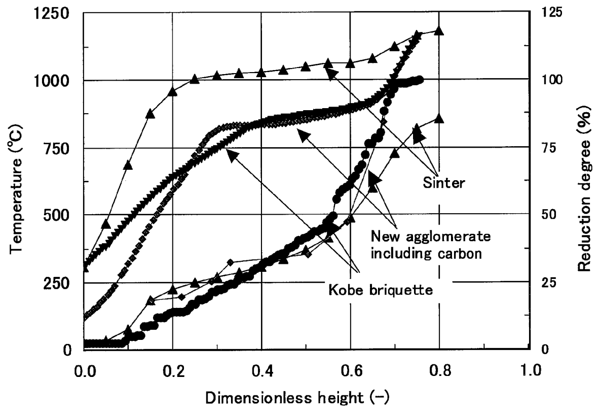


Fig. 22 Reduction behavior of carbon-contained agglomerates in a simulation of an actual furnace operation using BIS

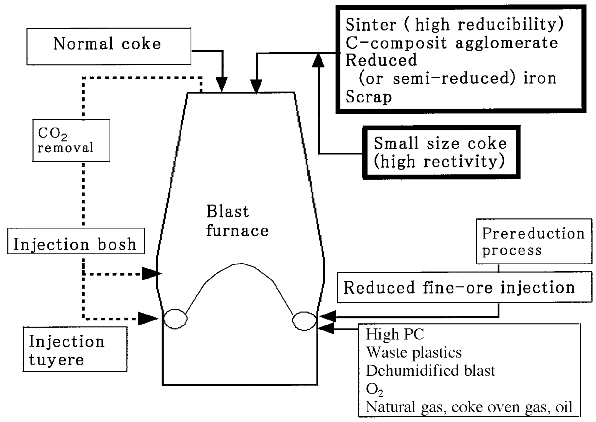


Fig. 24 Process image of next generation BF operation with low RAR

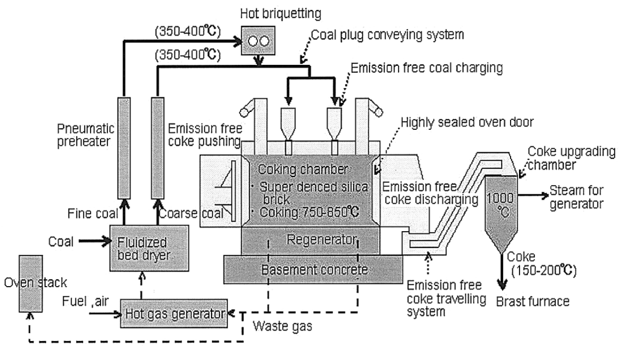


Fig. 23 Schematic diagram of the SCOPE21 process flow

agglomerate, the company (1) set out the structure of ore agglomerate capable of being rapidly reduced and dripping at low temperatures and an adequate rate of its use, and (2) test produced a variety of non-firing, carbon-containing ore agglomerate, and (3) demonstrated that the use of the agglomerate would allow to lower the temperature of the thermal reserve zone of a blast furnace by roughly 200℃ (from 1,000 to 820℃) (see **Fig. 22**)[21], and that the commercial use of the agglomerate would be promising for decreasing CO_2 emission. The use of the ore agglomerate need to be studied further as an important strategic subject of the Japanese steel industry.

On the other hand, as a result of the study on the development of next-generation coke ovens (SCOPE21, see **Fig. 23**)[33] promoted as another national project for about 10 years up to 2004, a 50-t/d pilot plant was constructed at Nippon Steel's Nagoya Works. Tests using the plant confirmed the possibilities of (a) a productivity 2.4 times that of a conventional coke oven, (b) an increase in the mixing ratio of non- and soft-coking coals (from 20 to 50%), (c) reduced environmental loads (a 30% decrease in NO_X emission (to less than 100 ppm)) and (d) a decrease in energy consumption by 21%. Based on the findings, construction of a commercial plant of SCOPE21 at Oita Works has been decided. The plant is expected to bring about a significant energy saving effect when commissioned.

2.6 Development into next-generation ironmaking technologies

Fig. 24 shows an outline of a future blast furnace, prospected based on conceivable technologies including those not commercially applied so far[34].

In such a future blast furnace process, while coke will continue to play the roles of the source of heat and reducing gas, it will also play the role as the medium of gas and liquid permeation (requiring a higher strength) as well as that of improving the efficiency of furnace-inside reactions by controlling the temperature of the thermal reserve zone (requiring a higher reactivity). With respect to the iron source, the use of high-strength, high-porosity, high-reducibility sinter, non-firing, carbon-containing ore agglomerate, pre-reduced iron ore[35] and/or steel scrap would be effective in raising productivity of a blast furnace and lowering the RAR. Other next-generation technologies effective for the purpose include the use of waste plastics for ironmaking, which is effective also in reducing CO^2 emission, the injection of furnace top gas into the shaft (including belly and bosh) or through tuyeres after removing CO_2 (top gas recycling), which is presently studied in European countries, and the injection of fine iron ore through tuyeres[36], which was energetically pursued in the past.

For reference purposes, **Table 5** shows the operation data calculated to minimize the total carbon rate based on the blast furnace process of Fig. 24. Here, it is assumed that coke and ore were of the same quality as those used at present (an ash content in coke of 11.5%), and that the equipment condition was also the same as that at present (an upper limit blast temperature of 1,250℃)[34].

In the table, the operation conditions of JFE Fukuyama No. 3 BF, which recorded the lowest RAR ever, were used for Base Case, and the operation data for Cases 4 to 7 were calculated based on those of Base Case (RAR 428 kg/t) and taking into consideration the following conditions: (1) injection of waste plastics [for Cases 4 to 7], (2) injection of fine ore (70% pre-reduced) through tuyeres [for Cases 5 to 7], (3) charging of pre-reduced iron (M-Fe, 100 kg/t) from the furnace top [for Cases 6 and 7], (4) control of the reduction equilibrium temperature by use of high-reactivity coke (a decrease in the temperature of the thermal reserve zone by 100℃) [for Case 7], and (5) injection of furnace top gas into the shaft or through tuyeres after CO2 removal [for Case 8]. The total carbon rate (TCR) at the bottom of the table is that of the whole ironmaking process, and therefore, in consideration of factors such as the yields in the sintering and cokemaking processes, it was calculated as $TCR = (CR/0.65 + PC + 73.6 \cdot SR/1000) \cdot (C)_{PC} + PC_2 \cdot (C)_{PC2}$. Note that the carbon rates of the production of oxygen and the overseas production of pre-reduced ore using natural gas were not taken into consideration. Assuming that the total carbon rate by the current furnace operation with the PCI is 580 to 630 kg/t, in order to decrease the rate by more

Table 5 Technologies for reducing the carbon ratio and their effects

		Base	Case 1	Case 2	Case 3	Case 4	Case 5	Case 6	Case 7	Case 8
RAR	kg/t	428.15	453	443.05	461.35	455.05	449.05	430.05	409.05	377.05
CR	kg/t	386.05	453	345.05	239.1	255.1	249.1	230.1	209.1	227.1
PCR	kg/t	0	0	98	222.3	150	150	150	150	150
Tar	kg/t	42.1	0	0	0	0	0	0	0	0
Plastic	kg/t	0	0	0	0	50	50	50	50	0
Reduced-ore injection (R: Pre-reduction degree = 0.7)	kg/t	0	0	0	0	0	100	100	100	0
Miscellaneous	kg/t	0	0	0	0	0	0	100	100	0
Shaft gas (CO: 72, CO_2: 1.5, H_2: 11)	Nm^3/t	-	-	-	-	-	-	-	-	348
Tuyere gas (CO: 72, CO_2: 1.5, H_2: 11)	Nm^3/t	-	-	-	-	-	-	-	-	216
SR	%	80	80	80	80	80	80	68	68	80
Ore/Coke	-	4.13	3.53	4.63	6.71	6.28	5.82	5.74	6.32	7.08
Blast temp.	℃	1250	1100	1250	1250	1250	1250	1250	1250	-
Blast moisture	g/Nm^3	5.6	15	5.6	5.6	5.6	5.6	5.6	5.6	-
Cold O_2	Nm^3/t	-	-	-	-	-	-	-	-	225
O_2 enrichment	%	0.00	0.00	0.00	3.67	3.98	7.43	25.34	21.15	79.1
Top gas temp.	℃	87	72	130	197	196	198	198	197	166
η H_2	%	50	50	50	50	50	50	50	50	50
η co	%	54.3	53.4	53.9	52.0	51.6	49.5	48.2	53.0	43.1
Coke ash	%	11.5	11.5	11.5	11.5	11.5	11.5	11.5	11.5	11.5
Drop of pig temp.	℃	0.0	–3.2	–6.1	–17.0	–17.7	–25.4	–28.2	–40.4	–32.6
Slag	kg/t	282	295	285	278	275	252	189	185	268
Heat flux	-	0.836	0.839	0.801	0.758	0.763	0.755	0.932	0.912	0.779
C sol.	kg/t	101.4	102.0	98.6	83.7	79.8	63.9	32.0	25.7	19.1
Shaft efficiency (η shaft)	%	97.6	97.6	97.6	97.6	97.6	97.6	97.6	97.6	100
Temp. of thermal reserve zone	℃	950	950	950	950	950	950	950	850	950
Flame temp.	℃	2285.7	2242.4	2216	2106.3	2093.5	2049.9	2265.8	2141.9	2252.4
Total coal rate	kg/t	725.1	792.7	724.3	685.3	637.5	617.4 + α	565.2 + α	532.8 + α	594.3 + β
Total carbon	kg/t	572.8	626.2	572.2	541.4	503.7	487.8 + α	446.5 + α	420.9 + α	469.5 + β
		Tar injection	(Muroran) All coke	(Oita) PC injection	(Pohang) PC injection	Plastic injection	Plastic injection + Ore injection	Plastic, ore injection + MFe	Plastic, ore injection, MFe + High-RI coke	Top gas recycling

α : carbon rate of producing pre-reduction ore

β : carbon rate of manufacturing O_2

than 10%, it is necessary to establish technologies for the commercial application of the measures employed in Cases 3 to 8.

3. Prospects of Next 10 Years

The conditions of the natural resources and environment surrounding the ironmaking processes will become more and more difficult. Furthermore, the Japanese steel industry will have to face increasingly tough competition with the counterparts of the near-by countries. In addition, the following problems are expected to become tangible:

- The reduction of pig iron production costs by the present technologies will come to a limit.
- The aging of the present production equipment will advance.
- In view of the increasingly tight supply of coke in the global market, overseas coke sources will be scarcely counted on.
- Environmental regulations will become more and more demanding in consideration of global warming and the construction of a recycling-oriented society.

To face and respond to these problems adequately, technical development from viewpoints different from conventional ones will be required. The possible avenues include, for example:

(1) Significant decrease in the reduction and smelting loads on the blast furnace process through reforming of the feedstock by measures such as pre-treatment by mining companies,
(2) Further improvement in efficiency and decrease in the number of units of equipment,
(3) Increase in the added value of the by-products arising from the ironmaking processes,
(4) Contribution to the recycling-oriented society through ironmaking processes closely linked with coal reforming processes and waste handling systems, and
(5) Fostering of experts and furthering of automation.

In the pursuit of subjects such as the above, the ironmaking organizations will have to deepen the cooperative relationships with mining companies and related technical fields, work together with academic entities more closely, and thus work out new technologies that meet the needs of the time.

References

1) Kase, S., Sugata, M., Okuda, K., Umetsu, Y., Amano, S., Ono, S., Mizuuchi, C.: Tetsu-to-Hagané. 67, S82(1981)
2) Kajikawa, S., Yamamoto, R., Nakajima, R., Kishimoto, J., Fukushima, T.: Tetsu-to-Hagané. 68, 2361(1982)
3) Waguri, S.: Bulletin of The Iron and Steel Institute of Japan. 8(6), 371(2003)
4) Nozawa, K., Maki, T., Shibata, K., Goto, T., Hori, R., Matsui, Y.: CAMP-ISIJ. 11, 833(1998)
5) Maruyama, T., Maki, A., Shimomura, A., Ohkohchi, I., Mori, K., Sato, M., Murai, R.: CAMP-ISIJ. 11, 834(1998)
6) Haga, T., Oshio, A., Nakamura, K., Kozono, T., Uekawa, S.: Tetsu-to-Hagané. 83, 103(1997)
7) Inazumi, T., Fujimoto, M., Kasama, S., Sato, K.: Tetsu-to-Hagané. 77, 63-70(1991)
8) Shibata, D., Haga, T., Oshio, A., Kasama, S., Watanabe, K.: CAPM-ISIJ. 14, 193(2001)
9) Higuchi, K., Kawaguchi, T., Kobayashi, M., Hosotani, Y., Nakamura, K., Iwamoto, K., Fujimoto, M.: ISIJ International. 40, 1188(2000)
10) Uematsu, H., Ishida, Y., Kushioka, K.: Ironmaking Conference Proceedings. 1989, p.109
11) Waguri, S., Ohnishi, T., Nakagawa, K., Ohno, M., Ogawa, S., Kushioka, K., Konno, Y.: Seitetsu Kenkyu. (322), 81(1986)
12) Nakashima, Y., Mochizuki, S., Ito, S., Nakagawa, K., Nishimoto, K., Kobayashi, K.: 2nd International Cokemaking Congress. London, UK, 1992, p.518
13) Saito, K., Komaki, I., Hasegawa, K., Tsuno, H.: Proceedings of 13th-International Symposium on Magnetic Resonance. Berlin. 2, 1998, Berlin Institute Technology, p.581
14) Uenaka, T., Miyatani, H., Hori, R., Noma, F., Shimizu, M., Kimura, Y., Inaba, S.: Iron & Steel Maker. (November), 34(1988)
15) Matsui, A., Kakiuchi, K., Akagi, K., Matsuzaki, S., Ootsuka, H.: ICSTI/Ironmaking Conference Proceedings. 1998, p.334
16) Naito, M.: Proceedings of 179th Nishiyama Memorial Technical Conference. 2003, p.87-121
17) Naito, M., Okamoto, A., Yamaguchi, K., Yamaguchi, T., Inoue, Y.: Tetsu-to-Hagané. 87, 357(2001)
18) Kajikawa, S., Yamamoto, R., Nakajima, R., Kishida, J., Fukushima, T.: Tetsu-to-Hagané. 68, 2361(1982)
19) Higuchi, M., Matsuoka, Y., Inoue, Y., Nakayama, T., Morimoto, S., Takao, M., Matsuzaki, S., Naito, M., Deno, T.: CAPM-ISIJ. 7, 1012(1994)
20) Nomura, S., Ayukawa, H., Kitaguchi, H., Tahara, T., Matsuzaki, S., Naito, M., Koizumi, S., Ogata, Y., Nakayama, T., Abe, T.: ISIJ International. 45, 316-324(2005)
21) Naito, M., Nakano, M.: Study on Innovative Blast Furnace Refining Reactions Aiming at Halving Energy Consumption and Minimizing Environmental Loads - Final Report, 2004
22) Yagi, J.: Tetsu-to-Hagané. 69, 1242(1983), 81, 258(1995)
23) Naito, M., Murayama, T., Usui, T.: Tetsu-to-Hagané. 80, 581(1994)
24) Nogami, H.: Tetsu-to-Hagané. 89, 211(2003)
25) Sugiyama, T., Sugata, M.: Seitetsu Kenkyu. (325), 34(1987)
26) Okuno, Y., Irita, T., Matsuzaki, S.: Tetsu-to-Hagané. 72, 783(1986)
27) Naito, M., Yamaguchi, K., Sugiyama, T., Inoue, Y.: AIME. 10th PTD Conference Proceedings. 1992, p.55
28) Shinotake, A., Nakamura, M., Ohtsuka, H., Sasaki, N., Kurita, Y.: CAMP-ISIJ. 14, 750(2001)
29) Oda, H. et al.: Shinnittetsu Giho. (376), 28(2002)
30) Kato, K. et al.: ISIJ International. 42, (Supplement), S10(2002)
31) Shibaike, H., Osada, M., Takamiya, K., Naito, M.: ISIJ International. 40, 252(2000)
32) Naito, M., Araki, K., Fukazawa, Y., Obara, T., Obara, Y.: Gakushin 54 Iinkai Shiryo. 2224, 2001
33) Nakai, H., Sasaki, M., Matsuura, M., Nishioka, K., Sugiyama, I., Suyama, S.: 3rd Int. Conference on Science and Technology of Ironmaking. 2003, p.550
34) Naito, M. et al.: Low-reducing-agent Operation of Blast Furnaces. Gakushin 54 Iinkai Shiryo. 2004
35) Kunitomo, K., Takagi, Y., Naito, M.: Gakushin 54 Iinkai Shiryo. 2251, 2002
36) Yamaguchi, K., Ueno, H., Naito, M., Tamura, K.: Tetsu-to-Hagané. 77, 1609(1991)