# Probing the inner structure of blast furnaces by cosmic-ray muon radiography

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**Abstract:** By using the detection system of the near-horizontal cosmic-ray radiography originally developed for probing inner structure of volcanic mountains, a measurement was conducted to probe the inner structure and its time-dependent change of the blast furnace for iron-making. Precise determination ($\pm 5$ cm) of the thickness of brick used for both base-plate and side-wall was made in 45 days; a crucial information to predict a life-time of the furnace. Also, the local density of iron-rich part was determined in $\pm 0.2$ g/cm$^2$ in 45 days; static structure as well as time-dependent behavior can be monitored for the iron-rich part of the furnace during operation.

**Key words:** Muon; cosmic-ray; radiography; industrial machinery.

**Introduction.** The KEK-RIKEN group has recently conducted a series of experiments probing the inner structure of a volcano by measuring the intensity attenuation, track by track, of near-horizontal cosmic-ray muons that pass through the volcano.[1)-3)] Several innovative technical developments were carried out in order to realize successful measurements of the volcanic inner-structure and its time-dependent behavior by using near-horizontal cosmic-ray muons: a) one detection system for a track determination comprises 2 sets (1.5 m apart) of position sensitive detectors, each of which is 10 segmented (each, 10 cm × 1 m × 3 cm thick) plastic scintillation counter pairs of x-y coordinate determination and, as seen in Fig. 1a, two systems with 2 m × 1 m sensitive area in total were used; b) accumulation of F (towards object)/B (towards sky) ratio data at each track of muons for self-normalization of the weak near-horizontal cosmic-ray events; c) multiplicity-event-cut through iron-plate for soft-component background removal. The sound operation of the system for a long-term (several months) measurement was confirmed in the measurements both at Mt. Asama[2)] and at Mt. West-Iwate.[3)]

**Experimental arrangement.** As indicated earlier,[4)] the radiography by using near-horizontal cosmic-ray muon should be useful for a large-scale industrial machinery like a blast furnace. By using the same muon radiography set-up as used for the volcano research, under a Collaborative Research Contract between KEK and Nippon Steel Corporation, the experiment has been carried out to probe the inner structure of the world's largest blast furnace (Blast Furnace No. 2, Dai-Ni-Kouro) at the Oita Factory of the Nippon Steel Corporation during a time of its full operation. As seen in Fig. 1b, the detection system was placed at the horizontal position of 17.3 m from the center of the furnace (nearly equal to the diameter of the furnace) and at the vertical position of, at first, at 2.7 m from the ground (the brick base is occupying from 4.97 m to additional a few

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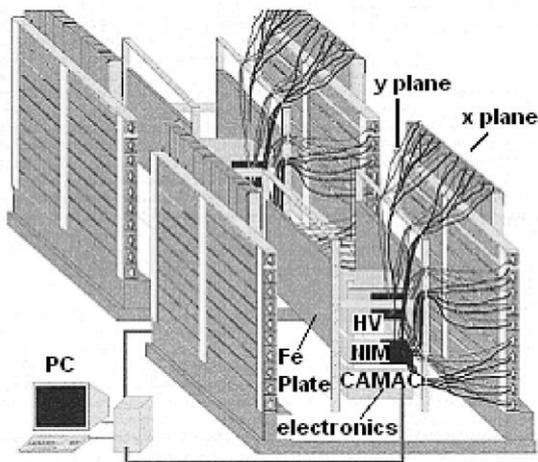
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Fig. 1a.  Detection-system set-up of cosmic-ray muon radiography.
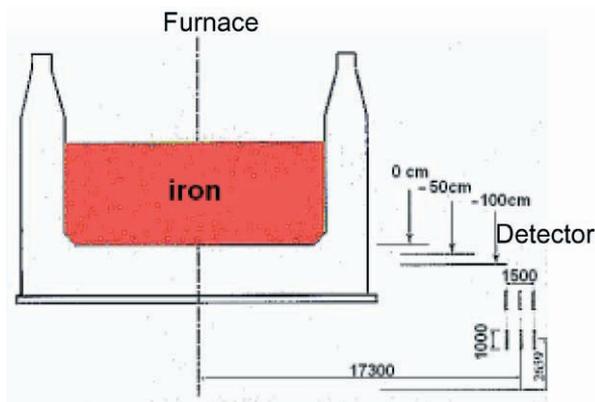


Fig. 1b.  Schematic view of experimental muon radiography arrangements of the blast furnace, where two sets of 1 m² sensitive-area detectors were placed in two different vertical positions.
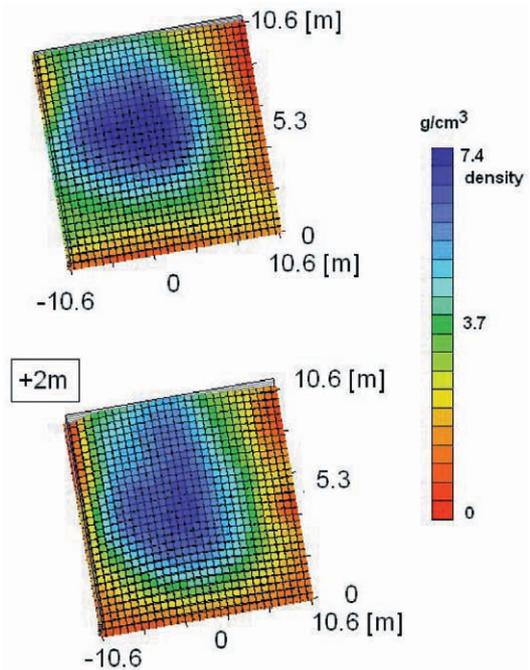


Fig. 2a.  Data of the two-dimensional density map of the penetrated cosmic-ray muons along the path through the blast furnace where coordinate is presented by the center plane perpendicular to the counter axis; for the ordinal geometry (above) and the upper counter geometry (bottom).
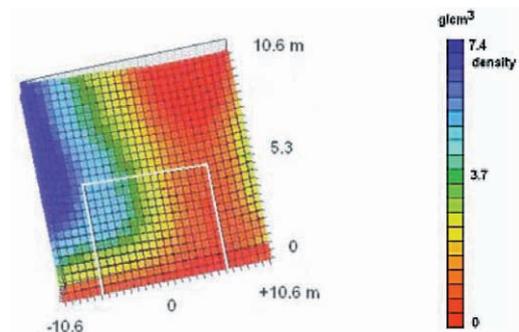


Fig. 2b.  Same density map when the counter axis was shifted by 15.2 ° towards the right-hand side wall.

m) and, then, at 4.7 m. The central horizontal line (counter axis) of each of the 2 sets detection system was placed in the direction towards the center of the furnace. Then, after 45 days measurements it was shifted by 15.2 ° towards the right-hand side wall for another 10 days.

**Experimental results.**  In 45 days of measurements (20 days for the original geometry and 25 days for the upper counter-geometry) starting at the end of November '04, the following results were obtained. As seen in the raw two-dimensional data of the density mapping obtained from the F (towards furnace)/B (towards the opposite-side, sky) ratio and the geometrical length (Fig. 2a), the components of the inner struc-

ture, namely, an iron-rich part and a brick wall/base part, were clearly identified.

Similar result was obtained during 10 days measurements for the brick side-wall as seen in Fig. 2b, when the counter axis was rotated by setting the counter axis at 15.2 ° off the furnace center line.

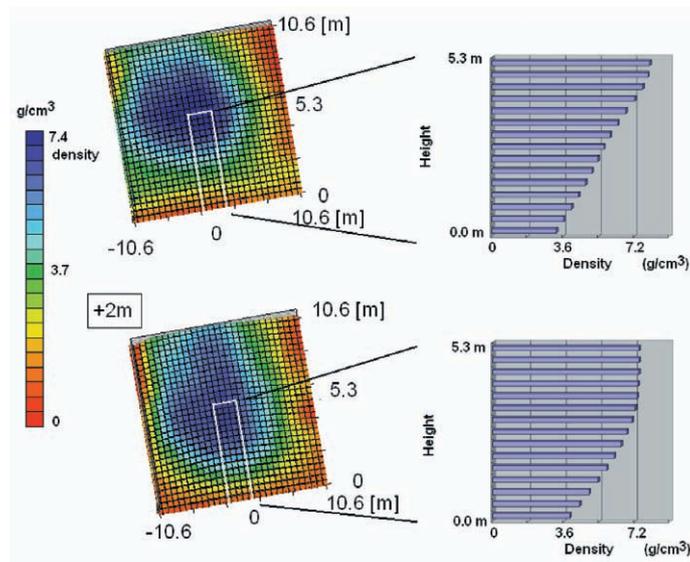**Discussion.**  In order to obtain the information of

Fig. 3. A density distribution of the boundary region between iron-rich part and brick base plate obtained by the fitting of a Monte-Carlo calculation to the F/B ratio data for the two vertical positions of the detection-system.
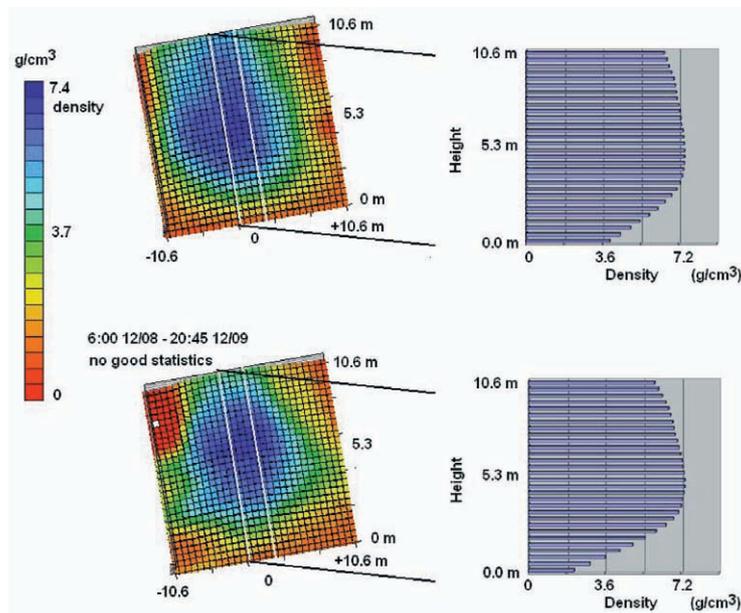


Fig. 4. A density distribution of the iron-rich part at the time of full operation (above) and at the time of a termination of hot-air supply (bottom).

the inner structure of the blast furnace, the following fitting procedure was undertaken. For the first analysis, the cylindrical symmetry was assumed for all the inner structure of the blast furnace so that the density distribution was assumed to take a form of $\rho(r, z)$, $r$ being horizontal distance from the center and $z$ being vertical height. Then, the data of a Monte-Carlo simulation calculation was obtained for every passage of the cosmic-ray muon going through the blast furnace towards the detection system with the correct information of the cosmic-ray muon spectrum at each zenith angle as well as a range attenuation.[1),2)] Thus, the F/B ratio is obtained in

the Monte-Carlo calculation. The fitting procedure was then carried out to find out the optimum $\rho(r, z)$ to reproduce the experimental F/B data.

The following results were obtained.

1. As seen partly in Fig. 3, the precision of the determination of the brick base-plate thickness can be ± 5 cm in 45 days for an original thickness of a few m, providing the most useful data for a prediction of the lifetime of the furnace. Similar results were obtained for the thickness of the side-wall. These information obviously can have a large economic impact.

2. The density of the iron-rich part can be measured with a precision of ± 0.2 g/cm$^3$ in 45 days, providing the first direct information on iron behavior in the operational furnace. A change of the iron-rich part structure was detected after a 1.5 day shutdown of the hot-air supply (Fig. 4).

**Conclusion.** Throughout all of these measurements described here the following conclusive view can be obtained.

i) Life-time or the end of the use of the furnace can be predicted within a precision of ± a few month in the two months measurement; usually 20 years of life-time is considered for a consumption of a few m thick brick equivalent to nearly 1 cm/month.

ii) Static inner structure of the iron-rich part can be monitored in 0.2 g/cm$^3$ for a sectional area of 50 cm × 50 cm in two months measurements.

iii) Time dependent behaviour of the iron-rich part, dynamics of iron, can be probed in the accuracy indicated by the above-mentioned results. Some real-time analysis of the time-dependent change can be realized by

a timing analysis with a time-trigger of the action of furnace operation e.g. stopping of hot-air supply, iron ore introduction, etc.

iv) Since the use of the near-horizontal cosmic-ray muon allows us to place many detection systems at any horizontal angles, it is easy to extend to a tomographic measurement.

All of these observations demonstrate the extremely high potential of muon radiography for industrial applications.

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