Flow Sheet Model Evaluation of Nuclear Hydrogen Steelmaking Processes with VHTR-IS (Very High Temperature Reactor and Iodine-sulfur Process)

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Nuclear hydrogen steelmaking (NHS) and nuclear hydrogen partial reduction steelmaking (NHPRS) systems were proposed using very high temperature reactor, and thermochemical hydrogen production iodine-sulfur process. Heat input and CO₂ emissions of these systems were analyzed by heat and mass balance calculation. Total net heat input to the NHS system was 28.4 GJ/t-high quality steel (HQS), including material production, material transportation, and power generation. This value was much larger than that of a blast furnace steelmaking (BFS) system of 17.6 GJ/t-HQS. Reduction of hydrogen consumption in the shaft furnace and electricity consumption in the electric arc furnace were desired for lowering the heat input. Total net heat input of a NHPRS system was 31.9 GJ/t-HQS. Optimization of operation parameters such as the reduction ratio of partial reduced ore (PRO) and ratio of the PRO input to the blast furnace is desired to decrease the heat input. CO₂ emissions of the NHS system and the NHPRS system were 9% and 50% of that from the BFS system. Substitution of coal by hydrogen and reduction of transportation weight contributed to the reduction. Steelmaking cost was also evaluated. When steelmaking scale of each system was unified to one million t-HQS/y, NHS was economically competitive to BFS and Midrex steelmaking. And NHS was advantageous at higher cost of resources.

KEY WORDS: nuclear hydrogen steelmaking; partial reduced ore; very high temperature reactor; nuclear hydrogen production; IS process; flow sheet analysis; CO₂ emissions; steelmaking cost.

1. Introduction

2.6 Gt of CO₂ emitted from steelmaking in the world including power generation for steelmaking in year 2006. Reduction of 0.35 Gt is estimated with the existing best technologies. However, in year 2050, CO₂ emissions should be reduced from 4.8 Gt to 1.4 Gt to limit the emissions to the half of the year 2006. Present technologies are not enough to achieve the objective. Use of low carbon materials such as natural gas and steel scrap, novel steelmaking processes such as smelting reduction, carbon capture and storage (CCS) should be introduced in large scale.¹⁾ The requirement is so serious that many methods should be developed. Hydrogen steelmaking can be one of such new CO₂ reduction methods. Usually, iron ore is reduced by coke. CO₂ production is inevitable because coke contains carbon element. Hydrogen can be used for ore reduction and only H₂O is made. However, hydrogen is mainly made by steam reforming of natural gas and CO₂ is emitted in the process of reforming. When hydrogen from steam reforming is used for ore reduction, total CO₂ reduction is limited. Hydrogen production methods from non carbon containing material are desired. Thermochemical water splitting is a method of hydrogen production from combination of several reactions which proceed thermally. Material source of hydrogen is H₂O, non carbon containing material. Heat

demand of the method can be supplied from, for example, nuclear heat source without CO₂ emissions. The integration of such heat source, thermochemical hydrogen production process and hydrogen steelmaking process is capable of producing iron with theoretically no CO₂ emissions.

When blast furnace (BF) plant is replaced to the hydrogen steelmaking plant, facilities of the BF plant are abandoned. Such facilities are very expensive and lifetime of them is long (15–20 years for BFs and about 40 years for coke ovens). Waiting for the replace could result in a delay of introduction of hydrogen steelmaking. An idea of hydrogen partial reduction (HPR) of iron ore at the site of the mining is proposed as an intermediate method in the way to the hydrogen steelmaking. HPR is expected to reduce CO₂ emissions by reduction of carbon containing reduction materials and by weight reduction of ore to be transported to the BF process with removal of oxygen bound to iron. Introduction of the HPR does not have to wait for replace time because existing BF plants are kept.

Very high temperature reactor (VHTR), a kind of nuclear reactor featuring high temperature helium gas heat carrier and graphite moderator in the core, and thermochemical hydrogen production iodine-sulfur (IS) process have been developed for several decades mainly in Japan Atomic Energy Agency (JAEA), Japan. VHTR is designed to remove core heat by itself because of its high thermal conductivity and heat capacity of the core graphite, and because heat radiation from the core vessel and natural convection. The heat removal works without special facilities in the case

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of accidents of loss of helium heat carrier or stop of helium circulation pumps. This inherent safety utilizing physical phenomenon is not achieved in light-water reactor, commonly used at present.²⁾ IS process is comprised of the three chemical reactions below;

The highest temperature requirement is 800–900°C in the reaction (2); the temperature matches the attainable temperature of 950°C from the heat from a VHTR. Hydrogen steelmaking needs H_2 as reduction agent and O_2 for fuel combustion and decarbonation in electric arc furnace (EAF) *etc.* IS process has an advantage that both gases are produced at the same time. Detail of the R&D of VHTR and IS process are summarized in another paper in this issue.³⁾

Reduction of iron ore by hydrogen has been researched in laboratory scale experiments aiming to clarify the reduction mechanism and reaction rate.⁴⁾ Hydrogen shaft furnaces have been simulated based on the knowledge obtained by such studies.⁵⁾ Experimental study of reduction by 98% of H_2 in a shaft furnace in the scale of direct reduced iron of 500 kg/day achieved reduction temperature of above 700°C and reduction ratio of more than 95%.⁶⁾ Recently hydrogen steelmaking is focused as a less CO_2 process. Hydrogen shaft furnace method was modeled and simulated in ULCOS (Ultra Low CO_2 Steelmaking), a European program during 2004–2006.⁷⁾ In U.S., hydrogen direct reduction method using gas-solid suspension of fine iron ore was researched under AISI (American Iron and Steel Institute) during 2005–2007.⁸⁾

Concept of partial reduction of iron ore has been proposed to reduce CO_2 emissions in the total steelmaking procedure.^{9,10)} In this concept, iron ore is reduced partially at the site of the mining and the partial reduced ore (PRO hereafter) is transported to the site of consumption and reduced completely to iron in BFs there. The partial reduction can decrease energy burden of transport by reducing weight of oxygen and adsorbed water from the ore. When direct reduction by reformed natural gas is used for the partial reduction, CO_2 emissions are expected to be decreased because H/C ratio of the reformed gas is higher than coke.

Specific heat consumption and CO_2 emissions per unit amount of pig iron were decreased by 0.3% and 2.0% from a BF process on assumption of 130 kg/t-pig iron of partial reduced ore of reduction ratio of 60%.¹⁰⁾ If hydrogen replaces the reformed gas in such partial reduction, the CO_2 reduction effect is expected to be greater.

In this study, the concepts of nuclear hydrogen steelmaking (NHS) method and nuclear hydrogen partial reduction steelmaking (NHPRS) method applying VHTR and IS process were introduced. Heat demand and CO_2 emissions of the steelmaking systems were compared with blast furnace steelmaking (BFS) system to show the effectiveness of the concepts. Preliminary cost analysis of the NHS system was carried out to show the goal of nuclear hydrogen production cost.

2. Calculation of Heat Demand, CO_2 Emissions, and Cost of Hydrogen Steelmaking Systems

2.1. Heat and Mass Balance and CO_2 Emissions of Steelmaking

NHS system and NHPRS system were analyzed through flow sheet calculation. Heat demand and CO_2 emissions were compared with a BFS system. Though many flow sheet analyses of BF processes have been reported (*e.g.*¹¹⁾), there is no published evaluation of the whole process with enough process data such as composition of materials, material balance, temperature and pressure of process components enough for comparison with other steelmaking processes. And only rough analysis of hydrogen steelmaking process flow sheet was published.^{12,13)} NHPRS system has never analyzed before the research of Green Energy Steelmaking Research Group, a research group of ISIJ (Iron and Steel Institute of Japan) during 2008–2012. The analysis should include transportation of resources to evaluate the influence of HPR. However, most analyses of steelmaking did not consider transportation. In this study, BFS system, NHS system and NHPRS system were analyzed using uniform data of materials only from published data with an evaluation of transportation.

Figure 1 illustrates schematic diagrams of systems of NHS method and NHPRS method with BFS method as a reference. In this study, the word “system” denotes the total

Fig. 1. Schematic diagram of steelmaking systems for heat and mass balance analysis.

steelmaking procedure being comprised of production of resources, transportation of resources, power generation for steelmaking, and steelmaking process itself. Coal and iron ore are transported from the mining site to the BF process in the consumption site in the BFS system. In the NHPRS system, some part of ore is partially reduced to produce PRO by hydrogen produced in an IS process using VHTR nuclear heat. The ore, PRO and mined coal are transported to a BF process to produce steel. In the NHS system, uranium fuel and ore are transported to a HR process at the consumption site. The uranium fuel is consumed in a VHTR to generate heat and electricity for an IS process hydrogen production and an electric arc furnace (EAF). The ore is reduced by the VHTR-IS hydrogen to produce steel.

Detail flow sheet of the BF process and the NHR process are explained here. **Figure 2** show the flow diagram of the BF process considered in this study. This flow diagram is a simplified one for the evaluation; heat exchangers, compressors and waste heat removals are not shown; heat and mass balance inside the components is not shown even if calculations were done. Coal is first dried in the coke drier and then fed to the coke oven (COV). Coking is made in the oven by the combustion heat of coke oven gas (COG) and blast furnace gas (BFG) produced within the process. Coke is produced and COG, tar and light oil are obtained as by-products. The coke is high temperature and its much sensible heat is recovered as steam in the coke dry quencher (CDQ). The cooled coke is separated by the particle size; fine coke is used in sintering and lump coke is fed to the BF. Small grain of iron ore is sintered before fed to the BF to prevent clogging in the furnace. Ore is mixed with coal, fine coke from the CDQ, and lime as flux. The coal and fine coke in the mixture are burned and sinter is produced. A little amount of COG is used for ignition of the sintering. The heat made in the sintering is recovered as steam. Smaller iron ore grain than that for sintering is used by pelletizing. Such ore is mixed with lime as flux, bentonite as binder, and water. The mixture is calcinated in a rotary kiln by flame of burning COG to produce pellet. BF is used to produce pig iron. Iron sources of ore, sinter and pellet are fed to the top of the furnace with coke. Blast is injected to the furnace with pulverized coal (PC) and reduction reaction of iron oxides in the iron sources happens. Blast is mixture of air, steam and oxygen; steam is fed from the CDQ and oxygen is made

by cryogenic separation of air. The mixture gas is heated to be the blast in the heat stove (HS) heated by combustion of COG and BFG. Liquid pig iron is produced and separated from slag in the BF. Sensible heat of slag is recovered as steam. BFG is blown off from the top of the furnace and a TRT (Top pressure Recovery Turbine, not shown in the figure) generates electricity by using high pressure of the BFG. The pig iron from the BF is pre-treated during the transportation to a converter in a torpedo car because the pig iron contains more Si than desired. Iron scale and CaO are added to the pig iron and oxygen is injected. Slag containing SiO_2 is separated and pig iron of low Si is produced. The pig iron is introduced to the converter and additional iron source of scrap, ore and iron scale, slag forming flux of CaO, dolomite and burnt dolomite are added. Oxygen is injected and carbon element contained in the pig iron is oxidized and removed as Linzer-Donawitz converter gas (LDG). Steel is tapped as the product of the converter and metal oxides in the materials are separated as slag. Sensible heat of the slag is recovered to produce steam. This slag contains much iron oxide and this is separated from other metal oxides by crashing. Secondary refinement of the steel from the converter is done in Ruhrstahl-Heraeus (RH) procedure to remove carbon and oxygen elements. High quality steel (HQS hereafter) of less carbon and oxygen elements are produced as the product of the process. Some part of COG, BFG and LDG by-products gases is consumed within the process. The remaining gases are used with tar and light oil from the COV to generate electricity by a gas turbine. The electricity is consumed within the process and sold to outside when excess electricity is generated.

Figure 3 illustrates the flow diagram of the HR process. Heat exchangers, compressors, and waste heat removals are not shown. And heat and mass balance within the process components are not either shown as in Fig. 2. H_2 and O_2 are produced in the IS process using heat and electricity from the VHTR and the power generator, respectively. All H_2 and small amount of O_2 are fed to the shaft furnace (SF) and reduction of iron ore takes place. Lump ore is used as iron source. Major part of H_2 is used for the reduction and a little H_2 and O_2 are burned to keep the temperature in the furnace. H_2O and unreacted H_2 are left the furnace from the top and cooled. H_2O is separated from H_2 in the scrubber and H_2 is recycled into the stream from the IS process. The iron ore

Fig. 2. Blast furnace (BF) process.

Fig. 3. Hydrogen reduction (HR) process.

Fig. 4. Hydrogen partial reduction (HPR) process.

is reduced to direct reduced iron (DRI) in the furnace. Recently, HOTLINK[®], the method to feed the hot DRI (HDRI) just produced directly to the electric arc furnace (EAF) to use sensible heat of the HDRI efficiently, is developed in Midrex[®] process.¹⁴⁾ Here, direct introduction of HDRI to the EAF is applied. In addition to the HDRI, iron source of scrap and CaO slag forming flux are fed. These materials are melted by electric heating. Carbon element from electrodes resolves into the melt. Decarburization occurs simultaneously and excess carbon is removed as CO₂ by O₂ injection. The electricity and O₂ supplied to the EAF are produced in the VHTR power generator and the IS process, respectively. Steel is produced and slag is separated in the furnace. Heat of the slag is recovered as steam and then iron oxide contained in the slag is separated as in the BF process. Carbon and oxygen impurities in the steel are removed in the RH procedure and HQS is made as the product of the process. O₂ for the secondary refinement process is fed from the IS process. No combustible by-product gas is produced in the process.

The NHPRS system uses the some part of the HR process and the BF process. **Figure 4** shows the HPR process. Only hydrogen production part and hydrogen shaft furnace part of the HR process are used. PRO is obtained from the SF instead of HDRI in the HR process. The PRO should be cooled to atmospheric temperature to be transported to the BF site. The cooling is done by inert gas injection and the heat is recovered to generate steam. In the BF process, the PRO is fed to the BF like lump ore. Reduction ratio of the PRO and ratio of PRO input to the BF were important oper-

ation parameters for the system. Reduction ratio of the PRO was defined as the ratio of removed oxygen element by the partial reduction (as mol) to oxygen element in the iron oxides in the ore (as mol). When the reduction ratio was small, effect of the partial reduction was small. On the other hand, high reduction ratio requires long reduction time and a large SF. To balance these factors, reduction ratio of 75% was assumed. Ratio of the PRO input to the BF of 100% was applied here to eliminate sintering and pelletization from the BF process.

Heat and mass balance of the steelmaking processes were calculated as follows. The calculation was made on Microsoft EXCEL, not using commercial process simulators. Composition of materials used in the BFS system and NHS system is summarized in **Table 1**. Composition data for NHPRS system is summarized in **Table 2**. Compositions of materials not displayed in the table are the same as those in Table 1. Elemental composition of coal, tar and light oil are shown in **Table 3** because these compounds are mixtures of many chemical species. Reference of the composition and thermodynamic data of the materials are not shown here because many references are used in the calculation. Only major impurity elements in iron ore (Al, Si, Ca and Mg) were considered; minor impurity elements such as S and P were not considered because these elements had little effect on heat and mass balance.

Heat and mass balance of the processes were calculated by integrating calculation of each part in a square of broken line in Figs. 2–4. Heat and mass balance of the total steel-making systems were made by normalizing the production

Table 1. Composition of materials used in the blast furnace steelmaking (BFS) and nuclear hydrogen steelmaking (NHS) systems.

Material	unit	Coal(dry ash free)	Tar	Light Oil	C	Fe ₂ O ₃	Fe _{0.947} O	Fe	Al ₂ O ₃	SiO ₂	Si	CaO	CaCO ₃	MgO	MgCO ₃	CH ₄	CO	CO ₂	H ₂	O ₂	H ₂ O	N ₂
Coal	wt fraction	0.927							0.021	0.036		0.001		0.001							0.015	
Pulverized Coal	wt fraction	0.927							0.021	0.036		0.001		0.001							0.015	
Dry Coal	wt fraction	0.941							0.021	0.036		0.001		0.001							0.000	
Tar	wt fraction		1.000																			
Light Oil	wt fraction			1.000																		
Coke	wt fraction				0.860				0.035	0.061		0.002		0.001							0.041	
Dry Coke	wt fraction				0.896				0.037	0.063		0.002		0.001								
Electrode	wt fraction				1.000																	
Ore	wt fraction					0.827	0.006		0.027	0.056		0.001		0.003							0.079	
Sinter	wt fraction					0.835	0.006		0.029	0.060		0.066		0.004								
Pellet	wt fraction					0.856	0.006		0.030	0.065		0.039		0.004								
Pig Iron(incl. Si)	wt fraction				0.048			0.948			0.004											
Pig Iron	wt fraction				0.045			0.954			0.002											
HDRI	wt fraction						0.000	0.869	0.040	0.084		0.002		0.005								
Scrap	wt fraction				0.002			0.962	0.005	0.021	0.001	0.005		0.004								
Scale	wt fraction					0.789	0.157			0.054												
Steel	wt fraction				0.001		0.001	0.998														
HQS(High quality steel)	wt fraction				0.000		0.000	0.999														
Iron oxide(Converter)	wt fraction					0.2792	0.7208															
Iron oxide(EAF)	wt fraction						1.0000															
Slag(BF)	wt fraction								0.233	0.429		0.311		0.026								
Slag(pre treatment)	wt fraction						0.864			0.113		0.023										
Slag(Converter)	wt fraction								0.020	0.108		0.746		0.126								
Slag(EAF)	wt fraction								0.231	0.489		0.249		0.032								
Bentnite	wt fraction					0.038			0.183	0.753		0.009		0.016								
CaO	wt fraction											1.000										
Lime	wt fraction					0.001			0.002	0.004			0.988	0.005								
Burnt Dolomite	wt fraction									0.005		0.656		0.338								
Dolomite	wt fraction									0.003			0.615		0.382							
Water	wt fraction																				1.000	
COG	mol fraction															0.331	0.137		0.512			0.019
BFG	mol fraction																0.219	0.211	0.033	0.000	0.076	0.461
LDG	mol fraction																0.780	0.178	0.043			
Air	mol fraction																			0.210		0.790
H ₂	mol fraction																		1.000			
O ₂	mol fraction																			1.000		
Blast	mol fraction																			0.258	0.029	0.713

Table 2. Composition of materials used in the nuclear hydrogen partial reduction steelmaking (NHPRS) system.

Material	unit	Fe _{0.947} O	Fe	Al ₂ O ₃	SiO ₂	CaO	MgO
PRO(Partial reduced ore)	wt fraction	0.367	0.513	0.037	0.077	0.002	0.005
Slag(BF)	wt fraction			0.330	0.614	0.018	0.037

Material	unit	CO	CO ₂	H ₂	H ₂ O	N ₂
BFG	mol fraction	0.282	0.118	0.058	0.037	0.504

Materials not in this table is the same as in Table 1.

of one ton of HQS. Data of mass balance, temperature and pressure of the parts were taken from literature. The data sources are summarized in **Table 4**. Heat and mass balance within the BF and the SF were calculated using Rist method.^{20,21)} The furnaces were separated to the upper pre-heating zone and the lower process zone. Iron oxides in the iron source (Fe₂O₃, Fe₃O₄) were reacted with CO and H₂ from the process zone to Wüstite (Fe_{0.947}O); Reaction equilibriums at 1 000°C (1 273.15 K) of,

were achieved in the pre-heating zone. BFG was flowed off from the top of the BF. Coke, PC and O₂ in the blast reacted to produce CO, and the reaction of coke, PC with H₂O pro-

Table 3. Element composition of materials.

		Elements			
		C	H	O	N
Coal(dry ash free)	mol/kg	68.3	51.5	2.8	0.8
Tar	mol/kg	76.5	55.2	1.1	0.6
Light Oil	mol/kg	72.1	135.1	0.0	0.0

duced H₂ in the process zone. Some part of the CO and H₂ reduced Fe_{0.947}O to Fe and the other part flowed up to the pre-heating zone. Pig iron and slag of defined composition as shown in Table 1 were obtained from the bottom. Total heat balance of the BF comprising of the pre-heating zone and process zone was attained. Coke and PC consumed in the BF were resulted from the BF calculation. We modified the original Rist model for the SF because the original model was for BF. In the case of SF, only H₂ injected from outside was considered as reducing material. Top gas of H₂ and H₂O mixture flowed from the top; HDRI (or PRO) containing oxides of impurities were obtained from the bottom. Reaction equilibrium of Eq. (5) was assumed at 1 000°C (1 273.15 K).²⁷⁾ Total heat balance of the SF comprising the pre-heating zone and process zone was made. The SF in the HPR process has also the cooling zone at the bottom to cool the PRO to atmospheric temperature.

Nuclear heat and electricity consumption and waste heat which must be abandoned to work the IS process to produce H₂ were calculated from a material and energy analysis of

Table 4. Data sources for the heat mass balance calculation.

	Part	Mass balance	Temperature	Pressure
Blast furnace (BF) process	Coking	15)	15) (main part), 16) (CDQ)	15)
	Sintering	17)	18)	18)
	Pelletizing	19)	19)	19)
	Blast furnace	19) (main part); 20, 21) (within BF)	19) (main part); 22) (FeO/Fe equilibrium)	19)
	Converter	19)	19)	19)
	Refinement	This analysis	23)	24)
Hydrogen reduction (HR) process	VHTR	25, 26) (uranium requirement)	-	-
	Hydrogen production	This analysis	This analysis	This analysis
	Shaft furnace	This analysis(main part); 20, 21) (within SF)	27)	27)
	Electric arc furnace	28)	19)	19)
	Refinement	This analysis	23)	24)
Hydrogen partial reduction (HPR) process	VHTR	25, 26) (uranium requirement)	-	-
	Hydrogen production	This analysis	This analysis	This analysis
	Shaft furnace	This analysis(main part); 20, 21) (within SF)	27)	27)

Fig. 5. Range of the heat and mass balance analysis.

the process in JAEA. Nuclear heat of 525.7 kJ/mol-H₂ and electric energy of 68.6 kJ/mol-H₂ including 29.5 kJ/mol-H₂ for auxiliary such as a helium circulator for heat transfer from the VHTR were used to produce 1 mol (2 g) H₂. Hydrogen production thermal efficiency using Eq. (6) was 42.6%.

$$\eta = \frac{\Delta H_{H_2, HHV}}{Q + \frac{W}{\eta_e}} \times 100 \quad \dots \dots \dots (6)$$

Heat loss from body of process components and pipes were not considered except the EAF. Electricity consumption of the EAF was set at 470 kWh/t-steel of an actual operation data.²⁹⁾ Heat loss was counted to achieve enthalpy balance of the EAF because the electricity consumption data included the heat loss from the body.

By-product electricity generation was enough for the BF process electricity demand; VHTR power generation was considered in the HR process and the HPR process. Electricity generation thermal efficiency, the ratio of electricity to combustion heat of fuels, from by-product gases was set at 55.8% assuming a combined gas turbine¹⁷⁾ and from tar and light oil was assumed as 40% in BF process. Electricity was also generated from the steam by using an adiabatic heat cycle. Electricity generation thermal efficien-

cy of the VHTR power generation was 47% assuming GTHTR300C, the heat-electricity cogeneration VHTR.³⁰⁾

The gray colored zone in **Fig. 5** shows the steelmaking process, that is, the range of heat and mass balance analysis. The power generator, the IS process, and by-product electricity generation are in the process; the VHTR is not included. Water input to the IS process is not shown because this is not expensive and can be obtained easily. Uranium consumption in VHTR is evaluated separately to investigate the heat input to processes. Material outputs are HQS product, by-products of slag and iron oxides, and exhaust. Heat input is the sum of the heat from the VHTR and combustion heat of the coal. For the NHPRS system, HPR process and BF process were investigated separately.

Heat input and CO₂ emissions for the production and transportation were considered for ore, coal and uranium. Other materials such as lime were not taken into consideration because relative amount of them was less than the materials considered. And heat input and CO₂ emissions in electricity generation itself were also considered. For NHPRS system, transportation of ore emitted no CO₂ because the HPR process was assumed at the ore mining site. Transportation of PRO was counted in the BF process. These data were taken from reports³¹⁻³⁴⁾ and summarized in **Tables 5 and 6**.

2.2. Steelmaking Cost

Cost of steelmaking by NHS was evaluated by comparing with BFS and Midrex steelmaking (MS). Rough images of the investigated systems are illustrated in **Fig. 6**. MS is a direct reduction steelmaking using reformed natural gas as reducing agent in SFs. The DRI produced in the SFs is fed to EAFs to produce steel.¹⁴⁾ Goal of this analysis was not to select the most economical steelmaking system because the estimation was a preliminary one. Estimation of VHTR-IS process hydrogen production cost at which NHS system was competitive to BFS system and MS system was the purpose on the evaluation.

Steelmaking cost was considered as sum of the cost of materials, plant, operation, and CCS. Material cost was also divided into the categories of material consumed in the

steelmaking; iron sources (ore, pellet, sinter and scrap), reduction agents (coke, natural gas and hydrogen), other materials (lime, carbon electrodes *etc.*). Material cost included mining, transportation and production (coking, sintering, pelletization and VHTR-IS process) cost of them. Plant cost meant the cost of plant facilities: a natural gas reformer, BF, SF, Converter, EAF, RH, ancillary facilities, and by-product power generation and the generated power from it. Operation cost meant the cost to operate the facilities of the plants, such as electricity and labor. CCS cost meant the cost to recover CO₂ from the process and the one to transport and store the CO₂. Main assumptions in the cost analysis were as follows. The data used to calculate the steelmaking cost was taken from a report³⁵⁾ if not elsewhere specified.

Table 5. Energy for production and transportation of resources, and power generation.

Production of resources			
Resource	unit		note
Ore	kJ/kg	330	Assumed as the same as coal
Coal	kJ/kg	330	Assumed to be from Australia

Ref. 31)

Transportation of resources

Resource	unit		note
Ore	kJ/kg	1 469	Average of exported countries
PRO	kJ/kg	1 469	Assumed as ore
Coal	kJ/kg	797	Average of exported countries

Ref. 31)

Power generation including production and transportation of fuels, and power generation itself

Power generation	unit		note
Coal	kJ/kJ _e	0.125	
VHTR	kJ/kJ _e	0.013	

Ref. 32) (Coal); 33, 34) (VHTR); 32) (calculation method)

Table 6. CO₂ emissions of production and transportation of resources, and power generation.

Production of resources			
Resource	unit		note
Ore	Nm ³ -CO ₂ /kg	1.03E-02	Assumed as the same as coal
Coal	Nm ³ -CO ₂ /kg	1.03E-02	Assumed to be from Australia

Ref. 31)

Transportation of resources

Resource	unit		note
Ore	Nm ³ -CO ₂ /kg	5.32E-02	Average of exported countries
PRO	Nm ³ -CO ₂ /kg	5.32E-02	Assumed as ore
Coal	Nm ³ -CO ₂ /kg	2.89E-02	Average of exported countries

Ref. 31)

Power generation including production and transportation of fuels, and power generation itself

Power generation	unit		note
Coal	Nm ³ -CO ₂ /kJ _e	1.36E-04	Including CO ₂ from coal fuel
VHTR	Nm ³ -CO ₂ /kJ _e	4.64E-07	

Ref. 32) (Coal); 33, 34) (VHTR); 32) (calculation method)

Fig. 6. Schematic diagram of steelmaking systems for steelmaking cost analysis.

Table 7. Recent estimation of VHTR-IS process hydrogen production cost.

Researchers	Hydrgen cost		Hydrogen cost converted to US\$/kg in year 2000	Note	Ref.
	Unit and year				
Allen <i>et al.</i>	US\$/kg, 2008	3.57	2.86	Range in original reference is 3.57–7.27 US\$/kg (2008).	39)
Leybros <i>et al.</i>	Euro/kg, 2008	9.1	10	Nth of a kind. Hydrogen production rate was 100 mol/s.	40)
Cerri <i>et al.</i>	Euro/kg, 2008	3.4	3.8	Case of 540 HPHE Pinch. Hydrogen production rate was 540 mol/s.	41)

Table 8. Cost data of resources for steelmaking cost analysis.

(a) Low cost case in 2000

	unit	Cost	Ref.
Ore	US\$/t	25.8	37)
Pellet	BFS system US\$/t	34.5	Calculated from data in 35)
	MS system, NHS system US\$/t	84.7	Calculated from data in 35)
Coal	US\$/t	24.2	38)
Natural gas	US\$/t	220.0	38)
Hydrogen	US\$/t	2 856.0	39)

Price is modified to that in year 2000.

(b) High cost case in 2008

	unit	Cost	Ref.
Ore	US\$/t	59.8	37)
Pellet	BFS system US\$/t	73.2	Calculated from data in 35)
	MS system, NHS system US\$/t	118.1	Calculated from data in 35)
Coal	US\$/t	41.1	38)
Natural gas	US\$/t	381.7	38)
Hydrogen	US\$/t	2 856.0	39)

Price is modified to that in year 2000.

- The range of evaluation was from mining of materials to HQS after secondary refinement. Steelmaking processes were located in midland of U.S.
- Scales of all steelmaking plants were fixed to one million t-HQS/y. This scale was small compared with actual steelmaking plants. Actual scale of BF plant is, for example, c.a. 10 million t-steel/y in Kimitsu site of Nippon Steel (2010), the largest BF plant in Japan.³⁶⁾ And the largest MS plant in the world is 1.8 million t-steel/y.¹⁴⁾ Plant cost per unit HQS production tends to be less expensive in large scale. Therefore, plant cost tended to be more expansive than actual plants. In particular, BF plant was estimated to be relatively more expensive due to the relative larger scale of BF plants to MS and HR plants.
- Plant components, heat and mass balance were different from the processes considered in section 2.1. Heat and energy requirement of the IS process was also different.
- For iron ore, coal, and natural gas, low cost case in year 2000 and high cost case in year 2008 were analyzed to consider the effect of the costs of them.^{37,38)} Cost of other materials, electricity and labor was fixed³⁵⁾ in all calculation. In particular, it should be noted that cost of uranium, fuel of the VHTR, was fixed.
- Plant cost was converted to annual cost³⁵⁾ to be integrated in the evaluation.
- Hydrogen requirement was determined as stoichiometric amount of oxygen to be removed from iron ore (1 mol of H₂ for 1 mol oxygen atom removed from iron source). This meant that hydrogen was recycled within the HR plant and that all hydrogen was consumed for ore reduction.
- Material cost of hydrogen from VHTR-IS process was taken from literature.³⁹⁾ Although this cost data was based on a flow sheet study, arbitrary cost reduction

Table 9. Operation and plant costs (same value in the low cost and high cost cases).

(a) Operation cost

	unit	Cost	Ref.
Labor	US\$/man-h	38.5	35)
Electricity	US\$/kWh _e /y	0.033	35)

Price is modified to that in year 2000.

(b) Plant cost

		unit	Cost	Ref.
Blast furnace steelmaking (BFS) system	BF	US\$/t-HQS	295.7	35)
	Converter and RH	US\$/t-HQS	85.3	35)
	Ancillary facilities	US\$/t-HQS	45.0	35)
Midrex steelmaking (MS) system	Pelletization	US\$/t-HQS	83.2	35)
	SF	US\$/t-HQS	151.8	35)
	EAF and RH	US\$/t-HQS	85.4	35)
	Ancillary facilities	US\$/t-HQS	45.0	35)
Nuclear hydrogen steelmaking (NHS) system	Pelletization	US\$/t-HQS	83.2	35)
	SF	US\$/t-HQS	101.2	35)
	EAF and RH	US\$/t-HQS	85.4	35)
	Ancillary facilities	US\$/t-HQS	45.0	35)

Table 10. CCS cost (same value in the low cost and high cost cases).

	unit	Cost	Ref.	note
Coal	t-CO ₂ /t-Coal	2.7	Calculated from data in 42)	
Natural gas	t-CO ₂ /t-Natural gas	2.7	Calculated from data in 42)	
Power generation (coal)	t-CO ₂ /kWh	0.000743	43)	
Power generation (VHTR)	t-CO ₂ /kWh	0	Assumption	
Blast furance steelmaking (BFS) system	US\$/t-CO ₂	33.2	43)	
Midrex steelmaking (MS) system	US\$/t-CO ₂	16.6	43)	“Direct reduction” in reference
Power generation	US\$/t-CO ₂	33.2	43)	
Others (from coal)	US\$/t-CO ₂	33.2	43)	
Others (from natural gas)	US\$/t-CO ₂	16.6	43)	

Price is modified to that in year 2000.

of plant, nuclear heat and electricity was assumed. As shown in **Table 7**, largely different values were reported for VHTR-IS hydrogen production cost. It is stressed that the cost estimation used in this study was rather inexpensive. Because of the uncertainty of the cost, effect of hydrogen production cost on the steel-making cost of NHS system was investigated.

- Cost of the NHS system was calculated using cost data of MS system³⁵⁾ as a basis. Natural gas and oxygen costs were subtracted from material cost because hydrogen is used instead of natural gas and because

Table 11. Mass balance of the steelmaking systems.

		Input							Output				
		Iron source				Reducing agent/fuel		Other	Product		By-product		Exhaust
Material		Ore	Scrap	Scale	PRO	Coal	Uranium	Flux	HQS	PRO	Iron oxide	Slag	CO ₂
unit		kg	kg	kg	kg	kg	kg	kg	kg	kg	kg	kg	Nm ³
Blast furnace steelmaking (BFS) system		1 688	71	43		755		212	1 000		50	409	1 047
Nuclear hydrogen steelmaking (NHS) system		1 589	107				4.8E-02	44	1 000		39	188	7
Nuclear hydrogen partial reduction steelmaking (NHPRS) system	Hydrogen partial reduction (HPR) process	1 651					3.5E-02			1 211			
	Blast furnace (BF) process	37	71	43	1 211	349		64	1 000		50	297	496
	Total	1 688	71	43		349	3.5E-02	64	1 000		50	297	496

oxygen was obtained as by-product of the IS process. Reformer cost was subtracted from plant cost. The reformer cost was assumed arbitrarily as 1/3 of the shaft furnace part in the MS plant cost.

- Excess oxygen from the NHS system was not sold.
- CCS cost was calculated as the product of material consumption per unit steelmaking amount,³⁵⁾ CO₂ emissions per unit material consumption,⁴²⁾ and CCS cost per unit CO₂ emissions.⁴³⁾ CO₂ from transportation was not captured. Electricity used in the BFS system and MS system was generated from coal power plant. CCS was not applied to the NHS system because CO₂ emissions were very small.
- Year of cost data was unified to year 2000 by using consumer price index in U.S.⁴⁴⁾

Cost data used in the analysis are summarized in **Tables 8–10**.

3. Results and Discussion

3.1. Heat and Mass Balance and CO₂ Emissions of Steelmaking

Small material, heat input and less exhaust per unit HQS production are desirable for steelmaking systems. **Table 11** shows the mass balance of the steelmaking processes. Although iron source inputs of the BFS system and NHPRS system were same at 1 802 kg/t-HQS, iron source input of the NHS system was 1 696 kg/t-HQS. As in Table 1, some iron element is moved to the slag of pre treatment in the BF process. More iron source was needed to compensate the loss. More scrap input, which contained less oxygen element, was another reason for the less iron source in the NHS system. Flux input of 44 kg/t-HQS in the NHS system was much less than that of 212 kg/t-HQS in the BFS system. Output slag was also different as the difference of the flux input. The difference was mainly from the difference of the ratio of ore, sinter and pellet input to BF and SF. To evaluate the system advantage of less flux input requires the most appropriate ratio of these sources. This is a future problem. For reducing agent/fuel, 755 kg/t-HQS coal was required for the BFS system. On the other hand, only uranium of 4.8×10^{-2} kg/t-HQS was needed for the NHS system due to the high energy density of nuclear materials. Smaller burden of transportation is expected in the NHS system.

Table 12 shows the heat input to the steelmaking systems. Power generation from by-product was more than the requirement of the BF process. The excess electricity was counted as converted to heat with efficiency of 55.8%. Excess electricity from BF process in the NHPRS system could not be used in the remote HPR process. Fuel of 22.1 GJ/t-HQS was input and excess electricity of 8.4 GJ/t-HQS was obtained from the BF process in the BFS system. VHTR nuclear heat of 17.1 GJ/t-HQS and electricity of 8.5 GJ/t-HQS were input to the HR process in the NHS system. For NHPRS system, fuel of 10.2 GJ/t-HQS, VHTR heat of

Table 12. Heat input to steelmaking systems including production and transportation of material and power generation.

		unit: GJ/t-HQS				
		Blast furnace steelmaking (BFS) system	Nuclear hydrogen steelmaking (NHS) system	Nuclear hydrogen partial reduction steelmaking (NHPRS) system		Total
				Hydrogen partial reduction (HPR) process	Blast furnace (BF) process	
Steelmaking process	Fuel VHTR	22.1			10.2	10.2
			17.1	14.2		14.2
Heat for power generation/Excess electricity (converted to heat)*		−8.4	8.5	4.0	−5.2	4.0
Net heat input		13.8	25.5			28.4
Material production		0.8	0.5	0.5	0.1	0.7
Material transportation		3.1	2.3		2.1	2.1
Power generation		0.0	0.1	0.0		0.0
Total		3.9	2.9			2.8
Total net heat input		17.6	28.4			31.2

*Converted to heat with power generation efficiency of 55.8% considering combined gas turbine¹⁷⁾ for BFS and BF process in NHPRS system and that of 47% considering VHTR power generation³⁰⁾ NHS for NHS and HPR process in NHPRS system.

Excess electricity in blast furnace process cannot be used in the remote location of hydrogen partial reduction process

14.2 GJ/t-HQS and 4.0 GJ/t-HQS were input; electricity of 5.2 GJ/t-HQS was obtained as the total NHPRS system. Net heat input (difference of heat input and output) of the BF process in the BFS system of 13.8 GJ/t-HQS was the smallest due to the high efficiency of coal combustion. Much amount of waste heat (9.1 GJ/t-HQS) from the IS process hydrogen production was a major reason of the large net heat input of 25.5 GJ/t-HQS of the HR process in the BFS system. Thermal efficiency of IS process of 42.5% was already high estimation;⁴⁵⁾ the extremely high value of Kasahara *et al.*⁴⁶⁾ assumed ideal rather than practical operation conditions. There is a limitation of improvement of the hydrogen production efficiency. Reduction of hydrogen consumption for combustion within the SF is desired. Heating H₂ before injection to the SF by a HS with combustion of fossil fuel is one idea. Of course, the balance of net heat input and CO₂ emissions should be considered. Waste heat of the EAF (1.3 GJ/t-HQS) was another reason of the large net heat input. Improvement of the EAF is also necessary. Net heat input to the NHPRS system was 28.4 GJ/t-HQS. Optimization of reduction ratio of the PRO and ratio of the PRO input to the BF is desired in addition to reduction of the heat input to the HPR process.

Table 13. CO₂ emissions from steelmaking systems including production and transportation of material and power generation.

	Blast furnace steelmaking (BFS) system	Nuclear hydrogen steelmaking (NHS) system	unit: Nm ³ /t-HQS		
			Nuclear hydrogen partial reduction steelmaking (NHPRS) system		Total
			Hydrogen partial reduction (HPR) process	Blast furnace (BF) process	
Steelmaking process	1 047	7	0	496	496
Material production	25	16	17	4	21
Material transportation	112	85	0	76	76
Power generation	0	2	1	0	1
Total	137	103	18	80	98
Total system	1 184	110	18	576	594

Table 12 also shows the heat input for material production, material transportation and power generation. Total amount of them was 3.9 GJ/t-HQS, 2.9 GJ/t-HQS and 2.8 GJ/t-HQS in the BFS system, NHS system and NHPRS system, respectively. Much less amount of uranium than coal had an effect on the less demand of the NHS system. Less PRO in the NHPRS system than ore in the NHS system as seen in Table 11 resulted in the smallest heat demand. However, the advantage was not so large to change the tendency of total net heat input. 17.6 GJ/t-HQS, 28.4 GJ/t-HQS and 31.2 GJ/t-HQS were resulted for the BFS system, NHS system and NHPRS system, respectively.

Table 13 shows the CO₂ emissions. Though CO₂ from the BF process in the BFS system was 1 047 Nm³/t-HQS, the one from the HR process in the NHS system was only 7 Nm³/t-HQS. Most of carbon element was fed to the process from electrode in the EAF. CO₂ of 496 Nm³/t-HQS was calculated in the NHPRS system due to the less coal consumption by the partial reduction. Total CO₂ emissions from material production, material transportation and power generation were 137 Nm³/t-HQS, 103 Nm³/t-HQS and 98 Nm³/t-HQS in the BFS system, NHS system and NHPRS system, respectively. Just as the discussion of the heat input, small amount of uranium fuel and weight reduction of ore by partial reduction had effect on the less CO₂ emissions. Total CO₂ emissions from the NHPRS system (594 Nm³/t-HQS) and NHS system (110 Nm³/t-HQS) were 50% and 9% of that from the BFS system (1 184 Nm³/t-HQS). The result shows the effectiveness of VHTR-IS process hydrogen ore reduction for smaller CO₂ emissions.

3.2. Steelmaking Cost

Figure 7 shows the steelmaking cost of the BFS system, the MS system, and the NHS system both in the low cost case in 2000 and high cost case in 2008. The difference of the iron source cost in the BFS system and the other systems was made from the difference of iron source. While ore, sinter and pellet were used in the BFS system, only pellet was used in the MS system and NHS system. Pellet cost itself was different between the BFS system and the other systems in the literature data. The difference of the cost of reduction agents was made from the different agents: coke for the BFS system, natural gas for the MS system, and hydrogen for the NHS system. In the low cost case, the steelmaking cost of the BFS system (640 US\$/t-HQS) was a little higher than others; those of the MS system (625 US\$/t-HQS) and NHS system (618 US\$/t-HQS) were very similar. However the

Fig. 7. Steelmaking cost.

Fig. 8. Effect of hydrogen production cost on steelmaking cost (low cost case in 2000).

Fig. 9. Effect of hydrogen production cost on steelmaking cost (high cost case in 2008).

ratios of factors of these two systems were different. The plant cost was lower in the NHS system because a steam reformer was not used in the system. Also no CCS cost was used. On the other hand, hydrogen cost as the reduction agent was much higher than that of natural gas. Hydrogen production cost and CCS cost were important factors for competitiveness of NHS system. In the high cost case, 700 US\$/t-HQS, 727 US\$/t-HQS and 678 US\$/t-HQS were estimated for the BFS system, MS system and NHS system, respectively. Only material cost was greatly influenced by the change. Increases of the cost were great in the MS system, where ratios of natural gas cost were larger. Magnitude relation of the BFS system and the NHS system reversed. For the NHS system, competitiveness would be expected if material cost of hydrogen was not changed in year 2008. Here, it is stressed that material cost of hydrogen was the same both in the low cost case and the high cost case. Actu-

ally, cost of uranium became about 4 times in year 2008 compared with that in year 2000³⁸⁾ and the ratio of fuel cost in nuclear electricity cost cannot be negligible. To evaluate the future competitiveness of the NHS system, breakdown of the VHTR-IS process hydrogen cost is necessary.

Figures 8 and 9 show the effect of hydrogen production cost on the NHS cost in the lower cost case in 2000 and higher cost case in 2008, respectively to evaluate the hydrogen production cost on the steelmaking cost. The cost was compared with BFS cost and MS cost. In the lower cost case, NHS cost at hydrogen production cost of 3.3 US\$/kg-H₂ was the same as the BFS cost. When hydrogen production cost was 3.0 US\$/kg-H₂, NHS cost was the same as the MS cost. Hydrogen production costs of 3.3 US\$/kg-H₂ and 3.8 US\$/kg-H₂ were of the equivalent cost of the NHS and the BFS cost, and NHS and the MS cost, respectively, in the higher cost case. These values can be considered as a cost objective of the NHS system. More accurate data of VHTR-IS process hydrogen production cost including uranium fuel cost, and influence of scale effect of steelmaking plants was necessary for further consideration whether the objective of the NHS cost can be attained.

4. Conclusions

NHS and NHPRS systems were proposed using VHTR and IS process to reduce CO₂ emissions in steelmaking. Heat input and CO₂ emissions of these systems were analyzed by heat and mass balance calculation. Total net heat input to the NHS systems was 28.4 GJ/t-HQS, including material production, material transportation, and power generation. This value was much larger than that of BFS system of 17.6 GJ/t-HQS. Reduction of hydrogen consumption in the SF and electricity consumption in the EAF were desired for lowering the total net heat input. Total net heat input of the NHPRS system was 31.2 GJ/t-HQS. Optimization of operation parameters such as reduction ratio of PRO and PRO input to the BF is desired to decrease the heat input. CO₂ emissions of NHS system and NHPRS system were 9% and 50% of that from BFS system. Substitution of coal by hydrogen and reduction of transportation weight contributed to the reduction. Stepwise introduction of these methods can be assumed considering increasing requirement for CO₂ emission reduction and replacement schedule of plant facilities. First, NHPRS is introduced keeping existing BF process. Then, the BF process is replaced to NHS when lifetime of the BF plant facilities ends. Steelmaking cost was also evaluated. When CCS was applied, steelmaking scale of each system was unified to one million t-HQS/y and uranium fuel cost was not changed, NHS was economically competitive to the BFS and MS. Further R&D of NHS method is desired as an option for the changing situation of resource cost and requirement for CO₂ reduction.

Nomenclature

Q:	Nuclear heat input (kJ/mol-H ₂)
W:	Electricity input (kJ/mol-H ₂)
$\Delta H_{H_2, HHV}$:	Higher heat value of H ₂ (Reaction enthalpy of H ₂ + 0.5O ₂ → H ₂ O(Liquid) at 298.15 K) (=285.8 (kJ/mol-H ₂))
η :	Hydrogen production thermal efficiency (%)
η_e :	Power generation efficiency (= 47%) ³⁰⁾

Subscripts

e:	electricity
t:	heat

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