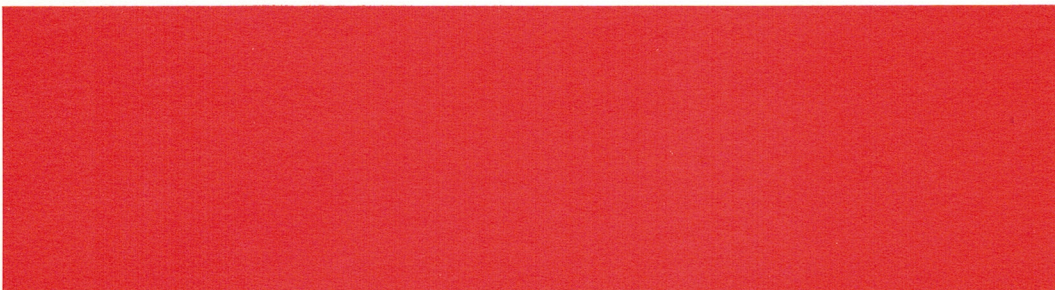


# Radioisotope Thickness Measurement Systems and Techniques



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# Progress Report—Radioisotope Thickness Measurement Systems and Techniques

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*Thickness is the most sensitive parameter in flat steel quality. Accurate and reliable control of thickness is necessary to meet today's market pressure.*

ONE of the greatest challenges facing the steel industry today is the requirement for ever higher standards of quality control. Customers and competition are demanding degrees of quality which, in many cases, actually exceed the capabilities of even modern production facilities. The rule of the marketplace today is that the higher the quality of steel produced, the more business that mill will obtain, and the quality specifications on the next order will be still higher.

The most sensitive parameter of quality in steel products is thickness. Accurate and reliable control of thickness is necessary to meet this market pressure. The key to superior gage control, regardless of the scheme of control used and the capabilities of the mill mechanical and electrical equipment, is a highly reliable and accurate means for making a representative measurement of material thickness. The requirement that the measurement be representative is emphasized because of the statistical nature of any such measurement, and because it is necessary to know the nature of thickness variations in order to determine how to control them.

*Nature of thickness variations*—Little is really known about the nature of thickness variations which exist in any particular product at any point in its processing, or where the thickness variations actually occur and why. It is known for instance, that coils are typically heavy on both ends because heads and tails are partially rolled without tension in all mills. Also, backup roll eccentricity produces a cyclical thickness variation, skid marks from the reheat furnace result in rather

wild heavy spots and the gradual temperature decrease in a slab as it passes through the hot mill causes an increasing thickness gradient from head to tail. Beyond these few qualitative generalities, however, there exists little evidence of the nature, source and cause of strip thickness variations. To achieve optimum gage control, this void must be filled.

*Representative measurement*—The first step toward good gage control is to make a representative measurement of the thickness variations existing in the material. Since the thickness of a given piece of steel may vary significantly at infinitesimally small increments throughout its width and length, the ideal measurement is a truly continuous one in all directions of every infinitesimal segment. This, of course, is impossible to achieve and one is left with the alternative of a sampling procedure whereby a statistical mean thickness over some finite area can be obtained, and the variance of the individual samples about that mean is a probability that any one sample will be representative of the mean. One then must determine a realistic sampling interval and the number of samples to be observed per unit length, width or time. The making of a representative measurement, thus, is a statistical process rather than an absolute one.

*Economic implications*—To the fabricator, the economic implication of his desire for tighter thickness tolerances is readily apparent. He wants to make more parts per ton of steel purchased. The closer to minimum design thickness that a part can be produced, the fewer are the tons of steel that will be required. The fabricator is also concerned with reducing die wear and breakage which can be caused by overgage steel. The idea of being able to achieve more sales by producing a higher quality product is also apparent to him.

The primary economic consideration to the steel producer is to maintain or increase his market share by producing the quality his customers demand and expect. He can further achieve direct manufacturing cost reduction through yield improvement. This can be

achieved through reliable, continuous gaging and control to: reduce scrap, increase salable production, save time of the machines and men used for production, and reduce time and scrap in subsequent processes because the quality of the raw material provided to them is improved.

One other area of economic importance to the steel-maker which is often overlooked is that of charge-backs or customer rejects. After a coil of steel is rolled to some control tolerances, some parts of the coil may still be out of tolerance (portions of the coil head and tail, for example). In some subsequent process, such as a tinning line, the coil is inspected and off-gage portions are normally culled out prior to shipment. To ensure that minimum scrap is created by this procedure and to be sure that the product shipped is correctly inspected and classified, thickness measurement precision is required when the actual material thickness is near the tolerance limits. Good measurement accuracy at the limits of thickness deviation from nominal, then, can both decrease scrap at the mill and reduce customer rejects.

Accurate, reliable, representative measurement of thickness is thus required to achieve the following ends:

1. Gage control.
2. Maintain and increase sales.
3. Increase yield.
4. Reduce customer rejects.

#### RADIOISOTOPE THICKNESS MEASUREMENT SYSTEM

The industry has proved that, in order to achieve the degree of reliability required, continuous noncontacting radiation-type thickness measurement systems must be used. This type of system has gained considerable popularity in the steel industry in recent years, and offers many unique, basic advantages. The physical size of the isotope permits it to be housed in a small enclosure requiring minimum mounting space. The isotope is solid state and requires no supporting equipment. The stability of the radiation further assures reliability of the gage and permits its greatest advantage which is the capability of being permanently calibrated so that it can be used as a direct reading device rather than as a deviation comparator.

Radioisotope thickness measurement systems are relatively new to the steel industry having been introduced in the early 1950's. There has been considerable and rapid development of their capabilities since that time, which enhances the basic advantages of the system and offers features, functions and performance capabilities previously unavailable to the industry. This article reports the present status of radioisotope measurement system capabilities and application techniques.

*Types of radiation*—Several types of radiation are emitted from the nuclei of radioactive elements. Of these, the only ones of significant importance in gaging systems are beta particles, and electromagnetic or gamma photons.

*Beta particle*—The beta particle is a high-speed electron. It has a small but significant mass of 1/1820 atomic mass unit. It is a negatively charged particle. Hence, its interactions with matter are both electric field interactions and mass interactions. It has a kinetic

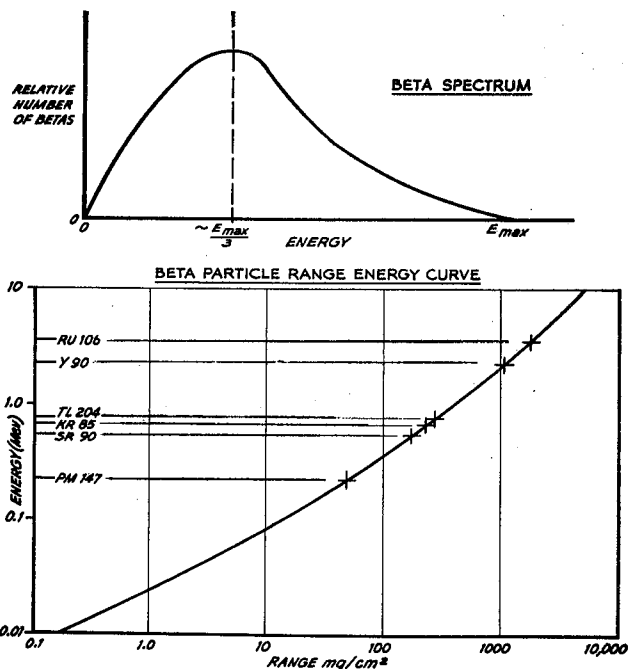


Figure 1 — Energy systems of the beta particle are continuous. The upper curve shows that some number of beta particles are present at all energy levels from zero to maximum. Lower curve is a plot of beta energy vs. range.

energy by virtue of its velocity which is classically expressed as one half its mass times its velocity squared. Its kinetic energy is expressed in electron volts or million electron volts. Its velocity is very nearly that of the speed of light. The energy spectrum of the beta particle is continuous. That is, there are always some number of beta particles present at all energy levels from zero to maximum (Figure 1, top).

Because a beta particle has both mass and charge it has a high probability of interacting with matter. The higher the energy of any given beta particle, however, the lower is its probability of interaction with matter, hence, the greater its range. The lower curve (Figure 1) is a plot of beta energy vs. range illustrating this fact. Points corresponding to the several beta emitting isotopes are indicated on the curve. Promethium-147, for example, is one of the weakest beta emitters. It has a maximum range of approximately 50 mg per cm<sup>2</sup>, which means that about 0.0025 in. of steel will completely stop all promethium-147 beta particles. Strontium-90 is commonly used as a source of beta radiation for measurement of tinplate gages.

Actually the strontium-90 beta radiation is not used directly since strontium-90 produces the daughter product of yttrium-90 which, as shown in the lower curve (Figure 1), has a maximum range of about 1000 mg per cm<sup>2</sup> or about 0.050 in. of steel.

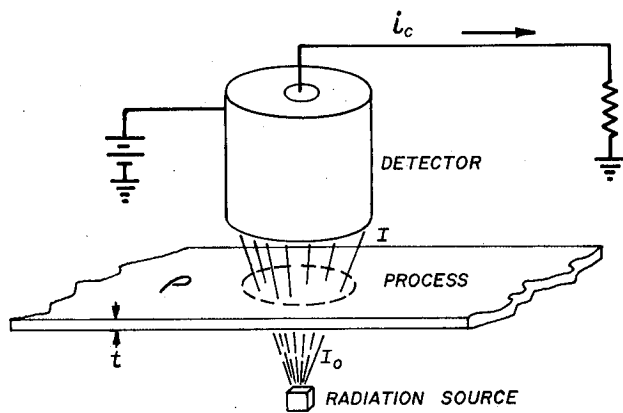
*Electromagnetic radiation*—Electromagnetic radiation has no mass and no charge. It is a radiation wave similar to radio and light waves. It has a kinetic energy, however, even though it has no mass. Any electromagnetic radiation has a kinetic energy equal to Planck's constant  $h$  times the frequency of the wave and can be expressed in electron volts. The spectra for the electromagnetic photons can be either continuous or monoenergetic.

It is appropriate here to distinguish among gamma,

Bremsstrahlung and x-rays; all are electromagnetic radiation. If a photon could be isolated in space, one could not determine which of these types of radiation it is. It is simply electromagnetic radiation having a given frequency. These names indicate only how the radiation was created. A gamma ray always comes from the nucleus of a radioisotope. Bremsstrahlung is radiation which is generated when beta particles bombard a target. X-rays are electromagnetic waves which are created when artificially accelerated electrons bombard a target. There are also characteristic x-rays which result when an orbital electron is knocked out of orbit, another electron drops into its orbit and the energy it had to give up in reaching this orbit is given off as electromagnetic radiation.

Illustrated in Figure 2 are spectra and ranges of various types of electromagnetic radiation. Gamma rays emitted from the nuclei of radioisotopes have one or a few discrete energies. Hence, gamma radiation is said to be monoenergetic. Both Bremsstrahlung and x-radiation have continuous energy spectra, just as does beta radiation. After initial interaction of these photons with the target material, however, the lower energy photons are absorbed so that the useful energy spectra of Bremsstrahlung and x-radiation is that shown by the dotted line in the upper portion of Figure 2. Characteristic x-rays are monoenergetic.

Since electromagnetic radiation has neither mass nor charge, it is much more penetrating than is beta radiation. The range for electromagnetic radiation cannot be defined because there is a probability that a gamma photon will never be stopped. To illustrate the ability of gamma photons having various energy levels to penetrate matter, transmission curves for various common gamma emitters are shown in the lower portion of Figure 2 for both iron and lead. These curves show the relative amount of incident gamma



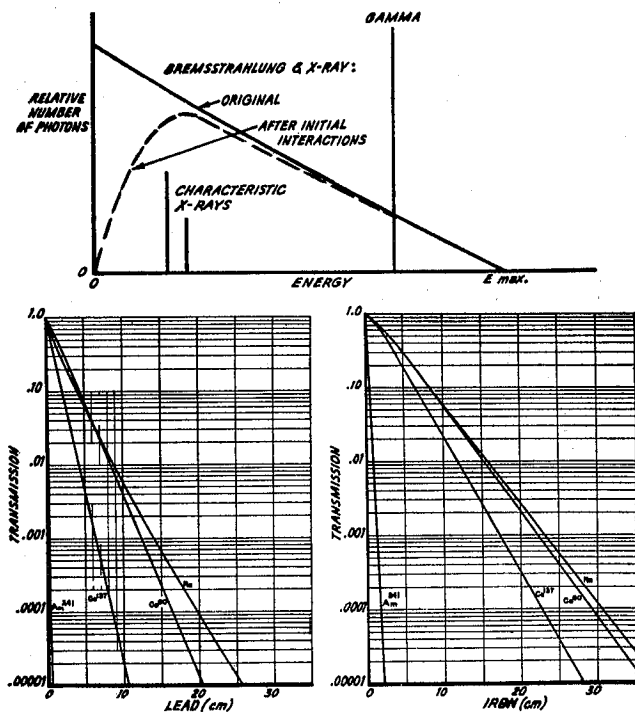
- $I_0$  = INCIDENT RADIATION INTENSITY
- $I$  = TRANSMITTED RADIATION INTENSITY
- $\rho$  = PROCESS DENSITY
- $t$  = PROCESS THICKNESS
- $i_c$  = DETECTOR OUTPUT CURRENT

Figure 3 — Complete source-detector geometry consists of: radiation source, strip being measured and radiation detector.

radiation which will be transmitted through various thicknesses of these two materials. The ability of gamma radiation to penetrate matter depends on its energy. The higher its energy the greater its penetration ability. Gamma radiation from americium-241, for example, has a relatively low energy and is very readily absorbed. Radium-226 radiation, on the other hand, is quite penetrating since it has a much higher energy. Bremsstrahlung and x-radiation are not illustrated in the lower curves of Figure 2 since their continuous energy spectra make mathematical prediction of their transmission capabilities difficult. For purposes of comparison, however, one can consider, for a continuous energy spectrum, the equivalent monoenergetic value that would give the same average transmittance as the continuous spectrum. A 100-kv x-ray tube, for example, can be considered to be equivalent to a monoenergetic source of 60 to 80 kev. Americium-241 has an energy level of 59.6 kev. Hence, the penetrating ability of the electromagnetic radiation from a 100-kv x-ray tube is very much the same as that for americium-241. For both, about one per cent of the incident radiation would be transmitted through about 0.5 cm or 0.2 in. of iron. Bremsstrahlung from the Sr-Y-90 source has a maximum energy of 2.28 mev, and its equivalent monoenergetic energy varies from 100 to 200 kev depending on the thickness being measured. It has a transmission value of one per cent at 15 cm or 6 in.

*Principle of measurement*—A complete source-detector geometry consists of the elements illustrated in Figure 3. First, there is the source of radiation with incident radiation intensity  $I_0$ . The second major element is the process or material being measured (thickness =  $t$  and density =  $\rho$ ). The third major element is the radiation detector which receives a radiation intensity transmitted through the process. When an electrical potential is connected across it, it produces an output current  $i_c$ , through an output load resistor. The rela-

Figure 2 — Various types of electromagnetic radiation spectra and ranges are illustrated.



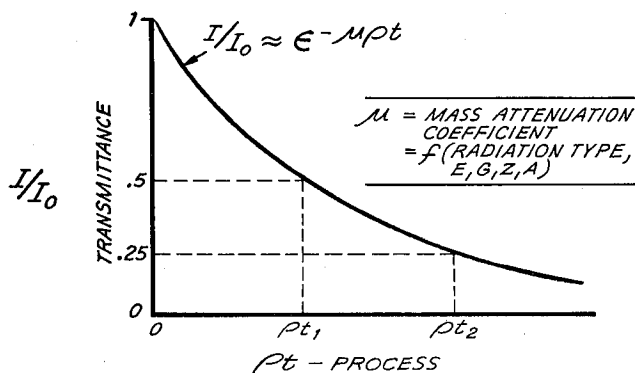


Figure 4 — Relationship among source-detector variables is shown.

relationship among the source-detector variables is illustrated in Figure 4. The transmittance, or ratio of transmitted radiation intensity to incident radiation intensity, varies inversely and exponentially with the density and thickness of the process and the mass attenuation coefficient  $\mu$ .

$$\frac{I}{I_0} = e^{-\mu pt} \quad (1)$$

The mass attenuation coefficient  $\mu$  is further a function of the type of radiation (beta or electromagnetic), the energy of the radiation  $E$ , the geometrical relationship between the source, detector and material being measured  $G$ , the atomic number  $Z$ , and the atomic weight  $A$  of the material being measured.

Given this basic exponential relationship, if any two of the three variable factors can be considered to be constant, variations in the third can be measured. For thickness measurement of steel, for example, density and mass attenuation coefficient are assumed to be constant and radiation absorption to vary only with material thickness (Figure 5). The degree to which density and mass absorption coefficient are not constant for any given gage calibration determines its measurement error.

#### ISOTOPE SOURCE-DETECTOR GEOMETRIES

The relative magnitudes of process density and of the various parameters of which mass attenuation coefficient is a function must be considered in the design and/or selection of the optimum source-detector geometry. The term, source-detector geometry implies all of these parameters; the type and energy spectrum of the source of radiation, the radiation detector, the material to be measured and the geometrical relationship among these three.

*Process resolution and measurement range*—Illustrated in Figure 6 are radiation absorption curves for four different source-detector geometries, each having a different mass attenuation coefficient for the same process material. The curve labeled  $\mu_1$  might represent high-energy electromagnetic radiation on steel, the  $\mu_2$  curve low-energy electromagnetic radiation, the  $\mu_3$  curve high-energy beta radiation and curve  $\mu_4$  low-energy beta radiation. The curve having the greatest total signal range for a given total process thickness range to be measured is the optimum selection.

#### PROCESS: STEEL

UNITS OF MEASUREMENT:  
 $t$  (THICKNESS) ( $\rho = \text{CONSTANT}$ )

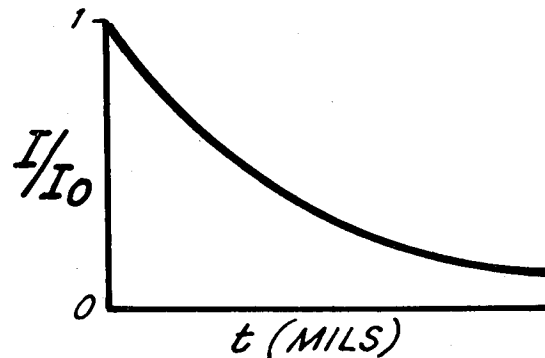


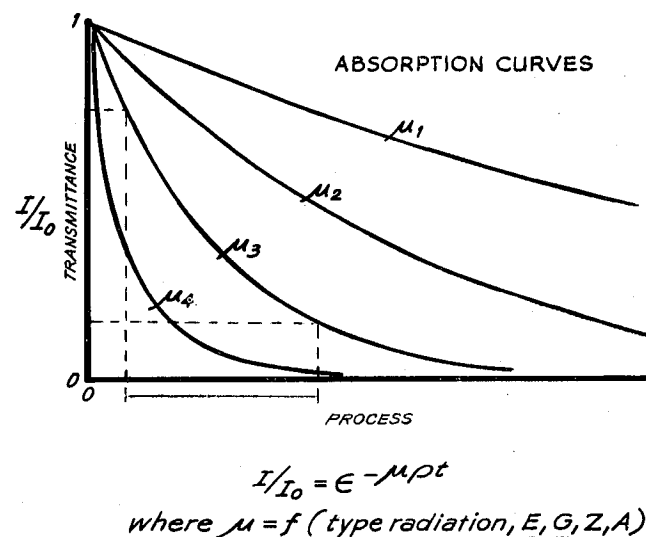
Figure 5 — In steel application, density and mass attenuation coefficients are assumed to be constant and radiation absorption to vary only with material thickness.

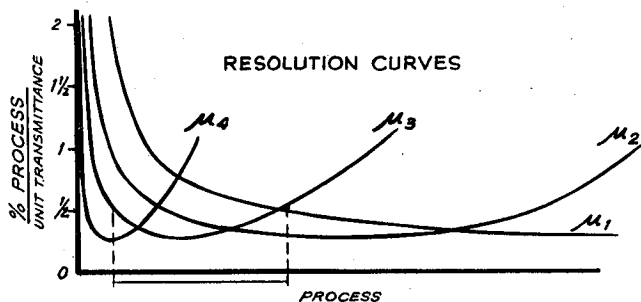
Next, resolution capability must be considered. Resolution defines the incremental change in thickness about a given nominal thickness represented by a given change in transmittance. Resolution is a function of the slope of the absorption curve and is usually expressed as a percentage of process thickness per 0.1 per cent change in transmittance.

$$\text{Resolution} \left( \frac{\text{Per cent process}}{0.1 \text{ per cent transmittance}} \right) = \frac{0.1 e^{\mu pt}}{\mu pt} \quad (2)$$

Resolution is a function of the nominal thickness being measured and has a minimum value (best measurement point) of 0.1e or 0.272 per cent process per 0.1 per cent transmittance. These units of expressing process resolution are selected merely for convenience. Process resolution for any geometry at any particular thickness value is not an expression of gage accuracy at that point since process resolution is only one element of overall measurement accuracy capability. The concept of process resolution is useful in comparing the

Figure 6 — Radiation absorption curves are plotted for four different source-detector geometries, each having a different mass attenuation coefficient for the same process material.





$$\frac{\% \text{ Process}}{\text{Unit Transmittance}} = \frac{d(\rho t)}{d(I/I_0)} \bigg/ \rho t = - \frac{\epsilon \mu \rho t}{\mu \rho t} \times 0.1$$

Figure 7 — Typical curves of resolution vs. process thickness are plotted for the four geometries of Figure 6.

capabilities of different geometries or in determining which has the best resolution capability for a given process range. In general, one per cent resolution is good and anything greater than one per cent is considered poor. The optimum geometry has a resolution of one per cent process thickness per 0.1 per cent transmittance or better throughout the total process thickness range to be measured. Typical curves of resolution vs. process thickness for the four geometries of Figure 6 are illustrated in Figure 7.

**Composition sensitivity**—Ideally, a thickness gage measures only thickness with total disregard for what material it is measuring. Unfortunately, however, radiation is absorbed by various materials to different degrees. Obviously, the density of the absorber is significant to its ability to absorb radiation. The closer its atoms are spaced the greater is the probability that a unit of radiation entering the absorber will be stopped or deflected by one of its atoms. In most metal thickness measurement applications, however, the assumption that density is relatively constant is valid. Few rolling mills are designed to roll both high and low-density materials. Even carbon steel and all stainless grades have very nearly the same density.

Of greater significance to composition effects is the dependence of mass attenuation coefficient on the atomic structure of the absorbing medium. Illustrated in Figure 8 is this dependence for both beta and gamma (electromagnetic) radiation. Beta radiation is very insensitive to composition. Because it has both mass and electrical charge its probability of interacting with matter is high regardless of the atomic structure of the matter. There is practically no composition effect with beta radiation on most metals applications.

Gamma radiation, on the other hand, is sensitive to atomic composition. There is a significant difference in the gamma absorption curves among silicon steels, different stainless grades and carbon steel. Even normal variations in the quantity of some alloying elements within a given alloy grade can cause noticeable composition effects. This is particularly the case with the low-energy gamma radiation, typical of x-ray tubes and the Am-241 isotope, since the mass attenuation coefficients of various elements are more divergent from each other at low photon energies than they are at higher ones.

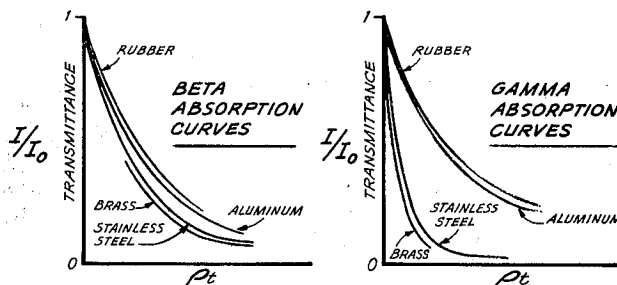
Hence, one must consider the composition differences among the various grades or alloys to be measured, and the anticipated variations in composition within each alloy class with respect to the type of radiation being considered and its energy spectrum in order to select the best source-detector geometry with regard to composition sensitivity for any particular application. Beta radiation is virtually composition insensitive. High-energy electromagnetic radiation is more composition sensitive than beta but less than low-energy electromagnetic radiation.

**Foreign material**—Just as the ideal thickness gage is insensitive to the type of material being measured, it also needs to be totally unaffected by any other material which is foreign to the process. Such things as rolling oil on the strip, dirt and grease on the windows of the apparatus and the water and dirt contained within the air gap are items having mass which will absorb some portion of the radiation.

The isotope gage provides automatic source standardization to compensate for foreign material build-up. Source standardization is the electronic readjustment of the absorption or calibration curve to the new value of  $I_0$ , which is that portion of the original incident radiation which passes through the foreign material and is available to make the measurement.

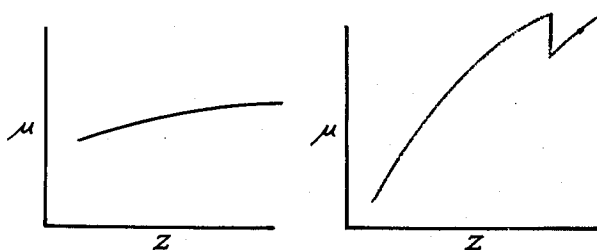
**Measurement noise**—Measurement noise has three major components. The statistical variation of the radiation emitted from the source appears as noise and varies with the square root of the number of particles detected. The number of particles detected is further a function of the quantity of the isotope material used, the energy of the radiation, geometry, detector type and construction, and the absorber. The second component of noise derives from unwanted signals generated in electronic components and can be controlled by selection of stable, reliable electronic components. Electronic noise in a radioisotope measure-

Figure 8 — The dependence of mass attenuation coefficient is illustrated for both beta and gamma (electromagnetic) radiation.



$$\frac{I}{I_0} = e^{-\mu \rho t}$$

where  $\mu = f(\text{type radiation } E, G, Z, A)$



ment system is usually insignificant compared to the source noise. The third component of noise is often overlooked in gaging applications, yet it is usually the largest; this is process noise. Process noise is high frequency or intermittent, short-term thickness variation which the gage control system is incapable of correcting because of its response limitations and/or which is not significant to the end users' requirements. Backup roll eccentricity is an example of process noise.

*Speed of response*—Noise is further a function of the response capability of the measurement system. Although such systems have complex transfer functions containing several cascaded time constants or frequency dependent components, most use a capacitive input time constant element to attenuate both source and process noise to achieve the required signal to noise ratio. This input time constant is usually the largest one of the system and it, therefore, governs overall speed of response. Noise varies with the square root of the system time constant. A value of measurement system input time constant is selected to adequately filter process noise and pass useful information concerning process thickness changes.

Discussion of speed of response of a thickness measurement system in the time domain is somewhat unwieldy. The system is not a simple, single-order one. A step-change in thickness is required to define a time constant or its response time, and step changes in thickness do not normally occur on most processes. Speed of response can be more easily and realistically considered in the frequency domain since all thickness variations (particularly if they occur somewhat periodically) can be expressed as a combination of sinusoids by a Fourier series. Further, since a thickness measurement system is effectively a low-pass filter, its frequency response can be considered, with respect to anticipated process signal variations and process noise, to be from d-c to its cutoff or half power frequency. Half power frequency is defined as that frequency of sinusoidal process thickness variation where the power contained in the measurement system signal is one half the power contained in the actual process thickness variation. The system is said to pass all frequencies below its half power frequency and filter all frequencies above it. Since power varies as the square of voltage or current and the measurement system measures one of these parameters, cutoff frequency occurs when the signal amplitude is  $1/\sqrt{2}$  of its value at d-c. Further, for convenience of comparison, cutoff frequency is directly related to time constant, for a single order system, by the following expression:

$$f_{\infty} = \frac{1}{2\pi RC} \text{ (cps)} \quad (3)$$

where  $f_{\infty}$  is cutoff frequency and  $RC$  is the time constant of the single-order system in seconds.

Once the required cutoff frequency of the overall gage control system is determined in a rolling mill application, for example, the cutoff frequency of the thickness measurement system is matched to or may be slightly higher than it. Cutoff frequencies of one cps or less are required for most applications to adequately filter out process noise.

*Air gap*—The natural tendency in rolling mills and

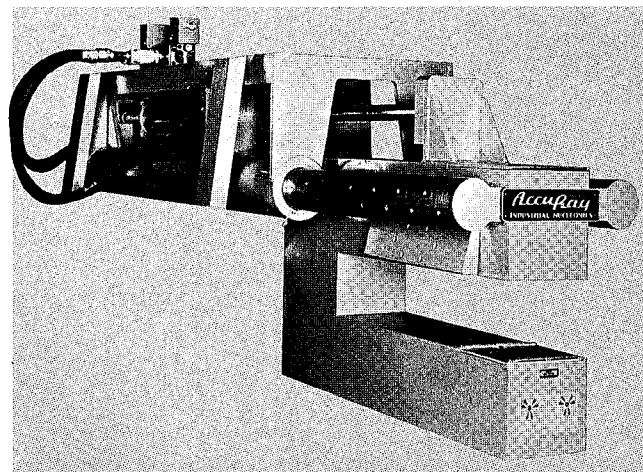


Figure 9 — The source-detector U-frame must be of rugged construction to eliminate deflection effects.

processing lines is to keep all line equipment as far away as possible from the moving strip to limit the probability of its being damaged in the event of a wreck or cobble. Accordingly, a noncontacting gage should not contact the strip, even if the strip is not where it is supposed to be. Wide air gaps between the source and detector units are desirable. There are practical limitations on air gaps so far as the gage itself is concerned, however, which must also be considered.

Lengthening the path which the radiation must travel in reaching the detector decreases the number of particles of radiation detected, hence, increases noise level. The inverse square law applies, approximately. Increasing air gap from 6 to 12 in., for example, reduces the number of radiation particles detected to approximately one fourth of their original value, hence, approximately doubles the noise level.

*Flutter and deflection*—Flutter, or vertical movement of the strip passline, is an important consideration. Both flutter and passline angle changes disturb the geometry, therefore, can have an effect on mass attenuation coefficient. Geometry changes also occur when the arms of the U-frame supporting the source and detector are deflected either vertically or horizontally. The measurement geometry can be (and is in the isotope gage) tuned to minimize flutter and deflection effects.

The best insurance against adverse deflection effects is rugged construction of the source-detector U-frame. Welded steel plate frames of rectangular cross section (Figure 9) are installed on most rolling mill applications. This unit is fabricated of  $1/2$ -in. steel plate and can be provided for either top or side mounting directly on the mill housing. The large air gap and deep throat requirements of rolling mill applications dictate this rugged design. Both horizontal and vertical deflection of this frame are negligible with regard to their effects on the measurement geometry.

*Standard geometries*—Because each gaging application is, in one way or another, different from every other, there are no standard radioisotope source-detector geometries. Nor are there general specifications which may be ascribed to the performance capabilities of a radioisotope gage for any specific application. Source-detector geometries are, in fact, custom designed for each application. Experience with some

300 radiisotope thickness measurement and control systems on all types of metal rolling mills and processing lines, however, has led to the development of several basic geometries. These are composed of standard components, which are tuned for any unusual requirements of specific metals applications. Some generalizations on performance capabilities of these pseudo-standard geometries can be made for the purpose of comparing the suitability of each for a specific application. Such characteristics of each of these geometries are in Table I.

The geometry-type designation applies to a family of geometries, each using the same radioisotope in a similar manner. A specific geometry is defined by its type designation, details of its internal design, its ionization chamber construction, the source design and strength, and the source-detector air gap. The points on the resolution curve where resolution is one per cent and  $\frac{1}{2}$  per cent of thickness per 0.1 per cent change in transmittance and the noise levels as a percentage of process thickness at each of these four points for several values of system frequency response are listed for each geometry.

The performance data apply specifically to the measurement of carbon steel. Since the densities and absorption characteristics of stainless, silicon, alloy steels, nickel, copper and brass are very similar to those of carbon steel, the data given are essentially applicable to these materials also. Aluminum and its normal alloys have substantially different densities and absorption characteristics from the heavier metals.

Since the density of aluminum is about  $\frac{1}{3}$  that of iron, the data presented apply approximately to measurement of aluminum thicknesses three times those shown for steel.

*Beta geometries*—The listing includes three beta geometries suitable for composition insensitive measurement of thin materials.

The TLK geometry is ideal for foil thicknesses in the range of 0.0001 to 0.005 in. It has been particularly popular on stainless steel and other high-alloy sendzimir mills where dynamic gage control accuracies of better than  $\pm 5\mu$  in. are being achieved. The TLK geometry uses the rather low-energy beta emitter; krypton-85, therefore, has a limited range.

For greater thicknesses the higher energy strontium-90 isotope is used in the TM geometries. TM geometries are available with both 25 and 100-mc source strengths; the latter being specified only when high response with low-noise levels is required. The TM measurement range overlaps the foil gages except for the area below 0.001 in. and extends upward well into tinplate thicknesses. TM is being used effectively on thicknesses up to 0.030 in.

*Monoenergetic gamma geometries*—The THAM family of geometries has been in production only since 1965. The greatest advantage is that it permits much higher operating signal levels than with previously available sources. This enables the measurement system to be operated at a very high speed of response with exceptionally low noise levels. Comparing the noise levels for the THA, 6-in. air gap geometry and the THAM, 6-in. air gap geometry at a measured thickness of 0.005 in., the latter has a noise level at the same speed of response of  $\frac{1}{4}$  that of THA. Since noise varies with the square root of signal level, this represents a ratio between the signal levels of the two geometries of 16 to 1. Likewise, THAM could be operated at a speed of response 16 times as fast as that of THA with the same noise level. Dynamic measurement accuracies of better

TABLE I  
Standard Geometries for Steel Application

Geometry type	Source	Half life, years	Type radiation	Strength, millicuries	Energy, mev	Range for steel, thousandths of an in.		Air gap, in.	Frequency response, d-c to cps	Source statistics as a percentage of thickness at 1 and $\frac{1}{2}$ per cent resolution			
						1 per cent resolution	$\frac{1}{2}$ per cent resolution			1 per cent low	$\frac{1}{2}$ per cent low	$\frac{1}{2}$ per cent high	1 per cent high
						TLK	Kr-85			10	Beta	1000	0.67 max.
TM	Sr-Y-90	28	Beta	25	2.28 max.	1 to 20	2 to 16	$1\frac{1}{2}$	0.3 0.6	1.5 2.2	0.8 1.1	0.3 0.5	0.4 0.6
TM	Sr-Y-90	28	Beta	100	2.28 max.	1 to 20	2 to 16	$1\frac{1}{2}$	0.3 0.6 1.6	0.8 1.1 1.7	0.4 0.6 0.9	0.2 0.2 0.4	0.2 0.3 0.5
THAM	Am-241	462	Gamma	1000	0.06 mono	5 to 150	12 to 120	6	0.3 0.6 1.6 3.5	0.4 0.5 0.8 1.2	0.2 0.3 0.5 0.7	0.1 0.1 0.1 0.2	0.1 0.1 0.1 0.2
THAM	Am-241	462	Gamma	1000	0.06 mono	5 to 150	12 to 120	12	0.3 0.6 1.6 3.5	0.6 0.8 1.3 1.9	0.3 0.4 0.6 0.9	0.1 0.1 0.2 0.3	0.1 0.2 0.3 0.4
THA	Sr-Y-90	28	Brem.	1500	2.28 max.	5 to 300	10 to 50	4	0.3 0.6	1.3 1.9	0.6 0.9	0.4 0.6	0.4 0.6
THA	Sr-Y-90	28	Brem.	1500	2.28 max.	5 to 300	10 to 50	6	0.3 0.6	1.6 2.3	0.7 1.0	0.5 0.7	0.5 0.7
TH	Sr-Y-90	28	Brem.	300	2.28 max.	10 to 600	40 to 250	6	0.3	2.3	1.0	0.6	0.8
TH	Sr-Y-90	28	Brem.	300	2.28 max.	10 to 600	40 to 250	12	0.3	3.4	1.4	0.9	1.2
TH	Sr-Y-90	28	Brem.	700	2.28 max.	10 to 600	40 to 250	6	0.3 0.6	1.5 2.2	0.7 0.9	0.4 0.5	0.5 0.7
TH	Sr-Y-90	28	Brem.	700	2.28 max.	10 to 600	40 to 250	12	0.3 0.6	2.3 3.2	1.0 1.4	0.6 0.8	0.8 1.1

than 0.5 per cent in the thickness range of 0.012 to 0.120 in. with a frequency response of d-c to 2.5 cps are being achieved with this geometry on a 2-stand cold rolled carbon steel temper mill.

**Bremsstrahlung geometries**—The strontium-90 isotope is used in the several Bremsstrahlung geometries listed. The shape of the absorption curve for any measured material for Bremsstrahlung is a function of the target material used. Hence, with the same basic isotope, the characteristics of both the THA and TH geometries can be achieved. THA is used only when high accuracy for thicknesses below about 0.040 in. and a good measurement of thicknesses above 0.150 in. are both required in the same application. THAM is specified when the latter condition does not exist and TH is the choice for predominantly heavy gage applications. The 300-mc TH geometry is suitable for most heavy gage applications since high speeds of response are not usually required in these cases because of the large mechanical system delays and relatively slow operating speeds. The 700-mc source is recommended for high-speed, heavy gage mills and when a 12-in. air gap is demanded by the application.

**Dual geometries**—For applications wherein the total thickness range to be measured is extremely wide and a single geometry is not capable of the required measurement accuracy throughout the entire range, a single source-detector frame housing two separate measurement geometries is often provided. Combinations of TLK and TM geometries in the same frame with a single measurement circuit have been provided for several wide-range stainless steel sendzimir mills. A dual THAM/TH geometry could be specified to cover a total thickness range of 0.005 to 0.300 in., for example, where very high response is required for the lighter gages. The dual-geometry application technique is a relatively new one and is unique to the radioisotope system in that it is direct thickness measurement system and requires that the source-detector unit house only the measurement geometry with the electronic measuring circuitry being remotely mounted.

### ELECTRONIC SYSTEM

The output signal from the source-detector unit is a very low-level d-c ionization current. The ionization current is a direct measure of transmitted radiation intensity ( $I$ , in the expression  $I/I_0 = e^{-\mu p b}$ ). An electronic system is required to convert this signal into a useful form. It must be related first to incident radiation intensity,  $I_0$ . The transmittance ratio  $I/I_0$  must then be related to units of process thickness (e.g., thousandths of an in. or mils) for any value of process thickness. Further the electronic system must provide the required output signals or presentations, which may be any or all of the following:

1. Direct reading measure of actual instantaneous thickness with a dynamic measurement span sufficient to accommodate the anticipated band of normal thickness variation.
2. Measure of the difference between actual instantaneous process thickness and some desired target or nominal thickness value. Such a deviation signal is required for AGC on rolling mills.
3. Continuous permanent record of gage variations

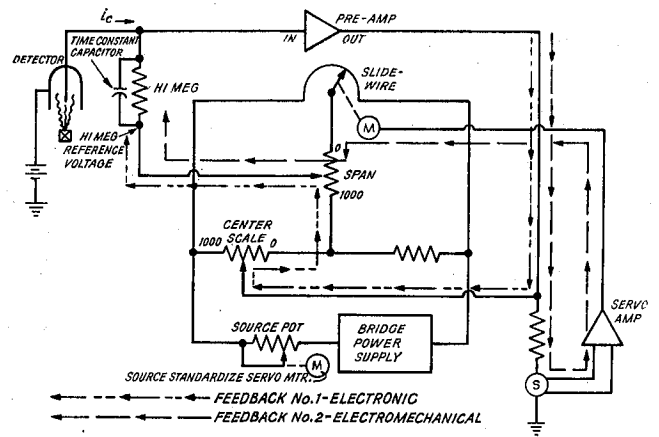


Figure 10 — Basic measuring circuit of the radioisotope thickness measuring system.

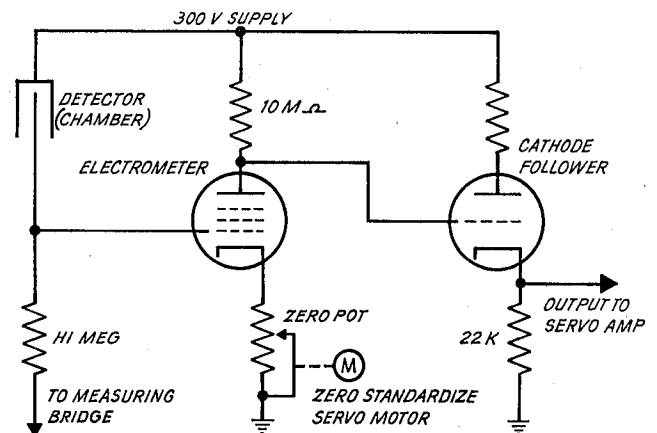
for use in process studies or as proof of quality to customers.

4. Classification or grouping of small units of production into two or more tolerance bands for the purposes of determining shippable vs. reject production, sorting total production into various quality classes, monitoring production quality as a quality control or production management function or providing accounting records.
5. Statistical information for use in determining the economic importance of the measurement and/or control system. Such data as average thickness and thickness variance per coil, order, turn and so forth are useful in this respect.

The basic measuring circuit usually converts the radiation signal to units of process thickness and satisfies the first three above listed possible readout requirements directly. At the same time it inherently preserves the basic reliability, consistency and accuracy capability of the radioisotope by permitting permanent calibration and ensuring both set point and span stability throughout the total process thickness range through automatic source and zero standardization.

Recently announced modifications to the basic measuring circuit (to include the solid-state power supplies, a unique digital setup scheme, and the introduction of a test meter circuit to aid in maintenance and troubleshooting) have even further increased its reliability and flexibility.

Figure 11 — Basic measuring circuit of the preamplifier.



Requirements 4 and 5 are satisfied by supplementary electronic equipments which have experienced similar recent development engineering effort. A new, digitally-set, electronic, signal classifier offers a versatile tool for inspection applications. Solid-state average and variance computers are also now available.

**Basic measuring circuit**—The basic measuring circuit is shown in simplified schematic form in Figure 10. Since the current output from the ionization chamber is in the order of  $\mu\mu\text{a}$ , a detector load resistor of extremely high value is required to develop a usable signal voltage. Resistances of 50 to 5000 megohms are commonly used and are called high meg resistors. To use the signal developed across the high meg resistor as an input to an indicating device requires that the input impedance of the indicator match the impedance of the high meg. This impedance matching is accomplished by the preamplifier. The preamplifier consists of an electrometer input stage and cathode follower output stage (Figure 11). Electronic feedback provides gain stability to the preamplifier and protects the electrometer tube from possible damage caused by excessive voltages being applied to the grid.

The output from the preamplifier produces an input to a servo system whose indicator shows the change in thickness which caused the original change in the electrometer input signal. As the indicator position is changed by the servo system, a reference voltage fed to the high meg is also changed. This electro-mechanical servo system feedback is the second part of the dual-feedback system. Since the servo system drives to a null, or zero point, it is also a null balance system which is not affected by changes in amplifier characteristics. In the standard system the measure servo indicator is the pen of a strip chart recorder which provides a permanent analog record of process thickness variations.

**Zero standardization**—The preamplifier is designed to give zero output for zero input. This condition is maintained by periodically standardizing the system. Zero standardization is accomplished by clamping the preamplifier input to ground and adjusting the electrometer cathode resistor (zero pot of Figure 11) until the preamplifier output is zero. This function is performed automatically any time the gage is not actually measuring, in order to continually compensate for temperature changes, component aging or other factors which might cause electronic drift. Standardization uses the same servo system as the measure indicator, the servo amplifier input and output being appropriately switched automatically.

**Measure bridge**—The measure bridge provides a bucking voltage at the input of the servo amplifier and is initially set to give zero voltage across its span leg when the slidewire is centered. The setting on the span potentiometer determines the difference between preamplifier output voltage and bucking voltage required for a given deflection of the slidewire arm from center. The span potentiometer is adjusted to give the desired measurement span or thickness range.

Both the center scale and the span potentiometers are 10-turn calibrated potentiometers in the standard analog system.

**Source standardization**—Maximum signal is obtained from the preamplifier when the gage is measuring only

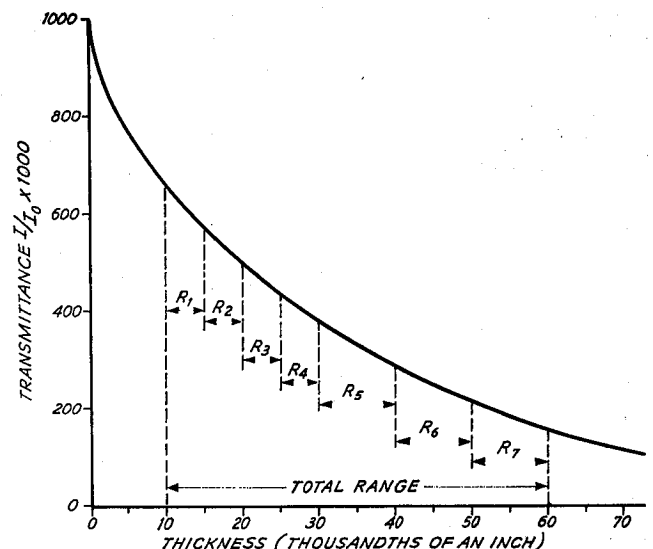
air. Maximum bucking voltage is, therefore, required at this time. Source standardization is a means for making the maximum bucking voltage exactly equal to the maximum signal voltage. Preamplifier output when measuring air is relatively constant, but will decrease as the source ages and as small quantities of foreign material build up in the gap. Source standardization thus compensates for source decay and an accumulation of foreign materials in the measuring gap.

Source standardization is accomplished with the gage measuring air and the center scale potentiometer set to 1000. In this condition, maximum signal and maximum bucking voltage are present and they must cancel with the indicator centered. The source pot is driven by the servo amplifier until the bucking voltage and preamplifier output exactly cancel. The value 1000 on the center scale potentiometer then represents maximum bucking voltage and each dial division equals 0.1 per cent of the total initial radiation intensity available.

**Calibration procedure**—Calibration of the measurement system is accomplished by consecutively inserting several samples of various thicknesses and the same composition in the air gap and adjusting the center scale potentiometer so that the servo indicator reads at center scale in each case. A plot of center scale dial reading (which equals transmittance  $I/I_0$  times 1000) vs. thickness is the absorption curve for that composition or alloy grade. A separate absorption curve is drawn for each significantly different composition.

**Permanent calibration**—Because of the stability of the energy spectrum of the isotope and the unique zero and source standardization functions of the measuring system, once such a calibration is performed it need never be repeated. The calibration procedure results in a tabulation of data and calibration curve of transmittance vs. thickness which is always repeatable. The isotope system is permanently calibrated for each composition or alloy grade and samples used for initial calibration may be destroyed.

**Figure 12** — Optimum readout resolution is provided by presenting only a part of the total thickness range on the readout indicator. The 0.010 to 0.060-in. range is divided into several consecutive ranges.



**Precalibration**—It is often necessary to run a new alloy grade which has never been run before on a particular facility. In such a case the thickness measurement system cannot be calibrated for the new alloy because no samples of it in the required thickness range are available. Yet a thickness measurement on the new product is desired. A means to predict gage response for the new material is required. The THAM, americium-241, geometry offers this capability. Since it is monoenergetic, its absorption curve for any given composition is a perfect exponential rather than an unpredictable approximation to an exponential as are absorption curves for continuous energy spectra sources. As long as the density and chemical analysis of the new material are known, its absorption characteristics for 0.060-mev gamma radiation can be accurately calculated using empirical values of mass attenuation coefficient.

Another useful capability to permit easy calibration of a THAM gage is available by virtue of its monoenergetic nature. That is, since its absorption curve plots as a straight line on semi-log paper, only a single sample is required for complete calibration of the gage for a given composition.

**Direct reading scales**—In order to provide optimum readout resolution, only a part of the total thickness range to be measured is presented on the readout indicator at one time. The total thickness range can thus be divided into several consecutive ranges (Figure 12). In the example shown, the total required thickness range of 0.010 to 0.060 in. is divided into seven smaller ranges. Factors which must be considered in determining the number of such ranges required for a given total process thickness range and the span or size of each are as follows:

1. Readout resolution desired. Since ranges R5, R6 and R7 of the example have twice the span of the other ranges, their readout resolution is half that of ranges R1 through R4. Greater measurement precision is usually required in the area of lighter thicknesses than is for heavier gages. Greater measurement spans are, therefore, usually used in the heavy gage area of the total range.

Figure 13 — Deviation signal circuit. If a deviation from target signal is required it is generated by the circuit illustrated.

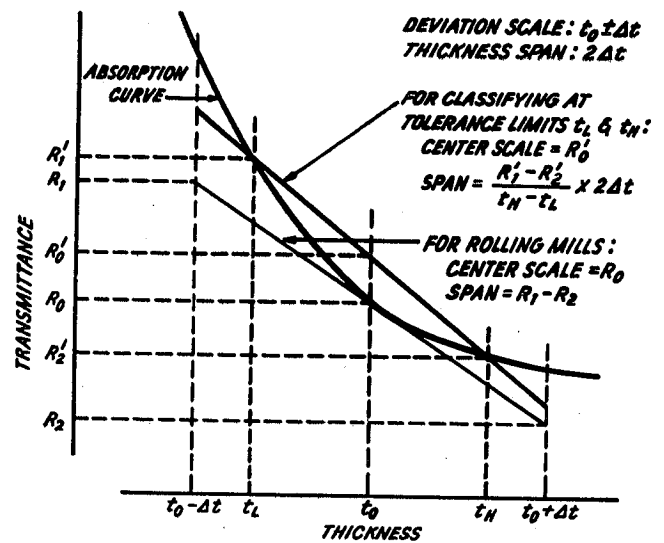
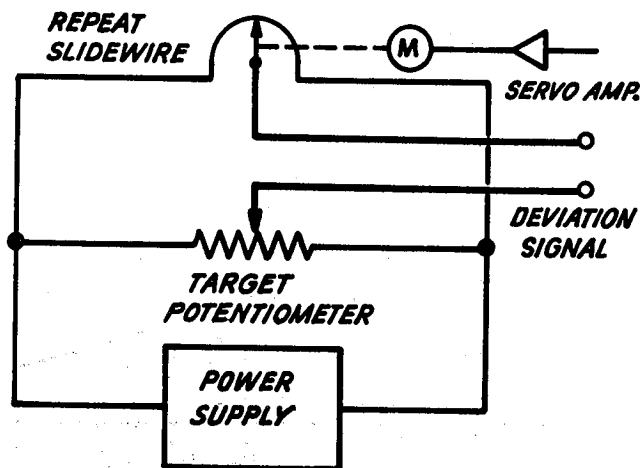


Figure 14 — Optional positioning of range.

2. Degree of absorption curve linearity. The absorption curve is an exponential function. The measuring circuit, however, is linear. The span of each range must be small enough so that the segment of the absorption curve it represents in each case has a sufficient degree of linearity so that measurement accuracy capability is acceptable.
3. Apparent noise levels. Although the actual total measurement noise is independent of measurement span, the width of the noise band presented on the output device is a factor in the readability of the readout device. For low-apparent noise levels, large spans are required.
4. Readability. For ease of operator interpretation, the readout must be such that each recorder chart line or meter division represents some easily recognizable unit of thickness. Thus, spans of 1, 2, 5, 10, 20, 50, etc., are desirable.

To set up the measurement system to measure thickness values within a range requires adjustment of the center scale potentiometer to the transmittance value corresponding to the midpoint of the range and setting the span potentiometer to correspond to the difference between the transmittance values at either end of the range. The system will measure any instantaneous thickness value falling within the range.

If a deviation from target signal is required, it is generated by a bridge circuit consisting of a target potentiometer and a repeat slidewire from the measuring circuit servo (Figure 13). The target potentiometer is ganged to a pointer on the system recorder. Both are positioned to the desired target thickness on the range by means of a knob mounted on the front of the recorder door. Where ultra-high system response is required in the deviation signal, a modified form of this circuit is specified whereby the delays attributed to the servo system are nullified.

**Deviation from target scales**— The measurement system can be set up to measure only deviations from a set point if direct reading measurement is not desired. In this case the transmittance value at target thickness is set on the center scale potentiometer and the span potentiometer is adjusted for the desired deviation

span about target. This scheme has advantage over the direct reading range setup scheme in that it permits greater measurement precision either at the target point or at two distinct points of deviation from target. Some degree of precision is usually lost over some areas of the scale for the direct reading scheme due to the absorption curve nonlinearities. Shown in Figure 14 is a portion of an absorption curve with its curvature greatly exaggerated for illustration and two different straight line approximations to the curve which might be set into the gage. Consider measurement errors due only to nonlinearities.

The straight line approximation to the absorption curve can be set any place with respect to the curve by adjusting the center scale potentiometer. For direct reading scales, the line is adjusted to its optimum position where equal errors exist at the center and both ends of the scale. These errors are usually no greater than  $\frac{1}{2}$  per cent of measured thickness anywhere on the scale.

For a rolling mill application where it is desirable to have the greatest precision of measurement near target thickness, the gage may be set up as indicated by the lower straight line. The measurement range is made tangent to the absorption curve at the point of target thickness. The center scale potentiometer is set to transmittance value  $R_0$  and the span of measurement in transmittance units is chosen as  $R_1 - R_2$ . With this arrangement, accuracies in the order of 0.2 to 0.1 per cent are achieved at target thicknesses, and for small deviations about target. For large deviations, however, the gage may be substantially in error. But, when actual thickness is much different from target, the strip is off gage anyway, so this is not objectionable.

For classifying applications it is desirable to have the highest measurement precision at the tolerance limits. In this case one is not really concerned about material which is exactly on specification but only whether its thickness is within certain plus and minus tolerance limits. When actual thickness is very close to these tolerance limits, it is of extreme economic importance whether the particular section of material is accepted or rejected. With the gage setup as indicated by the upper straight line of Figure 14, greatest measurement accuracy is achieved at and near the thickness tolerance limits,  $t_L$  and  $t_H$ , and correct on-gage or off-gage decisions are assured.

### SETUP SCHEMES

The simplest, most versatile and most accurate means of gage setup is by use of the two analog center scale and span potentiometers in the manner described above. This scheme requires no additional electronic components beyond those of the basic measuring circuit and is completely flexible.

Two-dial setup requires the operator to use a table and deal with relative numbers which may be foreign to him. Where this is objectionable, some users have elected to compromise the accuracy capability and flexibility of the two-dial approach in favor of one more easily interpreted by operators.

*Preset range switching*—Measurement ranges (Figure 12) may be programmed into the gage electronically.

Several small center scale and span potentiometers may be permanently set to the appropriate values and successively switched into the measuring circuit in place of the basic two-dial potentiometers to provide remote preset range switching. A combination of range switching and two-dial setup can also be provided for complete flexibility.

A recent readout innovation provides illumination of the preset range scales on the measuring system recorder to further simplify operator setup. To set up the gage, the operator merely rotates a range switch until the appropriate scale lights appear on the recorder, then adjusts the target indicator to the desired target thickness on that scale.

Preset range switching has a practical limitation in that as the total number of ranges required increases, system complexity increases. An additional pair of potentiometers and a set of switching contacts are required for each range. For multi-alloy applications this consideration has been significant. Further, this scheme does not easily lend itself to setup by an external programming device such as a digital process control computer.

*Direct digital setup*—Both of these limitations are overcome and additional readout functions are provided by a newly developed direct digital gage setup system. This system provides direct digital setup of target thickness and composition, by the operator or by an external programming device such as a digital process control computer, and complete annunciation and annotation on the strip chart recorder of selected target thickness.

To accommodate a digital language the system replaces the analog center scale and span potentiometers with digital potentiometers which are strings of binary coded precision resistors shunted by relay contacts. Digital computer-type logic circuits translate input thickness and grade information into gage language. The computer logic selects the correct values of center scale and span for the appropriate range and programs these values into the measuring circuit by energizing a combination of relays. It also produces a signal to drive a second pen of the system recorder to indicate the internally selected preset measurement range and the exact target thickness on the range. The system further provides a digital two-dial concept of setup for temporary use with uncalibrated grades. A full complement of digital repeat signals in any binary or decimal code can be supplied for annunciation, automatic control or data logging functions.

### APPLICATION TECHNIQUES

Overall system accuracy of measurement is affected by the following significant factors:

1. Geometry resolution capability.
2. Electronic measuring circuit resolution.
3. Resolution of readout.
4. Degree of absorption curve linearity.
5. Total noise level: source statistics and process noise.
6. Errors due to changes in geometry: flutter effects, deflection and passline angle.
7. Composition effects.
8. System speed of response.

9. Errors in referee.
10. Thickness uniformity of calibration samples.

The collective effect of all of these factors determines the degree of measurement accuracy. Few of these can be rigorously isolated and quantitatively measured. Verification of overall system accuracy, therefore, becomes a statistical process.

First, static accuracy is established by correlating the thickness measurement made by the gage to that made by the referee, usually a hand micrometer or bench-type supermicrometer. The measured area of the isotope gage is a circle about 2½ in. diameter. Several micrometer readings over this approximate area are averaged and the gage reading is correlated to this average for each sample. A good degree of correlation with this procedure defines accuracy except for errors due to items 5 (deflection), 6, 7 and 8.

To determine inaccuracies due to these effects, dynamic accuracy checks should be made. Again, it must be emphasized that correlation of accuracies is a statistical procedure. A reasonably large statistical sample must, therefore, be obtained to ensure reliable correlation. A single or even four or five consecutive micrometer or snap gage readings compared to gage recorder readout during dynamic conditions is not a sufficient dynamic accuracy determination. Several steel companies check dynamic gage accuracy by a technique of wrap checks. A coil is flagged at two spots some distance apart but near the middle of the coil while it is being wound. A machinist's scale measurement of the radial distance between flags divided by the number of wraps encompassed by them is a sound determination of average thickness which is compared with the average gage indication during the same period. Wrap checks are routinely performed several times per turn to accumulate statistical records of gage accuracy.

*Spectral density studies*—The measurement system recorder charts contain valuable information concerning the nature and degree of process thickness variations.

This information can be extracted with little effort through the aid of a digital computer program which has recently been developed. This program analyzes a set number of consecutive, equally spaced (in time) points on a section of recorder chart and produces a spectral density plot for that section of strip. A spectral density is a graph of process thickness variations in relative units vs. frequency such that the area under the spectral density curve is total process variance.

Such studies can aid in pinpointing major thickness variations and tracing their causes either within the process or in prior processes. They further can be used to determine the optimum frequency response required of a thickness measurement and control system in order to correct major gage variations and not be subjected to instabilities due to variations which should actually be regarded as process noise. Spectral density studies conducted on slow speed recoil lines can reveal even very high frequency thickness variations and help trace their causes.

*Data accumulation*—Several devices are available to assist in gathering statistical gage data for use in quality control and product quality studies. Devices already mentioned in this category are signal classifiers to indicate on-gage or off-gage strip or to classify product in several tolerance bands, a coil average computer and a process variance computer.

A special purpose gage data logger with punched paper tape output has recently been announced as a more refined quality control tool. This device, called a production data accumulator, receives manual inputs from operator control devices, thickness data from the measurement system and strip footage counts from a rotary contactor mounted to a billy roll. It provides five-band thickness classification and continuous visual indication of total footage of production falling within each band, outputs on demand by the operator accumulated footage in each band, and the manually input coil and order data on standard eight-channel punched paper tape.

## Discussion

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### PRESENTED BY

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measurement before the causes of thickness changes can be found, and before we know what should be demanded of a control system in order to produce quality strip.

The thickness measurement should be much better than the performance of the existing controller. For example, there is no thickness gage whose response is too fast. Short-term changes caused by an eccentric roll, for instance, may be considered as process noise to a controller whose response is limited. However, it is certainly desirable that the gage be fast enough to alert the operator that thickness changes are occurring so that he can replace that eccentric roll.

There is no thickness gage that is too accurate. Since yield is related to how close the thickness can be measured with confidence, the better the gage accuracy, the greater will be the savings that can be realized by the producer through tighter control within the ordered strip tolerance band. Also, the more accurate the sample measurement data is, the better the statis-

**George D. Cundra**: Through much effort and careful engineering design, the thickness gage has proved to be a valuable tool for the steel industry. However, the gage supplier should continue his efforts to attain a gage system that will give the true and complete picture of actual thickness as it is being rolled. The nature of the thickness variation must be determined first by

tical prediction will be in determining how representative a thickness measurement is when measuring only one portion of the strip. Such statistical data may show that an absolute measurement of the edge-center-edge portions of the strip, feeding into a roll bending controller, will be required to achieve a more constant thickness throughout the coil.

Every day valuable information is generated on strip chart recorders that is being wasted because it is not being further processed into the summarized form that supervision needs for production decisionmaking. Auxiliary gage readout devices that classify thickness variations and show process variance on a per coil or per shift basis will more fully utilize the information generated by a gaging system.

What new sources, like americium-241, will become available that will improve the basic thickness measurement to keep up with the tighter tolerance and higher rolling speed trends of the strip mill?

What progress has been made in replacing the critical electrometer tube with a more reliable component, possibly a solid-state device?

**James L. Griffith:** The ability of the gaging system to do more than merely operate a controller or turn lights on and off cannot be overemphasized. Its capabilities and utilization as a quality control and profit-producing tool indeed do need to be extended.

In answer to the questions regarding the anticipated development of new radiation sources and a replacement for the electrometer tube, one can only speculate on how rapidly such developments can be brought about. In those two specific cases, there are no immediate expectations of technological breakthrough but much research effort is being expended and will continue to be.

Progress in the discovery of new radioactive materials has been consistent but extremely difficult and slow. Americium-241 is a man-made isotope.

It is highly speculative to assume that nuclear scientists are on the threshold of another achievement of this magnitude which would be helpful to the steel industry in the near future. Other direct gamma radiation sources (cesium, cobalt and radium) are in use in industrial applications for very heavy materials. Their energy levels, however, are significantly higher than that of americium (59.6 kev). Hence, their mass absorption coefficients for most metals are so small that little of their radiation intensity would be absorbed by normal steel sheet or strip thicknesses. They may find suitability in the measurement of plate and slab thicknesses.

The electrometer tube is used as the first amplification stage of the low-level current from an ionization chamber in the measurement system discussed. Its extremely high input impedance (greater than that available with most solid-state devices) is required to isolate the measuring circuit from the primary sensing element. There are three tubes often used; 959, 1L4 and 5886. Each has some advantage over the other two. Nevertheless, since they are electron tubes, all are susceptible to mechanical damage and failure due to aging. The ionization chamber-electrometer tube combination is used because it is a much more reliable radiation detector than is the scintillation crystal-photomultiplier tube combination or the Geiger-Müller tube detectors, and because the electrometer

tube can be and is removed from the measurement head itself to prevent its being damaged by mill cobbles. Considerable research work is being done toward improving the reliability of radiation detectors in industrial environments. Some types of solid-state detectors are included in these studies.

**K. R. Canfor:** It would be useful to have an interstand measurement of gage on a hot mill. The compact size of an isotope gage would be ideal for the cramped area between stands. Do you propose to develop such a gage in the near future?

**James L. Griffith:** We certainly agree that the measurement of interstand thickness on a hot mill is required and is feasible for the compact radioisotope gage. It is our sincere hope that we will be able to devote the development effort required to satisfy this requirement in the near future. Presently available sources are suitable for the thicknesses involved. Temperature effects on the measurement geometry and component reliability must be evaluated for this development to proceed.

**John H. Rannells:** The importance of thickness is by no means overstressed in this article. Both the production of steel as a raw material and in its transformation to a finished product has made Interlake acutely aware of the absolutely necessity of maintaining minimum variation.

To provide this thickness accuracy and uniformity, both for customers' and our own internal requirements, Interlake has been relying on noncontact thickness gages since the middle 1950's. We have been, and are, installing thickness gages and automatic gage control systems on our major hot and cold rolling facilities.

As of 1966 we have in operation seven individual radioisotope gages on cold rolling mills and are in the process of replacing an early model with one of the newer improved versions.

For approximately five years I was responsible for the maintenance of these gages, and in two instances I also performed the field installation. An average measuring error for these systems involving four individual gages was 0.25 per cent compared against "super-miked" samples. Any system capable of these accuracies must be sophisticated and accordingly require highly skilled maintenance. Surprisingly we found ourselves (motor inspector, maintenance electricians—not instrument repairmen) capable of correcting all but a few of the difficulties that arose.

However, radioisotope gage measuring systems are not a "cure-all." Presently these gages are only found on cold mills, while hot mills with their inherent nonlinear temperature vs. apparent percentage thickness change curves are studiously avoided. Thus, while radioisotope gages are an excellent solution to cold steel measuring problems, they cannot yet be regarded as a panacea because of their absence in hot steel applications.

**James L. Griffith:** The reference to a nonlinear temperature effect in the measurement of hot steel is one of the geometry effects of concern. Whether this effect will be noticed with a radioisotope measurement system is unknown. We are measuring hot aluminum strip with a strontium-90 Bremsstrahlung geometry and are experiencing no adverse effects due to the temperature of the measured material. ▲

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