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Development of On-line Wall Thickness Gage for Seamless Steel Tubes

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Synopsis :
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The body can be viewed from the next page.

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1 Introduction

The new medium diameter seamless tube mill of Kawasaki Steel's Chita Works which started operation in 1978 achieved great improvements in quality, yield and productivity by introducing a highly advanced automation system which employs a process computer and a wide variety of on-line sensors.

In order to upgrade this automation system, Kawasaki Steel's jointly with Fuji Electric Co., Ltd. succeeded in developing a world's first gage to measure the wall thickness of pipe while it is still hot and recently introduced it into the aforementioned medium diameter seamless tube mill. With the use of this gage, the long-cherished dream of seamless tube manufacuring engineers about knowing the pipe wall thickness on-line has been realized.

In the following, the development of the wall thickness gage will be described.

2 Development Policy

The medium diameter seamless tube mill is a modern plug-mill type plant, as shown in **Table 1**, which can produce seamless tubes measuring 7″ (177.8 mmϕ) to $16^3/_4$″ (426.0 mmϕ). As mentioned earlier, a process computer has been introduced into this plant, and each of its mills has been equipped with extremely accurate on-line sensors such as radiation pyrometers, load cells, outside diameter gages and length gages, thereby realizing safe automation control of all the mills.

However, this automation control system was unable to measure directly the wall thickness of the pipe on the on-line basis; therefore, the average wall thickness was used, which was indirectly computed from measured values of the billet weight, and the length and outside diameter of the pipe at each mill.

2.1 Difficulties in Measuring Pipe Wall Thickness

Pipe wall thickness measurement on the on-line basis was considered important for improving the quality and yield. Nevertheless, no example of such measurement was available in the world's steel industry, and not even measuring principles were established. This was due to many difficult conditions involved, as mentioned below:

(1) Since the cross section of the pipe is of a closed shape, the conventional transmission-type thickness gage can measure only the so-called "double walls" (such gage measures the thickness of two opposite walls of the cross section of the pipe simultaneously).

(2) The hot rolling line encounters adverse environmental conditions at a high temperature of about 1 000°C.

* Received on June 3, 1981

** Chita Works

Table 1 Specification of main equipments

Equipment	Maker	Specification
Shot blasting machine	Shinto Industries Co., Ltd.	Type : Billet not turned, Motor : 37 kW×6 Projection density : Max. 50 kg/m^2
Billet cutting	Wagner-Tsune Machine Tool Co.	Type : Round saw blade, Main motor : 45 kW Cutting speed : Max. 164 m/min
Rotary hearth furnace	Daido Special Steel Co., Ltd.	Number of zone : Pre-heating 1, Heating 5, Soaking 2, Extracting 1 Capacity : 160 t/h, Furnace temperature : Max. 1 350°C Diameter of centerline circle of hearth : 12 m
Piercer	Demag-Meer, Mitsubishi Heavy Industries Co., Ltd.	Type : Vertical roll, Main motor : DC 3 500 kW×200/400 r.p.m.×2 Diameter of roll : Max. 1 350 mm, Feed angle : 5–14 deg.
Elongator	Ditto	Ditto
Plug mill	Aetna Standard, IHI Co., Ltd.	Type : Single groove, Main motor : AC 3 000 kW Outlet speed : Ave. 3 m/s
Reeler	Ditto	Type : Barrel roll, Main motor : DC 370/540 kW×2×2 Diameter of roll : Max. 1 000 mm
Reheating furnace	Daido Special Steel Co., Ltd.	Type : Walking beam, Furnace temperature : Max. 1 000°C Capacity : 160 t/h
Sizer	Aetna Standard, IHI Co., Ltd.	Type : 2 rolls, Stand : 8 Motors : DC 175 kW×480/1 200 r.p.m.×8
Cooling bed	Sumitomo Heavy Industries Co., Ltd.	Type : Roller chain conveyer with water-tank Total length of table : 400 ft.

(3) The pipe runs at a high speed of 2 to 7 m/s in the lengthwise direction and even rotates at a certain location.

2.2 Development of On-line Wall Thickness Gage

As a means of further improving quality and yield, the following conditions were presupposed to develop a wall thickness gage on the on-line basis.

(1) Instead of the average wall thickness of an entire pipe, accurately measured values should be obtained in respect of wall-thickness variations in the lengthwise and circumferential directions of the entire length of the pipe.

(2) Non-contact measurement is employed to obtain a high response speed and prevent defect occurrence due to the contact, because the object to be measured is very hot and travelling.

(3) Long-time continuous use should be ensured high reliability under the adverse environmental conditions of heat, dust and high moisture.

(4) In order to feed back measured values of wall thickness rapidly to mill control, measurement should be made on-line and signal processing should be easily realized.

3 Development of Measuring System

3.1 Circumstances of Development

Table 2 shows the development progress up to the present. The development was commenced in 1978 and it took four calendar years before it was completed in 1981. The circumstances of the development are described below.

The conventional "single-wall thickness gages," that measured exclusively the single wall, measured the wall thickness of cold pipes only by utilizing reflection of ultrasonic waves or that of radioactive rays, or by utilizing the transmission of radioactive rays from a source inserted into the cold pipe for about 1 m from the pipe end. Therefore, none were able to be used on-line. The electromagnetic ultrasonic sensor, whose application was a keen topic in recent years, seemed to hold promise for future development, but the distance between its detecting coil and the pipe to be measured was about 2 mm at the most. Thus it was a kind of the semi-contact type which posed problems for use in the hot working. Consequently, the authors came to the conclusion that as a non-contact on-line gage, the radioactive-ray transmission type was the best. As for the nuclide, γ rays were chosen, taking into consideration the wall thickness of the pipe; and for the radiation source, ^{137}Cs was selected. As for the radioactive-ray transmission method, the pipe end insertion method was usable for the hot working, but since it was of the insertion type, safety measures and heat protection were difficult to adopt; and because measurement was limited to the pipe end, the usefulness of this method seemed doubtful.

Table 2 Process of development

Item	1978	1979	1980	1981
1. Survey and pre-study	4 —— 12			
2. Development of scanning method (1st step)	Basic study (—3); Simulation (—7); Experiment by trial device (—12)			
3. Development of multi-beam method (2nd step)		Basic study (—2); Experiment by trial device (—7)	Study of pipe fractuation effect (—10); Prediction of practical device (—12)	
4. Design and manufacture of practical use device			Ddesign (—2); Manufacturing (—7)	On-line ⟶

3.2 Single-Beam Scanning Method

All the above-mentioned drawbacks have been overcome by the single-beam scanning method (hereinafter abbreviated to "scanning method") shown in **Fig. 1**. This method utilizes the fact that when the pattern of thickness of double walls of a pipe is measured in a certain direction, a drastic change takes place at points corresponding to the outside and inside diameters in the direction normal to the measured direction. This method has some characteristics as follows.

(1) Advantages
  (a) Single wall measurement is possible.
  (b) The equipment need not be inserted into the pipe. Therefore, it is more advantageous in carrying out safety measures and heat protection.
  (c) There is no need to align the detector with the center of the pipe. Therefore, measurement can be made, even if the roundness of the pipe is poor.
  (d) Since the gage employs the pattern system, measured values will not be affected by drift and variation in the absorption coefficient of the detector. Consequently, there is no need for temperature and material compensation.

(2) Drawbacks
  (a) Since measured values of wall thickness are obtained from data at multiple points by scanning, response speed becomes comparatively slower.
  (b) Since the shifting quantity for scanning itself is converted to wall thickness, highly accurate traversing apparatus and position detector are required.

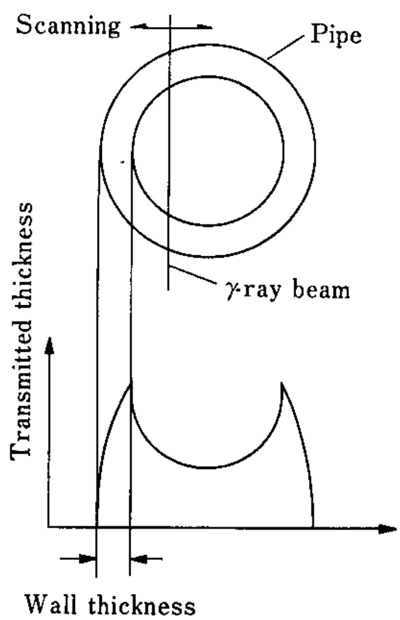

Fig. 1 Principle of measuring wall thickness by single-beam scanning method

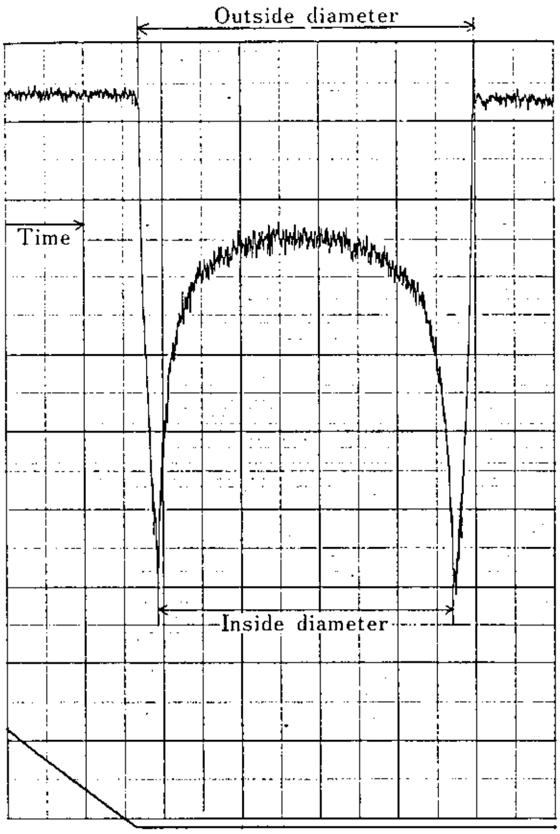

Fig. 2 An example of recorder chart by single-beam scanning method

Fig. 2 shows an example of measuring a pipe with a trial device using ^{137}Cs of 0.8 Ci as a radiation source. As a result of evaluating causes of various errors by means of various experiments using this trial device and computer simulation, a response speed of 4 sec. was obtained under the conditions of radiation source of 3.2 Ci, a γ-ray beam width of 2 mm, a scanning speed of 100 mm/s, and a required accuracy of 0.1 mm. Thus it was concluded that with the technical level of today's capacities of the detector, etc., it was impossible to further improve the response speed, and that the trial device was inadequate in terms of response for use in making medium diameter seamless tubes.

3.3 Multi-beam Method

In view of the above, the authors sought another measuring method and conceived the multi-beam method explained below. Principles of the multi-beam method are shown in **Fig. 3**. In this method, γ-rays are used as in the scanning method. As shown in the figure, γ-ray beams are applied to three or more points on the circumference of the pipe; and by changing the incident angle of the γ-ray beam, γ-ray beams are transmitted at least twice through the pipe wall thickness at each measuring point. Then the following equations stand, as basic formulas for general γ-ray transmission thickness gage, between output signal I of the γ-ray detector and pipe wall thickness X:

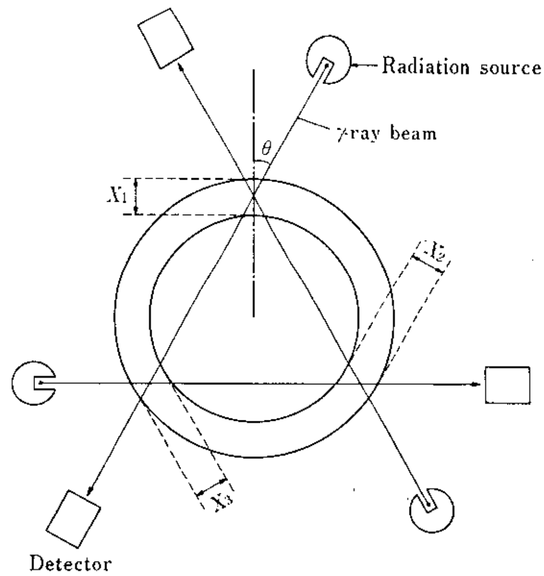

Fig. 3 Principle of multi-beam method

$$I_1 = I_{10}\exp\{-\mu K(X_1 + X_2)\} \cdots\cdots (1)$$
$$I_2 = I_{20}\exp\{-\mu K(X_2 + X_3)\} \cdots\cdots (2)$$
$$I_3 = I_{30}\exp\{-\mu K(X_3 + X_1)\} \cdots\cdots (3)$$

μ: Absorption coefficient of γ-rays used depending upon types of pipe material

K: Actual transmitted length in the pipe wall thickness by γ-ray beams that pass through the measuring point divided by pipe wall thickness, X.

The simultaneous equations **(1)**, **(2)**, and **(3)** are solved for X_1, X_2 and X_3 as follows:

$$X_1 = \frac{1}{\mu K} \cdot \frac{1}{2} \ln\left(\frac{I_{10}}{I_1} \cdot \frac{I_2}{I_{20}} \cdot \frac{I_{30}}{I_3}\right) \cdots (4)$$
$$X_2 = \frac{1}{\mu K} \cdot \frac{1}{2} \ln\left(\frac{I_{20}}{I_2} \cdot \frac{I_3}{I_{30}} \cdot \frac{I_{10}}{I_1}\right) \cdots (5)$$
$$X_3 = \frac{1}{\mu K} \cdot \frac{1}{2} \ln\left(\frac{I_{30}}{I_3} \cdot \frac{I_1}{I_{10}} \cdot \frac{I_{20}}{I_2}\right) \cdots (6)$$

Since the detector output signals of γ-ray beams can be measured continuously, values of pipe wall thickness X_1, X_2 and X_3 can be obtained by computing eqs. **(4)**, **(5)**, and **(6)**. This measuring principle is called the multi-beam method.

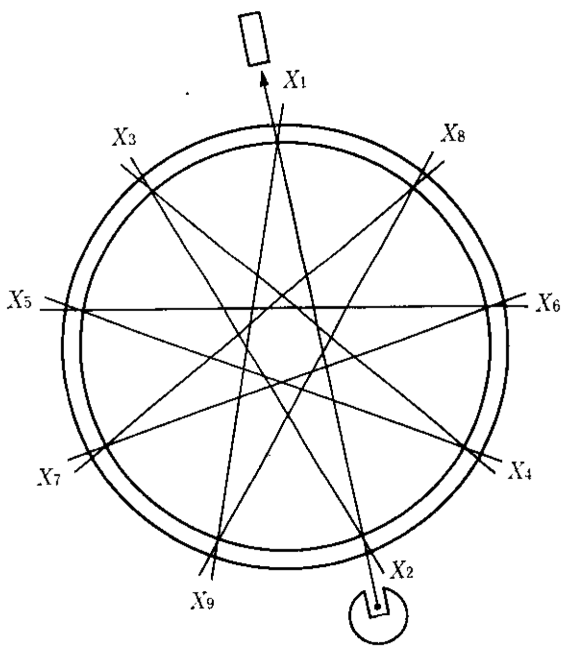

Fig. 4 Principle of multi(n)-beam method

In this method, the number of γ-ray beams need not be three, but can be n. When n γ-ray beams are used, the following matrix is obtained (refer to **Fig. 4**).

$$\begin{bmatrix} 1 & 1 & 0\cdots\cdots 0 \\ 0 & 1 & 1\cdots\cdots 0 \\ \cdots & \cdots & \cdots \\ 0 & 0 & 0\cdots 1 \; 1 \\ 1 & 0 & 0\cdots 0 \; 1 \end{bmatrix} \cdot \begin{bmatrix} X_1 \\ X_2 \\ \vdots \\ X_{n-1} \\ X_n \end{bmatrix} = \begin{bmatrix} b_1 \\ b_2 \\ \vdots \\ b_{n-1} \\ b_n \end{bmatrix} \quad \cdots(7)$$

$$b_n = \frac{1}{\mu K} \cdot \ln \cdot \frac{I_{n0}}{I_n}$$

When n is an even number, the equation **(7)** has no definite solution. Therefore, the number of γ-ray beams in the multi-beam method should be odd, i.e., wall thickness can only be measured at an odd number of points in the circumferential direction of the pipe.

4 Development of Practical Application Techniques

4.1 Pipe Fluctuation and Adoption of Pinch Rolls

The principles of the multi-beam method are based on a major premise that two γ-ray beams cross each other within the pipe wall thickness. In the actual rolling line, however, the pipe is not necessarily transported in an ideal condition owing to pipe bending and problems in the construction of the transportation table, and some means must be adopted to prevent pipe fluctuation. After examining various methods for suppressing or compensating pipe fluctuation, the authors have finally decided to constrain pipe fluctuation mechanically. Pinch rolls are provided on both sides of the wall thickness gage, so that they will constrain the pipe while it is travelling and maintain at a constant value the relative positional relationship between the pipe and γ-ray beams at all times during measuring. Since these pinch rolls are used during hot rolling line, their load for constraining the pipe is set within a certain range, so that they will not scratch the hot pipe.

4.2 Effects by Compton Scattering

In order to ensure the accuracy of wall thickness measurement, it is necessary to maintain the certain distance between the γ-ray source and the detector. However, there are many kinds of outside diameters and wall thicknesses of pipes to be measured, and the pass line center of the pipe also changes according to outside diameters. Since γ-rays pass through the wall thickness of the pipe twice without fail in the multi-beam method, it has been feared that the effect of lamination experienced in plate thickness measurement may result in the deterioration in the accuracy of wall thickness measurement. This effect is a phenomenon in which the apparent absorption coefficient of γ rays, when they pass through two overlapped steel plates of equal thickness, becomes smaller than when they pass through a single plate of the same thickness, owing to the Compton scattering of γ rays. In the multi-beam method, γ-ray beams passed through the pipe wall thickness twice and also passed the wall thickness in the inclined direction, thereby incurring Compton scattering. To solve this problem, the following measures have been taken:

(1) A collimeter is provided at both γ-ray source and detector sides to minimize detection of scattered γ rays (refer to **Fig. 5**).
(2) In setting the wave-height discriminate voltage of the detector counting rate, section "a" to "b" of the counting rate-discriminate voltage characteristics shown in **Fig. 6** is selected, so that the

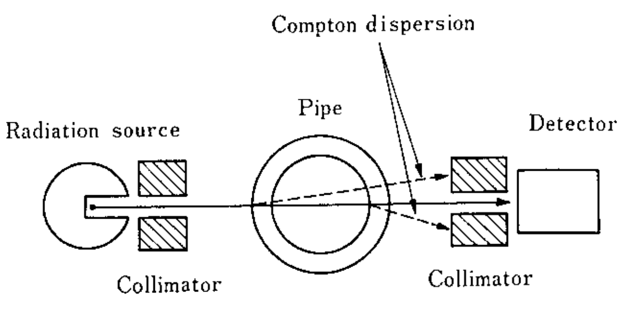

Fig. 5 Schematic diagram of compton desperSion

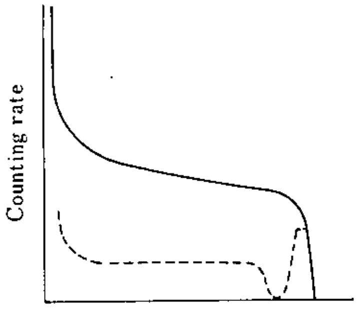

Fig. 6 Characteristics of discriminate voltage and counting rate

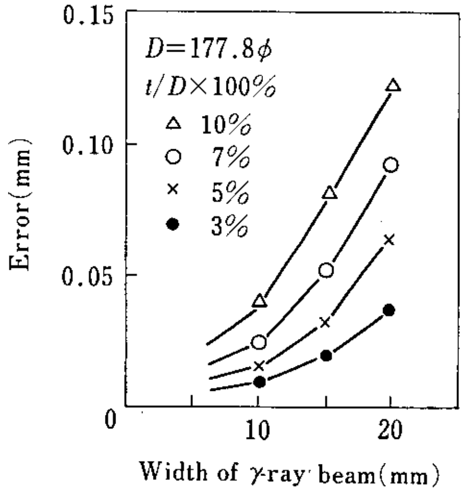

Fig. 7 Comparison of γ-ray beam width

number of miscountings of the detector itself due to scattering can be minimized. The solid line in **Fig. 6** shows the counting rate characteristics of the detector, and if this characteristics curve is integrated by the discriminate voltage, the dotted line curve is obtained. Portion "a" of this dotted line curve shows a portion affected by Compton scattering, and portion "b" is the portion due to γ-ray energy.

4.3 γ-ray Beam Width and Measuring Accuracy

As mentioned in the preceding section, γ rays were formed into almost parallel beams by the collimeters. An experiment was made to determine whether or not there was any relation between the beam width and measuring accuracy. When the beam width was narrowed down, γ-ray energy and detectable energy decreased. Therefore, the narrower the beam width the more radiation source strength would be required. This, however, was detrimental to safety and economy, and further examination was required. When the pipe wall thickness was measured on the off-line basis, by changing the actual γ-ray beam width from 5 to 20 mm, characteristics shown in **Fig. 7** were obtained. From these characteristics, the following was observed. Namely, although a narrower beam width yielded a higher measuring accuracy, a beam width up to 20 mm was permissible, in order to achieve the measuring accuracy of 0.1 mm which had been set up as the development target by the authors. Consequently, 20 mm was adopted as the γ-ray beam width of the hot wall thickness gage to be used for making medium diameter seamless tubes.

5 Constitution of Wall Thickness Gage

The on-line wall thickness gage consists, as shown in **Fig. 8**, of detector A to be installed in the line where actual pipe measurement is performed, sequence controller B which shifts the γ-ray beam position (to be mounted on the detector) according to the outside

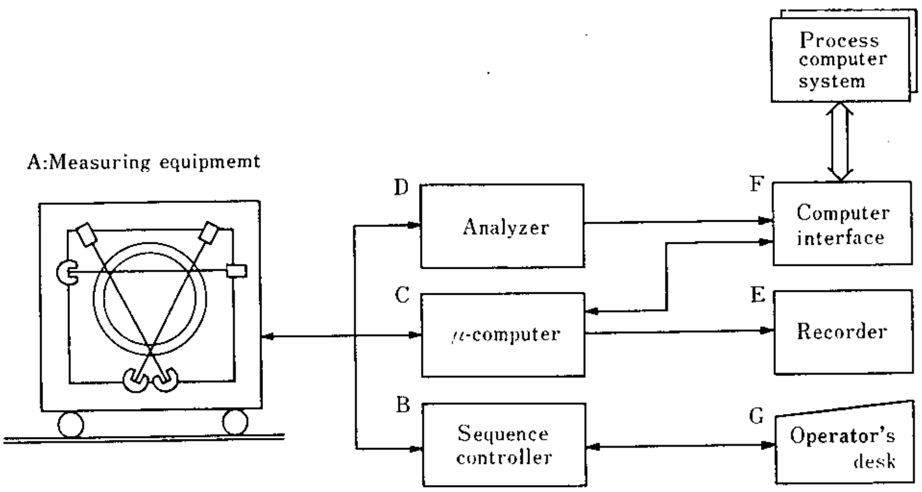

Fig. 8 Schematic diagram of wall thickness gage

diameter and wall thickness of the pipe, signal processor C which computes the γ-ray exposure count values into wall thickness values, analyzer D which analyzes the wall thickness pattern in the lengthwise direction of the pipe, recorder E which continuously records wall thickness of a single pipe, computer interface F and operator desk G.

The detector is of a steel structure with high precision construction capable of a long-time use in the hot line. The entire body of the detector is cooled with water at all times. For easy maintenance of the detector, the transfer car method is employed.

The three γ-ray beams should be moved and positioned properly according to the outside diameter and wall thickness of the pipe. When the operator sets the values of the outside diameter and wall thickness at the operator desk, the APC device automatically sets the γ-ray beams at the set position, thereby preventing operation errors and attaining high accuracy.

For the γ-ray source, ^{137}Cs is employed, and for the detector, a plastic scintillation detector is used, taking into consideration its high speed response and compact size. Signals from this scintillation detector pass through the scintillation counter and are led into the signal processor where wall thickness computation is performed. Simultaneously, the signals are also led into the analyzer where the wall thickness pattern in the lengthwise direction of the entire pipe is analyzed. For the signal processor and analyzer, microcomputers are used to ensure high-speed and high-accuracy computation. The computed wall thickness values are D/A-converted and continuously recorded into the analog recorder. With this record, the operator can quickly judge the wall thickness condition. The operator desk is installed in the operator room where he can monitor all the operations of the on-line wall thickness gage. Particularly, monitoring the γ-ray source shutter and cooling water is important for safety, and therefore a full-scale monitor mechanism is employed, permitting conversation between the operator and the monitor.

All data measured by the on-line wall thickness gage can be transmitted to the process computer. In the medium diameter seamless tube manufacturing line, the measured data are transferred to the rolling-control process computer, thereby forming a system for their organic utilization.

6 Performance of On-line Wall Thickness Gage

Not to mention the wall thickness gage, measuring systems for continuous measurement on the on-line basis are required to have high-speed response capability, because it is necessary to measure the total length of the pipe from top to tail without omission. However, infinitely-faster response speed cannot be obtained, and therefore, the response speed should be determined according to the objective of measurement and the technical level of hardware. Upon examining this point at the start of developing the on-line wall thickness gage, the authors established the target of 0.1 sec. for the response speed. For the radiation source strength, the value of 10 Ci/beam or below was established as the target, because greater strength would be inadequate for safety in view of the nature of the seamless tube rolling line.

Under the above-mentioned conditions, simulation of measuring errors and the design of the performance of the on-line wall thickness gage were performed, and the outcome was the performance shown in **Table 3**. This table shows the case where the radiation source strength is 10 Ci/beam. When the radiation source strength is lowered to 3 Ci/beam, the stochastic error

Table 3 Error estimation table at 10 Ci

(mm)

Diameter(mm)	177.8(7")			273.1(10¾")			406.4(16")		
Thickness/Diameter(%)	3	5	10	3	5	10	3	5	10
Thickness(mm)	5.3	8.9	17.8	8.2	13.7	27.3	12.2	20.3	40.6
Calibration error	0.03	0.04	0.05	0.03	0.04	0.07	0.04	0.06	0.10
Position error of γ-ray beam	0.02	0.02	0.02	0.02	0.02	0.03	0.02	0.03	0.04
Pipe size error	0.01	0.01	0.02	0.01	0.01	0.02	0.01	0.02	0.03
Pipe fluctuation effect	0.10								
Stochastic error	0.08	0.10	0.19	0.10	0.14	0.38	0.13	0.23	0.99
Total error	0.13	0.15	0.22	0.15	0.18	0.40	0.17	0.26	1.00

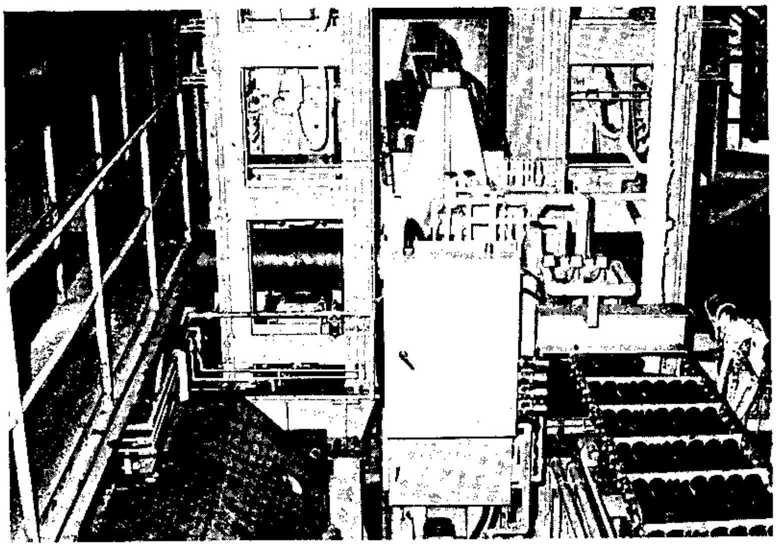

Photo. 1 Front view of wall thickness gage

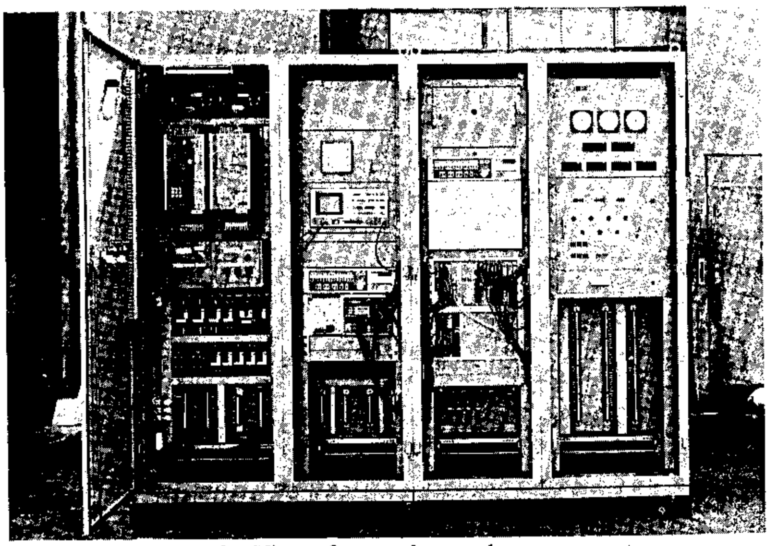

Photo. 2 View of control pannel arrangement

is expanded about $\sqrt{3}$ times, with the number of overall errors slightly increasing.

7 Result of On-line Measurement

Of the various units comprising the on-line wall thickness gage installed in the medium diameter seamless tube mill line, the detector, control panel incorporated in the microcomputer, and the outline view of the operator desk are shown in **Photos. 1, 2,** and **3**, respectively.

Fig. 9 shows the results of actual measurement of pipe wall thickness by the on-line wall thickness gage. The figure clearly indicates high responses to variations of wall thickness in the measurement.

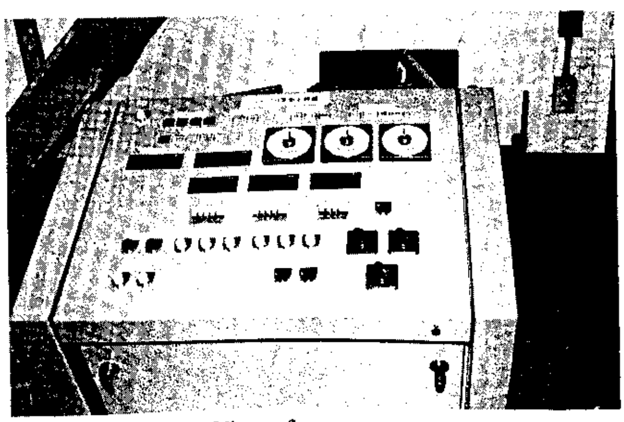

Photo. 3 View of remote operator's desk

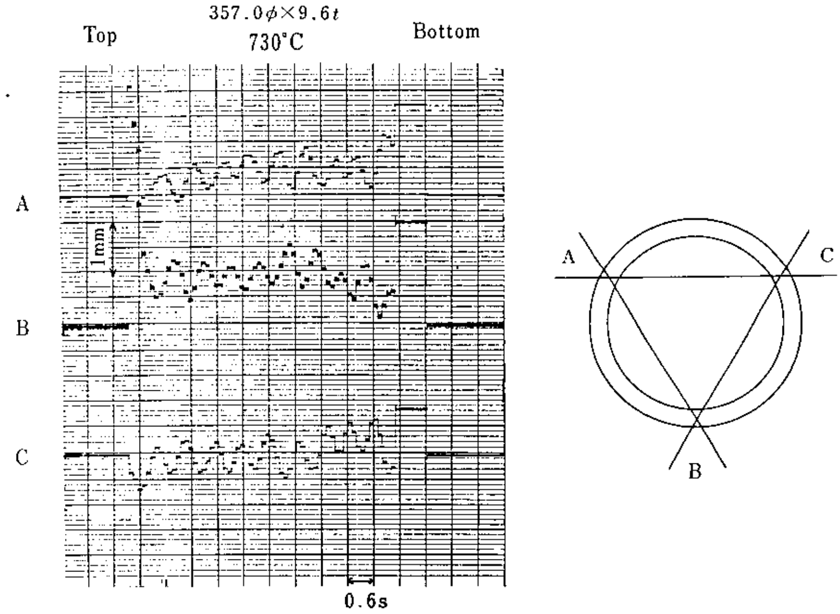

Fig. 9 An example of recorder chart by multi-beam method

8 Conclusion

In order to meet an increasing need for the medium diameter seamless steel tube mill to achieve more production and higher product quality and yield in future. The automation and sensor technology must be further promoted.

The on-line wall thickness gage has been completed through the efforts of many persons concerned. The authors will endeavor to further upgrade its on-line function and expand the scope of its application. Also, with the accumulation of techniques obtained from the present development, the authors will actively seek ways to use the on-line wall thickness gage for the manufacture of small diameter seamless tubes.

Finally, the authors would like to express their deep appreciation to the staff concerned of Fuji Electric Co., Ltd. for their valuable cooperation.