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# New Scrap Preheating System for Electric Arc Furnace (UL-BA)

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## Abstract

***In the steelmaking process by electric arc furnace, as a possible technique for realizing a substantial reduction in power consumption, the shaft type scrap preheating system is attracting attention recently. Nippon Steel Corporation has started development of its own original shaft type preheating system UL-BA (ultimate batch system) using a new concept, confirmed the scrap preheating characteristics in the pilot plant on 1/4 scale and established the preheating simulation method based on the test results. It has been concluded that the application of this method to actually operated furnaces will enable substantial reduction in power consumption by about 80 kWh/t.***

## 1. Introduction

Recent changes in economic and social situations within and outside Japan have also made a great impact on the steel industry. Amid hovering demand for steel due to such effects as the long-term decline in domestic business and economic anxieties in Korea and Southeast Asia, reducing costs in order to secure profitability and strengthen competitiveness is becoming an important issue for each steel-maker. As for the direction to solve this problem in the electric arc furnace (EAF) industry, the first to be mentioned is to reduce power consumption, the main energy. Among production costs, electric cost has the highest distribution ratio in the charging costs except material cost (scrap). Furthermore, the reduction in power consumption has the effect of reducing $CO_2$ emissions from electric power plants. It also corresponds with today's social needs to combat global warming and environmental pollution.

As to the technique for reducing the power consumption of EAF, the bucket type scrap preheating technique has been traditionally in wide use; it feeds the off gas generated from a furnace into scrap charging bucket and recovers energy by heat exchanging with scrap. But this system has some problems: low preheating effect since fed off gas temperature is kept low to prevent heat deformation of the charging bucket (around 20 kWh/t in power consumption conversion) or the occurrence of white smoke or bad smell as a result of preheating. At present, there is an increasing number of cases where facilities are suspended.

To overcome these defects of the bucket type scrap preheating system, the shaft type scrap preheating system (Fuchs system[1)], Daido system[2)], IHI system[3)]) and mono-power twin-vessel system[4)] have been developed in which scraps are preheated at a hotter off gas temperature. Among them, the shaft type scrap preheating system is attracting the most attention because of its most superior energy recovery performance.

Based on the above circumstances, Nippon Steel Corporation (NSC) has proposed its own new conceptual shaft type preheating system UL-BA (abbreviation of ultimate batch system) and worked on its development. In 1997 Nippon Steel Corporation constructed a 1/4 scale pilot plant and conducted tests to verify scrap preheating characteristics. It also established its preheating simulation method based on the results of these tests.

This report describes the preheating effects in the case of applying the preheating test results and UL-BA in the pilot plant to an actually operated furnace.

## 2. Outline

Scrap preheating systems within the vertical packed bed (called shaft type preheating system hereinafter) which have been seriously operated before 1998 encompasses three systems: Fuchs system, Daido system and IHI system. **Fig. 1** shows the conceptual difference between these systems and the UL-BA developed by Nippon Steel Corporation.

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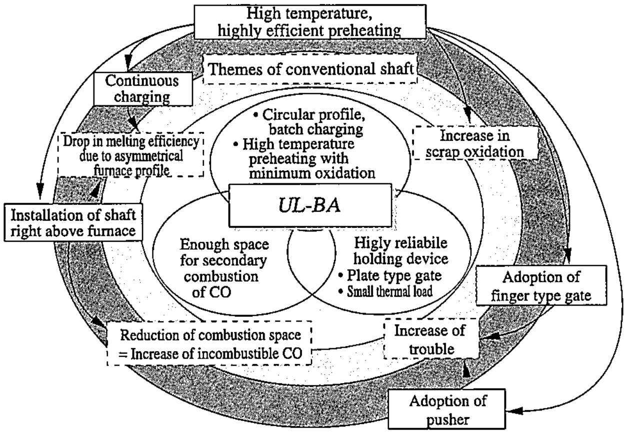


Fig. 1 Conceptual schema of shaft type scrap preheating

The design concept common to the three systems already actually operated is that the shaft is installed right above the EAF and high temperature off gas from the furnace is not fed through a connecting duct but fed directly into the scrap layer filled inside the shaft in order to realize high temperature and high efficiency preheating of scrap. Facilities to embody this concept also have the following common features.

- To feed off gas into the shaft and to discharge scrap from the shaft, the furnace profile is not conventionally circular but asymmetrical or oval.
- A scrap holding and discharging (cutting out) device is furnished between EAF and shaft. (Some Fuchs' shafts have no scrap holding and discharging device).
- The space from EAF to shaft is smaller than that of a conventional EAF with connecting duct or combustion chamber.

These three systems can be called ideal from the viewpoint of high temperature preheating of scrap because they can feed into the shaft off gas generating from EAF with almost no heat drop.

However, the following are issues in terms of preheating scrap at a high temperature and facilities to realize this.

- Imbalance of thermal load inside furnace and increased heat loss due to the adoption of asymmetrical or oval profile[5)]
- Oxidation of scrap due to high temperature preheating (decrease of tapping yield in EAF and increase of reducing energy)
- Endurance reliability of scrap holding device under the high thermal load
- Increased possibility of CO gas explosion due to smaller space for post combustion

Particular note must be taken of melting energy efficiency in EAF and oxidation of scrap. If too much pursuing high temperature preheating should cause reduction of energy efficiency and tapping yield as the entire EAF steelmaking process, the characteristics of the shaft type preheating system can not be well utilized.

Following is the concept for developing UL-BA to solve the above-mentioned problems and establishing an optimum process for a shaft type preheating system.

1) Minimization of total energy as an entire EAF steelmaking process

- High efficiency melting by scrap batch charging to an EAF furnace with circular profile
- High efficiency in preheating by high temperature off gas with minimum oxidation

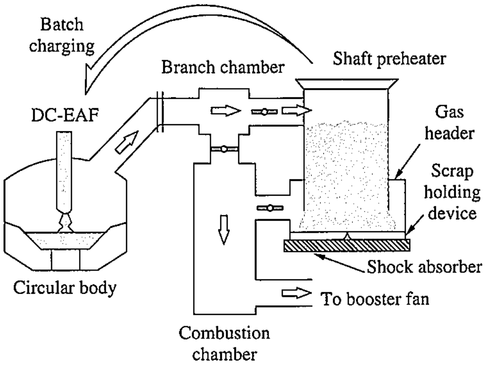


Fig. 2 Schematic drawing of UL-BA

2) High reliability of scrap holding device

**Fig. 2** shows a schematic of EAF equipped with UL-BA. UL-BA is installed near the EAF, and off gas from the EAF is fed into the shaft via a connecting duct and branch chamber, where CO in off gas is combusted. Because a gas header is installed underneath the shaft, off gas fed into the shaft flows inside uniformly and preheats the scrap efficiently.

Preheated scrap in UL-BA is transferred above the furnace using a lifting and rotating device and it is thereafter batch-charged into the EAF by opening the holding gate underneath. An EAF with circular profile can uniformly and most efficiently melt the scrap, which is filled inside the furnace, from the center. Also, as the scrap holding device, a plate gate is used. It is easy, therefore, to have sufficient mechanical strength to withstand scrap falling impact. Moreover, thermal load to the holding device is extremely small because it is subjected only to the thermal load coming from the upper side by low temperature gas. Hence, no special device has to be adopted as a heat resistant measure and a highly reliable holding device can be realized with the consideration of impact resistance.

So far, the concept of UL-BA and features have been described when such concept is materialized. Demonstration tests have been conducted to verify the following basic characteristics and functions before introducing this system into actually operated furnaces. Based on the test results, a preheating simulation method was established which can be applied to a larger scale.

- Preheating characteristics of scrap
- Oxidation characteristics of scrap
- Melting and fusion behavior of scrap
- Thermal and mechanical reliability of scrap holding gate

## 3. Demonstration Test

### 3.1 Pilot plant and test method

**Photo 1** shows the outward appearance of a scrap preheating pilot plant, and **Fig. 3** is an outline of a pilot plant. The inside diameter of the shaft is 1.25 m, height is 3 m, and a pipe type water cooled panel is installed on its inner wall. The inside diameter of the gas header is 1.7 m, height is 1.1 m, and the gas header is internally lined with 100 mm thick castable refractory. Also, the bottom of the gas header is equipped with a water cooled gate for holding scrap, and the entire shaft is supported by a buffer spring so as to mitigate impact when scrap falls down.

The above-stated gas header profile and gas flow height formed between the water cooled panel at the bottom of the shaft and the holding gate upper side were decided based on the results of a gas flow test using a 1/10 scale acrylic shaft model, conducted prior to

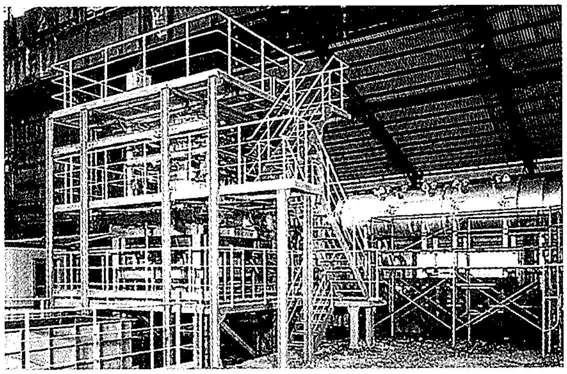


Photo 1 Picture of pilot plant

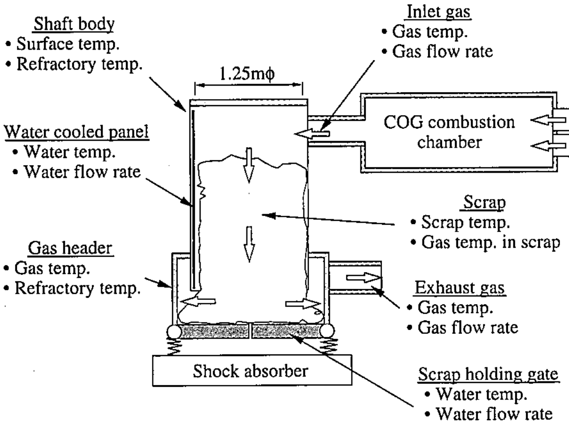


Fig. 3 Outline of pilot plant

this test. Preheating gas generated by combusting COG (Coke-oven gas) in a combustion chamber installed aside the shaft can be fed either from an upper or lower inlet by changing over the damper installed inside the duct. (Fig. 3 shows an operation in which preheating gas is fed from the upper inlet.)

An example of preheating test conditions and the composition of the preheating gas is shown in **Table 1**. Maximum temperature of the preheating gas is set at 1200°C and the maximum flow rate is set at 3.5 m/s, by which the average superficial velocity inside the unloaded shaft is almost equivalent to that in an actually operated furnace. Four kinds of scrap listed below were used so as to observe how preheating is influenced by bulk density, shape, adhesion of inflammables, etc.

- #2 Heavy (H2)
- #S1 Heavy (HS1)
- Mixture of turnings and heavy scrap (#2 Heavy: 85%, Turnings: 15%)
- Mixture of heavy scrap and shredded scrap (#2 Heavy: 10%, Shredded scrap: 90%)

Table 1 Preheating test conditions

| | | |
|---|---|---|
| Scrap | Amount | Approx. 2.7m$^3$ |
| | Bulk density:$\gamma_{sc}$ | 0.6 - 1.1 t/m$^3$ |
| Gas | Kind | Heating air |
| | Fuel | COG |
| | Temperature | Max. 1,200°C |
| | Flow rate | Max. 48Nm$^3$/min |
| | Direction in shaft | Upstream / Downstream |

Gas compositions (1,200°C, 48Nm$^3$/min)

| $H_2O$(%) | $O_2$(%) | CO(%) | $CO_2$(%) | $N_2$(%) |
|---|---|---|---|---|
| 11.4 | 7.7 | 0 | 5.9 | 75.0 |

Heat balance and scrap preheating efficiency in shaft were calculated under the following equation using temperature and flow rate measured at each portion shown in Fig. 3.

Sensible heat of inlet gas: $\frac{dQ_{gas\text{-}in}}{dt} = Cp_{gas} \times V_{gas\text{-}in} \times T_{gas\text{-}in}$ ·····(1)

Heat loss to cooling water: $\frac{dQ_w}{dt} = Cp_{gas} \times V_w \times \Delta T_w$ ················(2)

Heat storage to refractory: $\frac{dQ_R}{dt} = C_R \times V_R \times \Delta T_R$ ···················(3)

Diffused heat into air: $\frac{dQ_r}{dt} = \alpha_s \cdot S \cdot (T_{sur} - T_0)$

$$+ \sigma \cdot \varepsilon \cdot S \left\{ \left(\frac{T_{sur}+273}{100}\right)^4 - \left(\frac{T_0+273}{100}\right)^4 \right\} \quad \cdots\cdots\cdots(4)$$

Sensible heat of exhaust gas: $\frac{dQ_{gas\text{-}out}}{dt} = Cp_{gas} \times V_{gas\text{-}out} \times T_{gas\text{-}out}$

·········(5)

Heat storage to scrap:

$$\frac{dQ_{sc}}{dt} = \frac{dQ_{gas\text{-}in}}{dt} - \frac{dQ_{gas\text{-}out}}{dt} - \left(\frac{dQ_w}{dt} + \frac{dQ_R}{dt} + \frac{dQ_r}{dt}\right) \quad \cdots\cdots\cdots(6)$$

Scrap preheating efficiency: $\eta_{sc} = Q_{sc} / Q_{gas\text{-}in} \times 100$ ·············(7)

By using the relationship between temperature of mild steel and heat content, the average temperature of scrap was calculated from heat storage to scrap computed based on the heat balance calculation. Furthermore, in order to confirm the appropriateness of average scrap temperature and to develop the preheating simulation program, sampling test pieces with a sheath thermocouple were placed into scrap (3 places in vertical direction and 2 places in each sectional portion) and the actual scrap temperature was measured.

### 3.2 Heating characteristics and preheating efficiency of scrap

**Fig. 4** shows an example of scrap temperature transition when #2 Heavy was preheated by preheating gas from the upper inlet. By 20 minutes preheating with gas temperature of 1,200°C and gas flow rate of 48Nm$^3$/min, the temperature of the top layer of scrap $h_{sc}$ (2.1 m height from holding gate) exceeded 800°C and the average scrap temperature also reached approx. 600°C after 20 minutes of preheating. The heat balance in this case is shown in **Fig. 5**. The largest portion was the heat storage to the scrap (44%), followed by the heat loss to the water cooled panel (37%) and the sensible heat of the exhaust gas (18%). In the meantime, heat loss to the holding gate was very small, being 1% or so, and diffused heat from the shaft into the air was negligible.

Similarly, in Fig. 5 regarding the difference in preheating efficiency due to different gas flow directions under the same gas conditions (1200°C, 31 Nm$^3$/min), the preheating efficiency is 7% lower in the case of feeding preheating gas from the lower inlet. This is

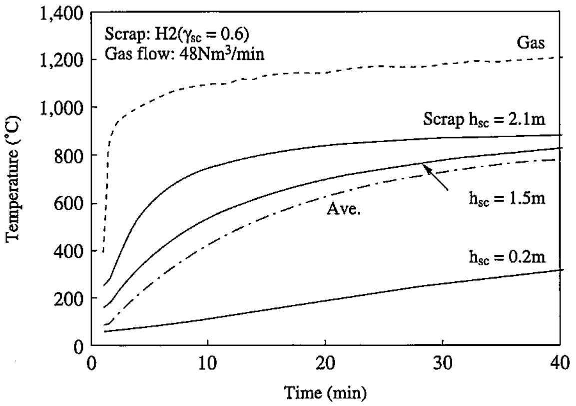


Fig. 4 Scrap temperature transition (#2 Heavy)

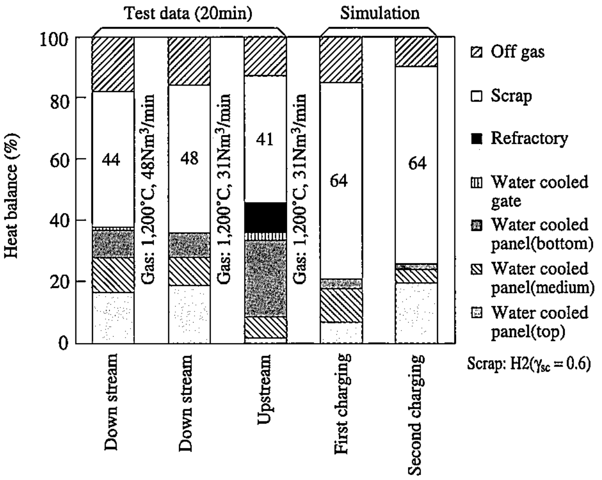


Fig. 5 Heat balance of UL-BA

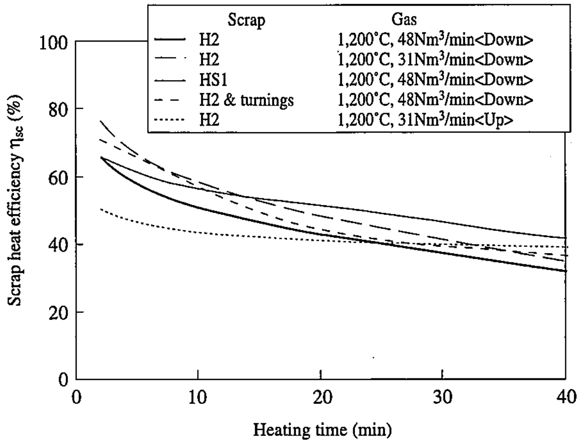


Fig. 6 Relationship between heating time and scrap heating efficiency

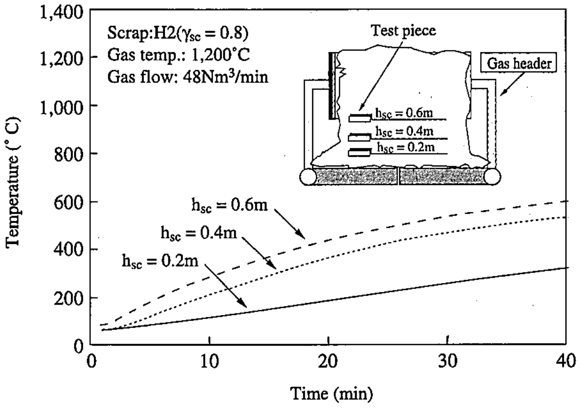


Fig. 7 Vertical temperature transition of scrap at lower part of shaft

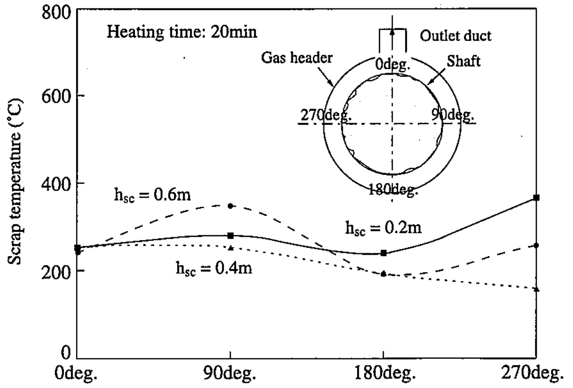


Fig. 8 Horizontal temperature transition of scrap at lower part of shaft

because of greater heat storage to the gas header refractory. When the refractory has enough heat storage, preheating efficiency can be virtually equivalent regardless of gas flow in the shaft.

**Fig. 6** shows the preheating efficiency in the case where the kind of scrap, gas condition and gas flow direction in the shaft are changed. The preheating efficiency goes down as time goes by. The decrease of preheating efficiency becomes smaller in the order of mixture of turnings and heavy scrap, #2 Heavy and #S1 Heavy. It is thought that this is because 1) adhered flammables cause combustion in the early preheating stage in the case of the mixture of turnings and heavy scrap and 2) the heat transfer area of #S1 Heavy is small and the scrap weight (heat capacity) to be preheated is large. Although there are some differences as stated above, preheating efficiency in each scrap condition is nearly 45 to 50% (for 20 minutes of preheating).

### 3.3 Preheating uniformity of scrap

Since local gas flow changes complexly inside the gas header, gas flow directivity conceivably influences heat transfer to the scrap. Therefore, the preheating temperature of the lower layer of scrap was measured in detail when preheating gas was fed from the upper inlet. **Figs. 7 and 8**, respectively, show the temperature transition of scrap in each part of the vertical section and the temperature distribution of scrap on the horizontal section. Fig. 7 proved that scrap is fully preheated also in the lower layer of scrap. Fig. 8 confirms that the scrap temperature at the position opposite the gas outlet duct (180°) tends to be a little lower, but preheating is almost uniform.

### 3.4 Scrap melting and fusion behavior

**Fig. 9** shows the condition of scrap melting and fusion. In this test, preheating gas (1200°C, 48 Nm³/min) was fed from the upper inlet. Heavy scrap did not melt nor fuse even when it was preheated longer than 90 minutes. With the mixture of heavy scrap and turnings, only the turnings partially melted when it was preheated for about 50 minutes. With the mixture of heavy scrap and turnings,

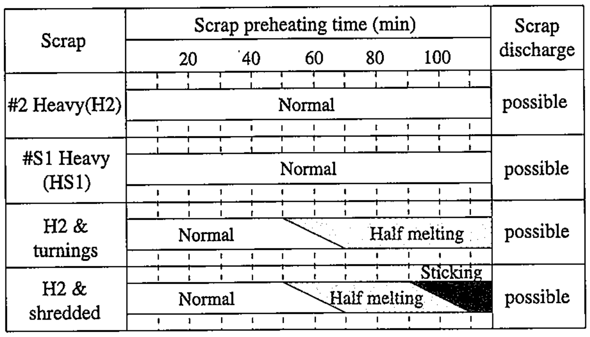


Fig. 9 Condition of scrap melting and fusion

melting started partially after about 50 minutes and fusion of the shredded scrap occurred after 90 minutes.

Both melting and fusion occurred at the upper layer of scrap preheated at high temperature. It was further observed that even in the upper layer, scrap near the shaft inner wall did not melt owing to the cooling effect of the water cooled panel. In none of the tests were there observed any such phenomena as solidification, bridging to shaft wall or holding gate, etc. and consequently scrap was discharged smoothly after preheating.

### 3.5 Scrap oxidation characteristics

Scrap oxidation test conditions are shown in **Table 2**. In this test, oxygen concentration in preheating gas was set to be nearly equal to that in exhaust gas from an actually operated EAF. The test piece was preheated to the specified temperature and time. Then, it was immediately watercooled and the difference in weight of the test piece before and after preheating was measured. Gained weight of the test piece by preheating was attributed to scrap oxidation and the oxidized amount was calculated from this weight difference.

Generally speaking, scale is mostly FeO if steel is heated at high temperature exceeding 750°C. Meantime, FeO is unstable and does not exist below 750°C. Most of the scale occurring below 750°C is $Fe_2O_3$[6]. Consequently, the relationship between oxidation amount of scrap (*ox-Fe*) and the weight difference in the test piece before and after preheating ($\Delta w$)was defined as shown in the equation below.

$$(ox\text{-}Fe) = (Fe)/(O) \times \Delta w = 55.8/16 \times \Delta w \qquad \text{over } 750^\circ\text{C} \cdots\cdots(8)$$

$$(ox\text{-}Fe) = (2Fe)/(3O) \times \Delta w = (2 \times 55.8)/(3 \times 16) \times \Delta w \qquad \text{below } 750^\circ\text{C} \cdots\cdots(9)$$

**Fig. 10** shows oxidized amount of scrap calculated by the above equation. The figure shows oxidation characteristics[7] at the same time. The test revealed that oxidation of scrap started at the temperature exceeding around 600°C and proceeded rapidly above 800°C. The comparison between these results and reported values shows oxidation characteristics below 800°C which was actually measured agree well with those under the conditions inside the furnace (very little oxygen) in documents, and exceeding 800°C, the oxidized amount gets closer to that under atmospheric conditions.

Table 2 Oxidation test conditions

| | | |
|---|---|---|
| Test piece | Size | 300×50×1.6 - 6.0 mm |
| | Material | Structural steel (SS400) |
| | Temperature | Approx. 400 - 1,000°C |
| Gas | Flow rate | Max. 48Nm³/min |
| | Oxygen in gas | Approx. 6 -17% |
| Heating time | | 30 min |

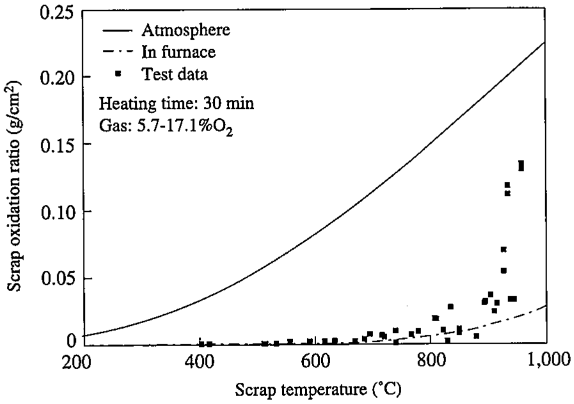


Fig. 10 Characteristics of scrap oxidation

### 3.6 Reliability of holding gate

Thermal load on the holding gate during preheating is 1 to 2% as shown in Fig. 5 regardless of direction of preheating gas flow. Furthermore, thermal load on the holding gate remains low and creates no thermal problems even when preheating is conducted so long that the scrap starts to fuse.

In addition, shock force affecting the holding gate at the time of charging scrap into the shaft was investigated. In the test, deflection of the buffer spring was measured when various kinds of scrap were charged, from which the shock force affecting the holding gate was calculated. **Fig. 11** shows the relationship between scrap weight and shock force when scrap weighing less than 20 kg in single weight was charged. As the figure shows, the shock force is almost fixed irrespective of charged scrap weight. This reveals that in charging light scrap, the scrap itself is working as a buffer.

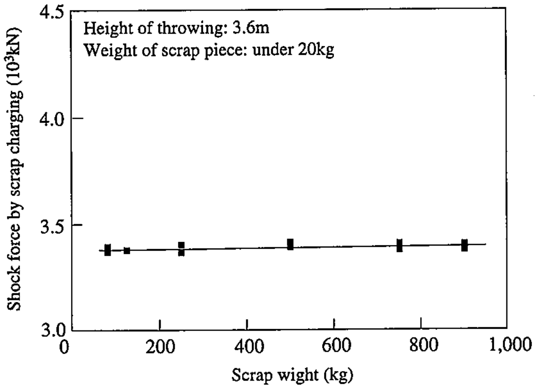


Fig. 11 Shock force by scrap charging

## 4. Preheating Simulation

### 4.1 Heat transfer model in the shaft

Based on the test results mentioned above, a preheating simulation method was established that can be applied to an actually operated furnace. At first, a heat transfer model in the shaft was made, and the measured value and calculated value of scrap temperature were compared. Calculation flow of heat transfer model is shown in **Fig. 12**. In this transfer model, scraps in the shaft are divided in the vertical direction and in each layer, heat shall be transferred from gas to scrap. The calculation was conducted on the assumption that scrap temperature and gas temperature in each layer are constant and scrap is homogeneous. Heat volume per unit time transferred from gas to scrap is given in the equation below.

$$\frac{dQ_{sc}}{dt} = A_s h_s \times V_s \times (T_{gas} - T_{sc}) \cdots\cdots (10)$$

In this equation, $A_s$ is heat transfer area per unit volume, $h_s$ is heat transfer coefficient between scrap and gas, $V_s$ is volume of scrap, $T_{gas}$ is gas temperature and $T_{sc}$ is scrap temperature. Here, actual scraps have a mixture of various shapes and thicknesses, which makes it impossible to measure strict . Therefore, a heat transfer model was completed after the heat transfer coefficient of gas and scrap was treated as $A_s h_s$, which conformed to all the preheating test results.

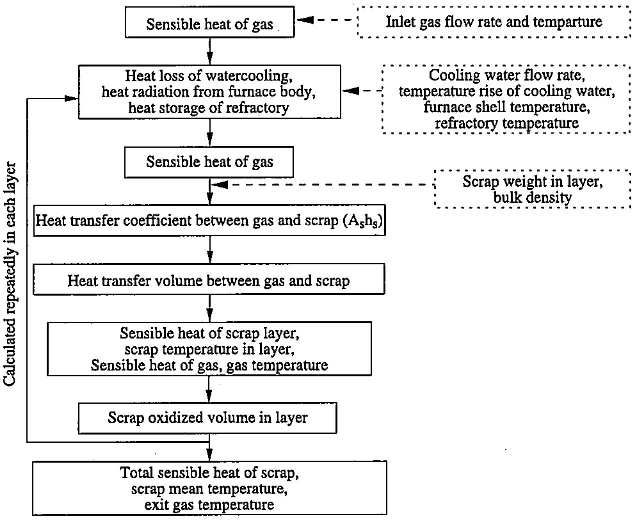


**Fig. 12 Calculation flow for heat transfer model in shaft**

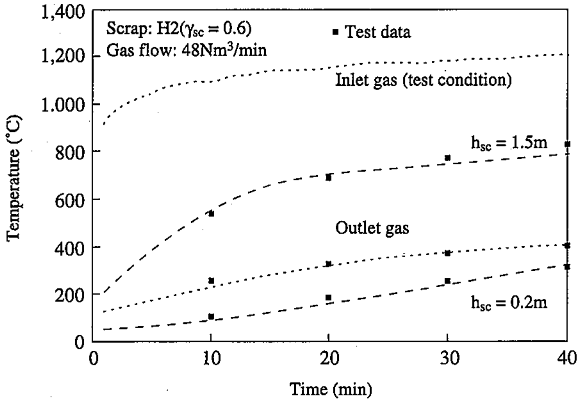


**Fig. 13 Comparison of calculation and measurement of scrap temperature**

**Fig. 13** shows a comparative example of scrap temperature between measured value and calculated value obtained from this model. Scrap preheating efficiency in this example was 46% and it nearly conformed to the test result of 44%.

### 4.2 Simulation for actually operated furnace

4.2.1 Simulation method and calculation assumption

Based on the heat transfer model inside a shaft whose propriety could be confirmed in the preceding paragraph, a preheating simulation program for the EAF steelmaking process with the application of UL-BA has been developed. Using this program, total energy balance in a 100 t EAF with UL-BA was experimentally calculated.

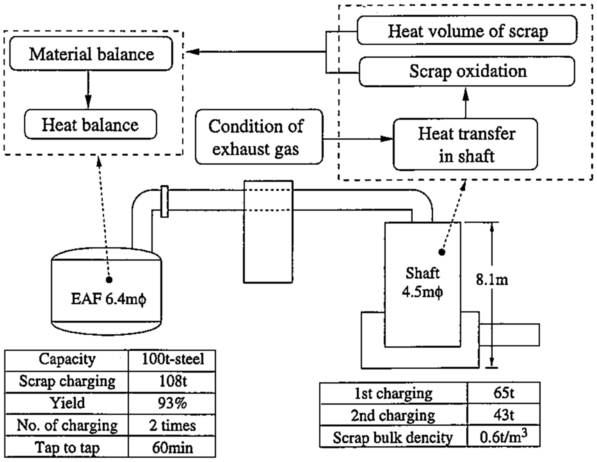
The calculation flow of this simulation is shown in **Fig. 14**. At first, based on the gas condition obtained from the calculation of material balance and heat balance of EAF, scrap storage heat volume and scrap oxidized volume are calculated by heat transfer model and fed back to the calculation of material balance and heat balance. By repeating these calculations, the energy balance for the whole process is obtained.

The operation pattern of EAF used in this calculation is shown in **Fig. 15**. The whole quantity of scrap (108 tons) is preheated and charged in two buckets (First charging: 60%, Second charging: 40%). In this operation pattern, scrap can be preheated for 26 minutes for the first charging and 13 minutes for the second charging.

4.2.2 Calculation result

According to the simulation results, average temperature of the scrap is approx. 500°C (**Fig. 16**) for the first charging and approx. 200°C for the second charging. Scrap preheating efficiency against gas sensible heat at shaft inlet is 64%. (Fig. 5)

Calculation result of the final energy balance is shown in **Fig. 17**. Power consumption of EAF applying UL-BA is 287 kWh/t, which is 78 kWh/t less than that of EAF without preheating (365 kWh/t), which has the effect of reducing power consumption. In this simulation, scrap oxidation was very low because the scrap preheated to 800°C or more, at which oxidation proceeds rapidly, is only at the upper layer and less than 10% of the whole scrap, as is known from preheating temperature transition of the first charged scrap in Fig. 16. Thus, there is no reduction in production yield and the preheating effect mentioned above can be enjoyed directly as a cost merit.



| Capacity | 100t-steel |
|---|---|
| Scrap charging | 108t |
| Yield | 93% |
| No. of charging | 2 times |
| Tap to tap | 60min |

| 1st charging | 65t |
|---|---|
| 2nd charging | 43t |
| Scrap bulk dencity | 0.6t/m$^3$ |

**Fig. 14 Calculation flow for operation furnace**

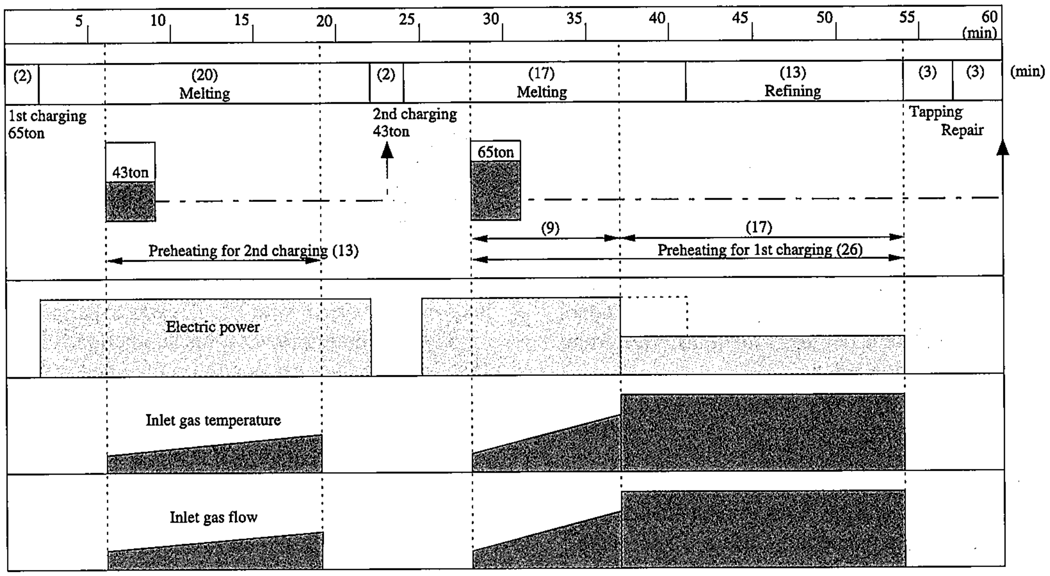


Fig. 15 Electric arc furnace operation pattern

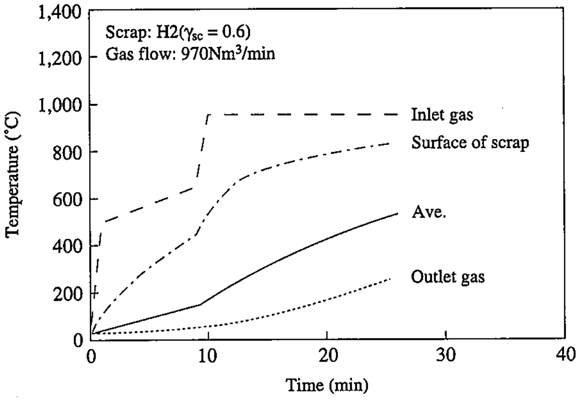


Fig. 16 Temperature transition of first charging scrap

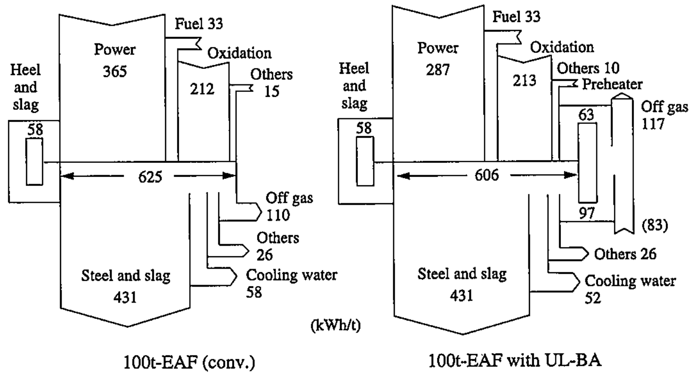


Fig. 17 Total energy balance

## 5. Conclusion

By use of the preheating simulation method established on the basis of demonstration test results of scrap preheating characteristics in a 1/4 scale pilot plant and calculation of energy balance for an actually operated furnace, the following were ascertained:

1) Scrap preheating characteristic

The average temperature of scrap was approx. 600°C (preheating efficiency 44%) after preheating gas of 1200°C was fed from the upper inlet and #2 Heavy was preheated for 20 minutes. In the preheating test of various scraps, preheating efficiency at 1200°C preheating gas was almost 45-50%. In energy balance experimental calculations for a 100t EAF to which UL-BA is applied, using heat transfer model inside the shaft with the actually measured values of preheating test, UL-BA preheating efficiency is about 65% and a reduction of around 80 kWh/t in power consumption can be obtained.

2) Scrap oxidation characteristic

Scrap oxidation begins when scrap temperature exceeds 600°C and rapidly progresses at 800°C. Based on this result, scrap oxidation amount is experimentally calculated at an actually operated furnace with UL-BA application, and oxidation hardly occurs.

3) Scrap holding gate reliability

The result of preheating tests under various conditions, extracted heat of cooling water at the holding gate is about 1-2 % of fed gas sensible heat. This trend was the same under conditions such as when scrap melting and fusion occur. Thermal load on the scrap holding device of UL-BA is extremely small, which is no problem, and impact added to holding gate at the time of charging scrap was measured to obtain a design guideline for the holding gate under impact.

From the above conclusion, UL-BA can actually be made as a highly reliable preheating system which allows obtaining enough energy reduction effect. Nippon Steel Corporation hopes to develop and offer EAF steelmaking plants that can realize further energy-saving and environmental protection in the future, too.

### References

1) Clayton, J. et al.: SEAISI Conference, Sendai,1993-4
2) Honjo, N. et al.: Electric steel-making, 68(1), 13(1997)
3) Takeuchi, O. et al.: SEAISI Seminar, Thailand,1994-3
4) Takahashi, M.: Electro-heat, 82, 44(1995)
5) Nakayama, T. et al.: SEAISI Conference, Korea,1997-5
6) Okada, K.: Progress in Anti-Corrosion Technology, Tokyo, Japan Society for the Promotion of Science, 1963,p.66
7) Rfpfywtd, T.B.: Industrial Furnace Design Handbook. Japan-Soviet News Agency,1997