Method for Predicting Gas Channeling in Blast Furnace

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In order to maintain stable operation of a blast furnace, deviations from the steady state should be quickly detected and corrected. Because internal physical states are difficult to measure directly, experienced operators play a crucial role in integrating information from various sources such as sensors and visual observations so as to recognize, predict, and react to probable anomalies. Overlooking undesirable symptoms or delayed actions possibly leads to the excessive loss of heat, which, in the worst case, can cause the abnormal shutdown of operation. One of the events highly associated with the risk of heat loss is gas channeling, which sets off an alarm signaling to the operator to decrease the flow rate of input hot gas. Gas channeling is judged to be imminent by the integration of indices designed so as to detect unusual changes in the variations and patterns of sensory data. The precision of our prediction method is evaluated by using actual data.

Introduction

In an integrated steelworks, iron ore, auxiliary materials and sintered ore, which is pretreated iron ore, are constantly charged from the top of a blast furnace and are reduced, melted, and carburized inside the furnace to continuously produce high-temperature molten iron. The interior of a blast furnace is a high-temperature, high-pressure, dusty environment, and it is difficult to directly measure the conditions inside the furnace. Hence, a number of sensors are installed on the furnace walls. It is important for the stable operation of a blast furnace to estimate and predict the state and its changes inside the furnace from the data acquired by these sensors such that appropriate operational action can be taken. Overlooking anomaly symptoms and/or making an erroneous judgment may result in equipment damage due to high-temperature gas, or the solidification of pig iron inside the furnace due to the lack of a heat supply: this can lead to the discontinuation of production. Since a blast furnace is located at the uppermost stream of each steelworks, a disruption of the blast furnace production will affect the entire steelworks.

Thus, maintaining the stable operation of the blast furnace is an important task, and a variety of research has been carried out on the subject. Examples include estimating the shapes formed by fused matter in the furnace, which influence the state of the blast furnace,[1)] and furnace heat control using AI technology.[2)] These technological developments have been carried out to support stable operation by estimating and evaluating the furnace conditions from burden materials and sensor information. A blast furnace process, however, has various factors that are complicatedly intertwined, and, in reality, a large part of the furnace operation relies on the comprehensive judgment and skills of experienced operators.

Meanwhile, experienced operators are being replaced by younger ones as the generations change, causing concerns about missing anomaly symptoms and making erroneous judgments due to the lack of their experience and resulting lack of skills. Therefore, there is a demand for technologies and tools that support the awareness and judgment of operators.

Recent advancements in ICT have made significant progress in the technology for analyzing a large amount of data to support human judgment and actions. It was against this backdrop that Kobe Steel began to develop a gas-channeling prediction technology based on data analysis for supporting operators in order to raise awareness of the risk of gas-channeling occurrence, which is one of the anomaly events in blast furnace operation. Gas channeling is a phenomenon in which the pressure inside a blast furnace gradually increases, and the blast furnace gas is discharged from the furnace top at a pressure and temperature higher than usual. This is caused by disturbed furnace conditions obstructing the flow of the hot air, which is blown from the furnace bottom and rises up in the blast furnace as reductant gas (hereinafter referred to as ventilation failure).

Various methods have been attempted to predict gas channeling, including the analysis of pressure frequency[3)] and the analysis of the main component.[4)] The cause of gas channeling, however, is complicated, leaving some room for the operators' judgment.

Hence, Kobe Steel applied statistical processing and pattern classification techniques to various types of sensory information and defined a plurality of feature quantities that correlated highly with the risks of gas channeling. By combining these feature quantities, the company has put into practical use an operation support system that provides operators with a quantitative index of gas channeling risks. This paper gives an outline of the system and reports the results of its application.

1. Outline of gas channeling prediction system

Once it occurs, gas channeling may cause serious troubles such as the destruction of furnace-top equipment and furnace heat drop due to increased heat loss. A precursor phenomenon of this gas channeling is a pressure rise due to a failure in the ventilation of reductant gas. Ito et al. use the magnitude of monitoring data including pressure as the criterion for gas channeling prediction.[5] The pressure rise, however, occurs due to various factors, and considering only the occurrence of pressure rise as a "gas channeling risk" leads to overdetection. From the viewpoint of data processing, such a problem can also be regarded as a change-point detection problem in time series data. There is, for example, a technology that detects internet virus infection on the basis of changes in data communication volume;[6] however, gas channeling is an event occurring in a nonsteady state, and it is not easy to detect changes in a great fluctuation in the first place. A detailed examination of the data on actual gas channeling occurrence has revealed that the pressure rise is immediately accompanied by a significant deviation from the normal state of the furnace temperature and its spatial distribution.

Therefore, an attempt was made to express the risk of gas channeling by a permeability index that involves not only pressure but also a number of the temperatures of these anomaly states, which appear before gas channeling. Kobe Steel has now developed a system for predicting gas channeling in which an alarm, "Timing for lowering blow," is issued at the time when pressure suddenly rises during a period with a high index of permeability.

A method has been proposed in the past for predicting the occurrence of gas channeling by calculating a plurality of feature quantities from such data behavior before gas channeling.[7] Prediction based on a plurality of feature quantities, however, requires a plurality of parameters corresponding thereto, and it is necessary to adjust each parameter each time the operational state changes. Adjusting these parameters with operation analysis done by hand can hinder long-term stable operation.

Hence, a tool has also been developed to enable the adjustment of multiple parameters with less effort by standardizing the method of parameter adjustment.

2. Constitution of permeability index and method of calculating it

This section details the feature quantities and how they are calculated; feature quantities constitute the permeability index, which is the core of the gas channeling prediction system.

2.1 Selection of feature quantities constituting permeability index

As mentioned above, gas channeling phenomena deeply involve temperature distribution in a furnace in addition to pressure rise. For this reason, feature quantities, SC_1 to SC_8, described below, are set as the constituents of the permeability index. As will be described later, the permeability index is finally derived by combining these feature quantities.

2.1.1 Pressure fluctuation

Data analysis has revealed that the pressure violently fluctuates each time before gas channeling occurs. Two fluctuation patterns have been found: one that continues for a long period of time and another that becomes concentrated in a short period of time. Furthermore, it has been found that the fluctuations occur across furnace walls. Therefore, these phenomena with different time scopes were quantified using multiple variances of the measured values of the pressure, and the pressure fluctuation was quantified by combining them. More specifically, four time periods of 5 minutes, 60 minutes, 120 minutes, and 240 minutes are set for four height positions: that is, 4 heights × 4 time periods = 16 periods are set. On the basis of the number of periods where the fluctuation exceeds the threshold adjusted on the basis of the actual results, a score is calculated by Equation (1):

$$SC_1 = N\left(\sum_h f_1(P_{h,t}(t-5), P_{h,t}(t-60), P_{h,t}(t-120), P_{h,t}(t-240))\right) \quad \cdots\cdots (1)$$

wherein

SC_1: temporal fluctuation feature quantity of pressure (hereinafter, different subscripts indicate respective feature quantities),

t: time (minute(s)),

N: function to convert input value to the index value of 0~1 (detail is described in Section 3),

f_1: value scored by counting the number of items of input variables exceeding the threshold and giving the zeroth and first items 0 points, second item 1 point, third item 2 points, and fourth item 3 points,

h: height in the blast furnace (for the present feature quantity, the four heights from the upper furnace to the lower furnace[Note 1]),

$p_{h,t}(t_1)$: time average value between t_1 and t of 120 minutes variance of the average value of total pressure at height h.

2.1.2 Uniformity of temperature distribution in circumferential direction

For a case where the gas flow is disturbed (drifted), the temperature distribution and the position of the center of gravity in a cross-section of a blast furnace are shown by the star in **Fig. 1**. The temperature distribution becomes uneven in the cross-section of the furnace, and the high temperature range expands in a specific direction. Then, the center of the mass coordinate is calculated on the basis of the temperature distribution in the circumferential direction, as expressed by Equation (2), so that the deviation from the center is incorporated in the permeability index. The deviation is calculated for each one of multiple heights and indexed into a real value from 0 to 1 (indexing method will be described later), and the maximum value of the index value at each height is taken as the score of the temperature distribution evaluation:

$$SC_2 = \max_h N(f_2(T_{h,d}, n_h, \theta_{h,d}))$$
$$f_2 = \frac{1}{n_h}\sqrt{\left(\sum_{d=1}^{n_h} T_{h,d}\cos\theta_{h,d}\right)^2 + \left(\sum_{d=1}^{n_h} T_{h,d}\sin\theta_{h,d}\right)^2} \quad \cdots\cdots (2)$$

wherein

h: heights in the blast furnace (the upper three heights in this feature quantity),

d: the serial number of each sensor at height h,

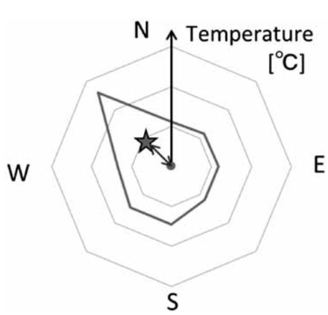

Fig. 1 Temperature distribution in circumferential direction

Note 1) In this paper, the blast furnace is divided into three parts in the perpendicular direction; i.e., upper furnace, mid-furnace, and lower furnace, in order from the top.

$T_{h,d}$: measurement value of d^{th} temperature sensor at height h,

n_h: number of temperature sensors at height h,

$\theta_{h,d}$: angle of the d^{th} sensor with respect to the first sensor at height h.

2.1.3 Uniformity of upper furnace temperature

Before gas channeling occurs, there is a tendency for the stave temperature distribution in the height direction to change greatly: e.g., the mid-furnace temperature becomes higher than the upper furnace temperature. In order to capture such phenomena, a feature quantity as in Equation (3) is defined:

$$SC_3 = N\ (T_{h1} - T_{h2}) \quad \cdots\cdots (3)$$

wherein

$h1, h2$: heights in a blast furnace (in this feature quantity, representing two heights in the upper furnace),

T_h: 120 minutes time average of the average values of all temperature sensor measurements at height h.

2.1.4 Upper furnace temperature

Before gas channeling, the temperature in the upper part of the furnace often becomes markedly high, and if the upper furnace temperature is uneven, it is assumed that the risk of gas channeling has increased further. Therefore, in addition to the upper furnace temperature, a feature quantity that also takes into account the feature quantity of *"upper furnace temperature uniformity" is defined:*

$$SC_4 = \frac{\Sigma_h N(T_h) + SC_3}{4} \quad \cdots\cdots (4)$$

wherein

h: heights in a blast furnace (in this feature quantity, it represents three heights in the upper furnace),

T_h: average value of the average values, for the past 120 minutes, of all the temperature sensors at height h.

2.1.5 Mid-furnace temperature

So far, in the main, temperatures measured in the upper part of the furnace have been used to calculate the score. However, when the furnace condition deteriorates, the temperature in the mid-furnace tends to rise greatly as compared with what is usual. Therefore, the increase in the mid-furnace temperature is captured as a feature quantity in Equation (5).

$$SC_5 = N\left(\max_{(h,d)} Z_{h,d}\right) \quad \cdots\cdots (5)$$

wherein

h: heights in a blast furnace (in this feature quantity, it represents two heights in mid-furnace)

d: the serial number of each sensor at height h,

$Z_{h,d}$: normalized temperature of $T_{h,d}$,

μ : average over time,

σ : standard deviation over time

2.1.6 Temperature difference in perpendicular direction

Fig. 2 shows the values at three time points before gas channeling that occurred in the past, with the vertical axis as height in the blast furnace and the horizontal axis as normalized temperature. It is shown that, as gas channeling approaches, the temperature difference between the high temperature part and the low temperature part becomes remarkable, and the temperature distribution deviates from normal. The change in the distribution at that time is captured by a feature quantity expressed by Equation (6).

$$SC_6 = N\left(\max_{d}\left(\max_{h} Z_{h,d} - \min_{h} Z_{h,d}\right)\right) \quad \cdots\cdots (6)$$

2.1.7 Temperature of furnace-top gas

The temperature of furnace-top gas rises when furnace conditions deteriorate. Therefore, its maximum value for a certain period is used as the feature quantity:

$$SC_7 = N\left(\max_{t} T_{top}\right) \quad \cdots\cdots (7)$$

wherein T_{top}: temperature of furnace-top gas

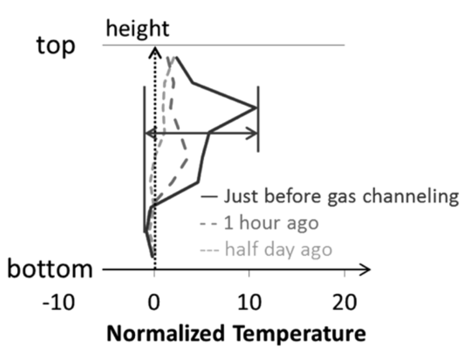

Fig. 2 Temperature distribution along furnace axis immediately before channeling

2.1.8 Blast pressure

Like the furnace-top gas temperature, the blast pressure has the same tendency to rise and is defined as the feature quantity:

$$SC_8 = N\left(\max_{t} P_{bottom}\right) \quad \cdots\cdots (8)$$

wherein P_{bottom}: blasting pressure.

2.2 Method of indexing feature quantities

Before combining these feature quantities, indexing was carried out to express the degree of deviation from the median value in the distribution of each feature quantity. The method of indexing is shown in **Fig. 3**. Fig. 3 shows the frequency distribution of the data collected in the top of the furnace, the cumulative distribution in the middle, and the indexed function using the parameters determined from the distribution in the bottom. As shown in Fig. 3, the indexing is performed as follows using the 50% value of cumulative frequency and α% value.

0 ～50%: 0 (regarded as the normal state)

50%～α%: 0～1 (regarded as a period of transition to a deviated state)

α%～100%: 1 (regarded as the deviated state).

The parameter α is determined by a method explained in Section 3.

2.3 Definition and evaluation of permeability index

Kobe Steel has developed a permeability index with a combination of feature quantities and

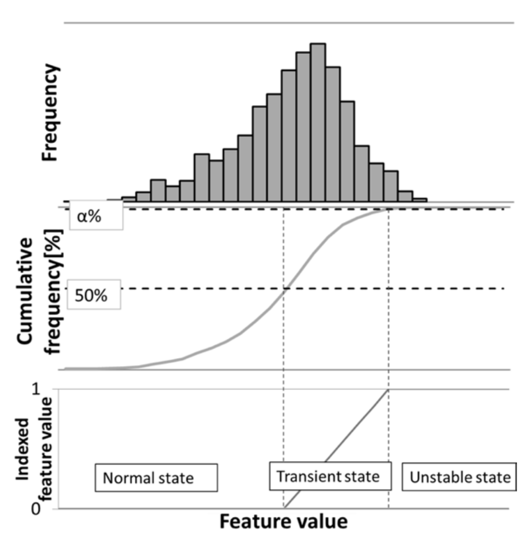

Fig. 3 Conceptual representation of indexed feature quantity using parameter α from cumulative frequency distribution

developed an approach to select the best candidate among three types of index candidates (SC_A, SC_B, SC_C).

In the first candidate, SC_A, the "pressure fluctuation" (Section 2.1.1), has been defined as the permeability index as expressed by Equation (9), focusing on the large pressure fluctuation before gas channeling:

$$SC_A = SC_1 \quad \cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots \quad (9)$$

In the second candidate, SC_B, considering the feature quantities of the temperature patterns (Section 2.1.2 and Section 2.1.3) characteristically observed before gas channeling that is difficult to detect by SC_A, the permeability index is defined by Equation (10):

$$SC_B = \min\,(SC_1, SC_2, SC_3) \quad \cdots\cdots\cdots\cdots\cdots \quad (10)$$

In the third candidate, SC_C, considering that the SC_A and SC_B are often overdetected, the number of fulfillment for the determination indices (SC_4-SC_8) is added when the SC_B is large in order to define the permeability index as expressed by Equation (11):

$$SC_C = \begin{cases} SC_B & (SC_B < 0.8) \\ \dfrac{SC_B - 0.8}{2} + 0.8 & (SC_B \geq 0.8 \cap K < T_k) \\ 0.9 \sim 1\,(\text{determined by K}) & (SC_B \geq 0.8 \cap K \geq T_k) \end{cases} \quad \cdots \quad (11)$$

wherein K is the number of the fulfillment of SC_4 to SC_8, and T_K is its threshold. Since the parameters for indexing each score are adjusted, there is no need to adjust these parameters for each operational change; they are given in advance as fixed values.

The performance of these three types of permeability indices, SC_A, SC_B, and SC_C, has been evaluated with one year's actual operational data, which has confirmed that each index can detect all the large-scale gas channeling.[Note 2)] In addition, as shown in **Fig. 4**, it has been found that SC_C results in the smallest number of times when a threshold is exceeded, best suppressing overdetection. From this, it has been found that SC_C is the most appropriate index for the risk of gas channeling. **Fig. 5** includes charts showing the transitions of the permeability index (Index value), the pressure in the blast furnace shaft and its temperature. Since multiple sensors for pressure and temperature are disposed at each height, each chart depicts multiple pressures or temperatures. As shown in Fig. 5, the pressure fluctuation increases, which disturbs the temperature distribution, triggering the increase in the permeability index. The reason why the change in the permeability index is delayed

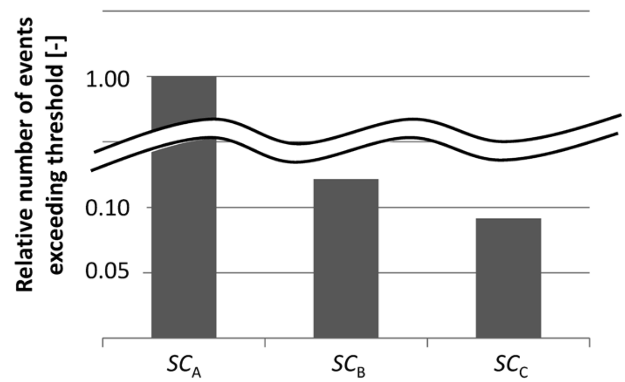

Fig. 4 Relative number of times of SC_A, SC_B, and SC_C beyond threshold (assuming 1 for the number of times of SC_A)

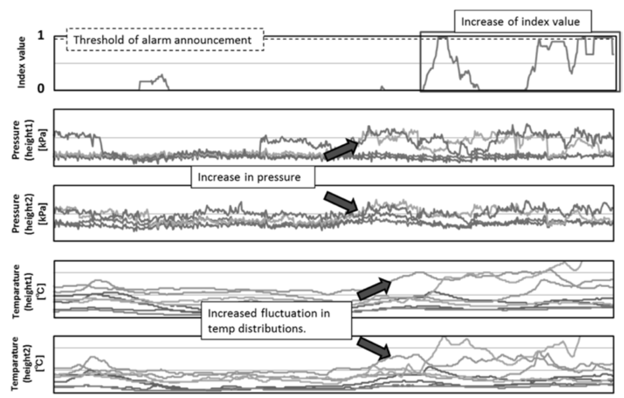

Fig. 5 Transition of index value in deteriorating furnace conditions

relative to the change in pressure and temperature is that the permeability index detects continuous fluctuation rather than the temporary fluctuation of pressure and temperature. During the period when this permeability index increases, deterioration of the raw material quality and the rise of the residual iron occurred, which verifies the fact that the deterioration of the furnace condition has been expressed.

3. Parameter adjustment technique

This section describes the technique for adjusting parameter α used for the indexing described in Section 2.2. In the case where the characteristics of the raw materials and the composition of sintered ores, etc., used in the blast furnace have changed drastically, significantly affecting the population data set and the frequency distribution obtained from them, it is important to properly adjust the parameters to accurately quantify the furnace conditions. Therefore, the frequency distribution of the target feature quantity is constantly monitored and, if there is a change, the adjustment of parameter α is performed uniformly. Distribution calculation is performed on the cases for a certain past period

Note 2) Large-scale gas channeling is defined as having a blow-lowering rate of 30% or greater.

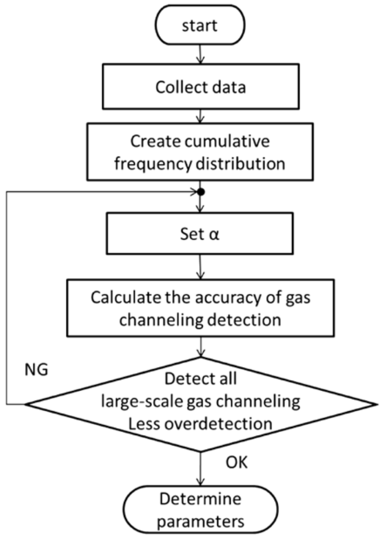

Fig. 6 Adjustment method of parameter α

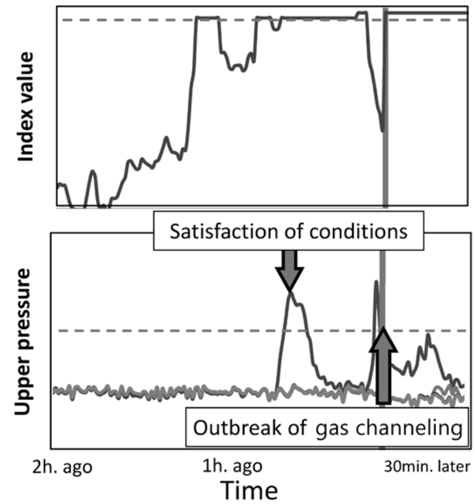

Fig. 8 Transition of index value and pressure before gas channeling

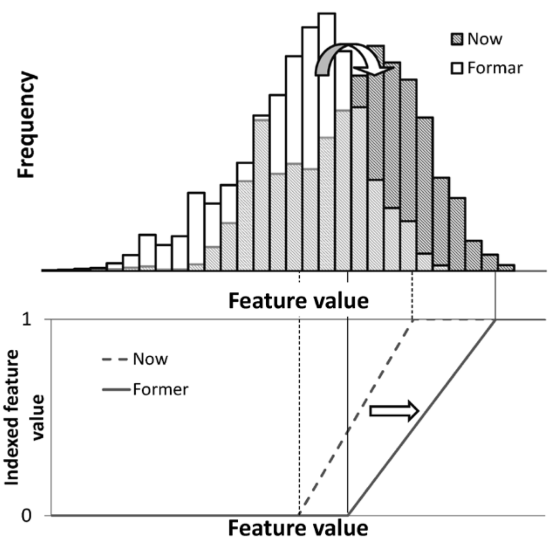

Fig. 7 Change of frequency distribution of feature quantities and method of indexing

including gas channeling incidents to adjust the parameters to optimum values so as not to overlook the large-scale gas channeling and to minimize overdetection.

This parameter adjustment technique was standardized in accordance with the flow chart shown in **Fig. 6**. A tool to automatically perform this iterative process has been developed to facilitate the parameter adjustment.

Fig. 7 shows the frequency distribution (top) obtained from two different data sets and the indexed feature determined using parameter α (bottom).

As shown in Fig. 7, when the frequency distribution changes, the indexing function changes, and the permeability index matching the change in blast furnace operating conditions can be calculated.

4. Evaluation of gas channeling prediction system

On the basis of the permeability index and parameter adjustment technique developed, a standard has been formulated for gas channeling prediction. That is, when performing the gas channeling preventive action, instructions are issued for "blow lowering" when the following two conditions (blow-lowering conditions) are simultaneously satisfied:

(1) the index value exceeds the threshold,
(2) the maximum pressure in the upper furnace exceeds the threshold.

As a specific example, **Fig. 8** shows the transition of the index value and upper furnace pressure upon gas channeling in the past. The blow-lowering condition has been reached before gas channeling, showing that gas channeling is prevented by preliminarily lowering the blow.

To assess the accuracy of this technology, an evaluation was performed on two aspects of data in a period not used for the parameter adjustment, i.e., to see whether there was overdetection when the blow-lowering condition had been reached, and whether there was any large-scale gas channeling had gone undetected. As a result of investigating the timing when the blow-lowering condition was reached in the data for the previous year and a half, gas channeling occurred in more than 90% of the cases. Although gas channeling did not occur in the remaining 10% of the cases, those were cases where the furnace conditions were so poor that it could have occurred, according to the operations department, so those cases were not considered to be overdetection. In addition, the blow-lowering conditions had been met before all the large-scale gas channeling occurrences, verifying the correctness of the prediction.

Thanks to the above accuracy evaluation, the present system is now being utilized in actual operation for instructing blow-lowering timing.

Conclusions

For gas channeling, an anomaly state of blast furnaces, a gas-channeling prediction technology has been developed by quantifying the deterioration of furnace conditions, which is a background event, and by detecting the timing on the basis of furnace pressure.

This technique has enabled the prediction of gas channeling with high accuracy and is being utilized in actual equipment. In reality, the estimation of permeability deterioration in other processes relies heavily on operators, and the application of this technology is believed to enable the prediction of an anomaly state only on the basis of objective information.

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