JAERI-M
85-180

RADIOGRAPHIC EXAMINATION TECHNIQUES FOR DETECTION OF INTERNAL DEFECTS

December 1985

Kiichi OOKA

日本原子力研究所
Japan Atomic Energy Research Institute

JAERI-Mレポートは，日本原子力研究所が不定期に公刊している研究報告書です。

入手の問合わせは，日本原子力研究所技術情報部情報資料課（〒319-11 茨城県那珂郡東海村）あて，お申しこしください。なお，このほかに財団法人原子力弘済会資料センター（〒319-11 茨城県那珂郡東海村日本原子力研究所内）で複写による実費頒布をおこなっております。

JAERI-M reports are issued irregularly.

Inquiries about availability of the reports should be addressed to Information Division Department of Technical Information, Japan Atomic Energy Research Institute, Tokaimura, Naka-gun, Ibaraki-ken 319-11, Japan.

編集兼発行　日本原子力研究所
印　　刷　日青工業株式会社

Radiographic examination techniques for detection of internal defects

Kiichi OOKA

Department of JMTR Project
Oarai Research Establishment, JAERI

(Received October 15, 1985)

This report included the following contents; radiographic contrast, radiographic conditions and image quality of radiograph, determination of exposure conditions, viewing conditions and image quality of radiograph, improvement of image quality of radiograph and conversion of penetrameter sensitivity.

Moreover, the contents from practical field such as characteric curves, method of preparing exposure chart of obtaining absorption coefficient and scattered radiation to direct radiation ratio had been shown in Appendices of the report.

Keywords: Radiographic Contrast, Image Quality, Exposure Conditions, Penetrameter Sensitivity, Characteristic Curves, Exposure Chart, Scattered X-Rays, Absorption Coefficient, Scattered Radiation to Direct, Radiation Ratio.

This report has been compiled as a lecture notes, which was presented to the 2nd Singapore training course for "Regional training of advanced non-destructive testing"

内部欠陥検出のための放射線透過試験技術

日本原子力研究所大洗研究所材料試験炉部
大岡紀一

（1985年10月15日受理）

本報告は，放射線透過試験により内部欠陥を検出するための関連因子として透過写真のコントラスト，撮影条件と透過写真の像質，露出条件の決定，観察条件と像質，像質改善方法及び透過度計の識別度の換算について述べたものである。

さらに，実用のための特性曲線，露出線図の作成方法，吸収係数及び散乱比の求め方についても付録として詳細に述べている。

本報告はIAEA／RCAのRI・放射線の工業利用に関する計画に基づき行われた第2回のシンガポールでの非破壊検査トレーニングコースにおいて講義した内容をとりまとめたものである。

Preface

This report has been compiled as a lecture notes, which was presented to the 2nd Singapore training course for "Regional training of advanced non-destructive testing" organized and financially supported by International Atomic Energy Agency / RCA and implemented by the Expert Advisory Group.

This report included the following contents; radiographic contrast, radiographic conditions and image quality of radiograph, determination of exposure conditions, viewing conditions and image quality of radiograph and conversion of penetrameter sensitivity.

Moreover, the contents from practical field such as characteristic curves, method of preparing exposure chart and of obtaining absorption coefficient and scattered radiation to direct radiation had been shown in Appendices of the report.

Whether a defect can be identified on a radiograph or not is determined by the relationship between the density difference shown by defect image, namely, the radiographic contrast corresponding to the defect and the minimum density difference that allows the defect to be identified, namely, the minimum perceptible density difference.

To discuss the perceptibility of a defect quantitatively, it is necessary to obtain the value of the minimum perceptible density difference which is related to the image size and radiographic density, brightness of film illuminator and observation conditions of film. This report may provide for the useful examination techniques in order to detect the internal defects.

Contents

Page

1. Radiographic Contrast 1
1.1 Film contrast γ 1
1.2 Absorption coefficient μp 1
1.3 Correction coefficient σ 2
1.4 Scattered radiation to direct radiation intensity ratio 2
2. Radiographic Conditions and Image Quality of Radiograph 5
2.1 Radiation quality and influence of scattered radiation 5
2.2 Influence of photographic density 7
2.3 Influence of geometrical conditions 8
2.4 Influence of combination of radiographic screen and X-ray film 12
3. Determination of Exposure Conditions 15
3.1 How to determine exposure conditions 15
4. Viewing Conditions and Image Quality of Radiograph 18
4.1 Apparent radiographic contrast 18
4.2 Influence of the brightness of film illuminator 18
4.3 Influence of room brightness 19
5. Improvement of Image Quality of Radiograph 21
5.1 Detection of defect 21
5.2 Minimum perceptible contrast 21
5.3 Method of improving the image quality of radiograph 22
5.4 Method of improving the image quality by enhancing the radiographic contrast 23
5.4.1 Improvement of image quality by reduction of scattered direct radiation intensity ratio 23
5.4.2 Improvement of image quality by selection of optimum X-ray quality 29
5.5 Methods of improving the image quality by lowering minimum perceptible contrast 31
5.5.1 Improvement of image quality by selection of proper radiographic screens 31
5.5.2 Enlarging radiography 32
6. Conversion of Penetrameter Sensitivity 34
6.1 Conversion of the sensitivity of penetrameters differing in material 34
6.2 Conversion of penetrameter sensitivity when the penetrameter profile differs 38

Page

Acknowledgements

References

Appendix A Characteristic Curves 42

Appendix B Method of preparing exposure chart when the amount of scattered X-rays is negligibly small 42

Appendix C Method of preparing exposure chart when there are scattered X-rays 45

Appendix D Method of obtaining absorption coefficient and scattered direct radiation intensity ratio 47

目　　次

1. 透過写真のコントラスト …… 1
1.1 フィルムコントラスト γ …… 1
1.2 吸収係数 μp …… 1
1.3 補正係数 σ …… 2
1.4 散乱比 n …… 2
2. 撮影条件と透過写真の像質 …… 5
2.1 線質と散乱線の影響 …… 5
2.2 写真濃度の影響 …… 7
2.3 幾何学的条件の影響 …… 8
2.4 X線フィルムと増感紙の組合せによる影響 …… 12
3. 露出条件の決定 …… 15
3.1 露出条件の求め方 …… 15
4. 透過写真の観察条件と像質 …… 18
4.1 見掛けのコントラスト …… 18
4.2 フィルム観察器の明るさの影響 …… 18
4.3 室内の明るさの影響 …… 19
5. 透過写真の像質の改善 …… 21
5.1 欠陥の検出 …… 21
5.2 識別限界コントラスト …… 21
5.3 像質改善の方法 …… 22
5.4 透過写真のコントラストを増加させて像質を改善する方法 …… 23
5.4.1 散乱線を減少させることによる像質改善の方法 …… 23
5.4.2 最適X線の線質を選択することによる像質改善の方法 …… 29
5.5 識別限界コントラストを低下させて像質を改善する方法 …… 31
5.5.1 増感紙の選択することによる像質改善の方法 …… 31
5.5.2 透過写真の拡大 …… 32
6. 透過度計識別度の換算 …… 34
6.1 材質が異なる場合の換算 …… 34
6.2 透過度計の種類が異なる場合の換算 …… 38

謝　辞

参考文献

付録A 特性曲線 …… 42
付録B 散乱線を含まない場合の露出線図の作成方法 …… 42
付録C 散乱線を含む場合の露出線図の作成方法 …… 45
付録D 吸収係数と散乱比の求め方 …… 47

1. Radiographic Contrast

Radiographic contrast ΔD corresponding to a wire of diameter d of a penetrameter placed on a plate whose thickness is T can be obtained from the following formula.

$$\Delta D = -0.434\gamma\mu\rho\sigma d/(1+n) \quad \text{.........} \quad (1.1)$$

where

γ : Gradient of the tangential line at density D of X-ray film characteristic curve

$\mu\rho$: X-ray quality when the sensitivity coefficient of the X-ray film is considered

σ : Correction coefficients by focal spot size and geometrical conditions of irradiation

n : Quotient obtained by the dose rate of the scattered radiation that reaches the X-ray film uniformly multiplied by its sensitivity coefficient divided by the dose rate of the penetrated radiation multiplied by its sensitivity coefficient

Therefore, once basic data on each factor is obtained, ΔD corresponding to the radiographic conditions can be obtained by calculation.

1.1 Film contrast γ

Fig. 1.1 shows a characteristic curve of the no-screen type X-ray film as an example. Assuming that γ is the gradient of a straight line that connects two points corresponding to $D + 0.1$ and $D - 0.1$, the relationship between density D and γ is as shown in Fig. 1.2.

When the screen type X-ray film is combined with a fluorescent intensifying screen, the characteristic curve will be as shown in Fig. 1.3, and the relationship between the density and γ will be as shown in Fig. 1.4.

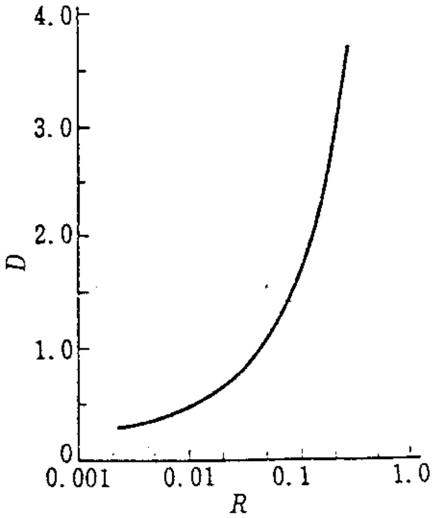


Fig. 1.1 Dose characteristic curve of no-screen type X-ray film (film SAKURA R, no intensifying screen, Konidol X 20°C, 5-min tank)

1.2 Absorption coefficient $\mu\rho$

Absorption coefficients μ decrease with increase in the thickness of an absorber to be radiographed even when the tube voltage of an X-ray unit is constant, but the absorption coefficient can be regarded as nearly constant when the thickness becomes greater than a certain value.

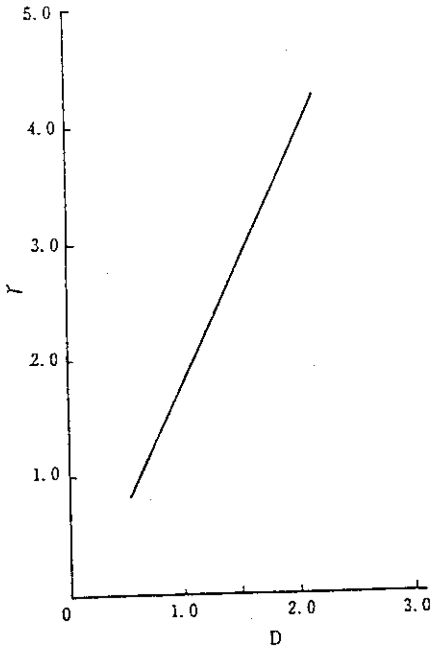


Fig. 1.2 Relationship between density and γ (obtained from Fig. 1.1)

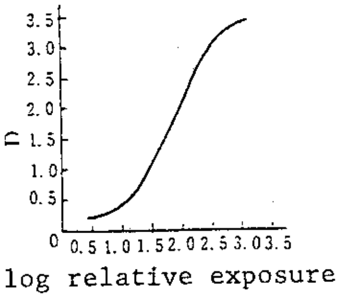


Fig. 1.3 Characteristic curve of fluorescent intensifying screen type X-ray film (#400, KZ-S, Rendol, 20°C, 5-min pan)

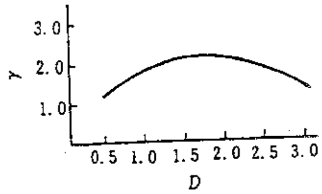


Fig. 1.4 Relationship between density and γ (obtained from Fig. 1.3)

When the dose rate is 1 mR/min mA at a distance of 1 m -- which is a practical exposure condition -- after X-rays generated by a tube voltage of the X-ray unit have penetrated a steel plate of proper thickness, the quality of the penetrating radiation is expressed by μ (Fe), and the relationship between the tube voltage and μ (Fe) is shown in Fig. 1.5 as an example.

When μ is constant, μp can be regarded as being equal to μ even if the absorber thickness increases, with the result that μp is eventually the same as μ (Fe).

1.3 Correction coefficient σ

When radiography is made with the arrangement shown in Fig. 1.6, the apparent focal spot size d' at the position of a wire of a penetrameter can be obtained from the following formula.

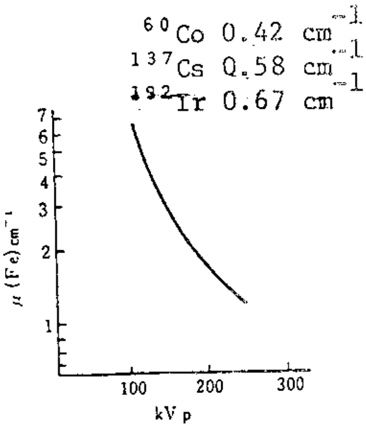
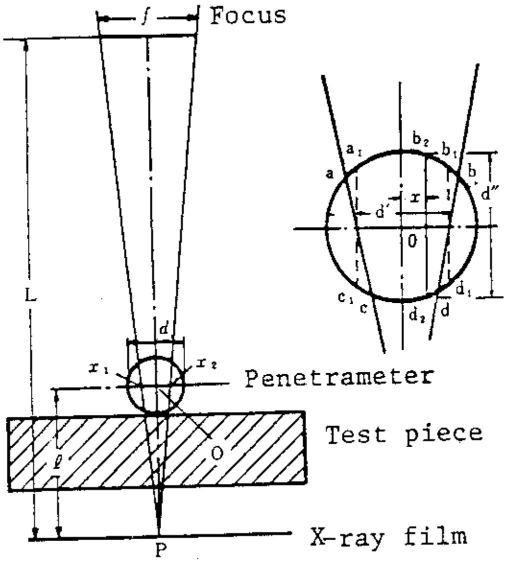


Fig. 1.5 Relationship between tube voltage and μ (Fe) (X-ray unit MACROTANK H)

$$d' = f\ell/L \quad \text{.........................} \quad (1.2)$$

where, ℓ is the distance from the center of the wire to the film, and L is the focus-film distance.
Fig. 1.7 shows the relationship between d'/d and σ.



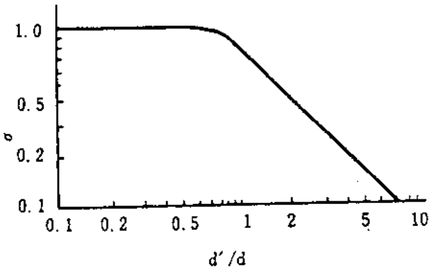


Fig. 1.7 Relationship between d'/d and σ (wire)

Fig. 1.6 Absorption of X-rays by wire of penetrameter
f: Focal spot size
L: Focus-film distance (F.F.D)
d: Wire diameter
ℓ: Penetrameter-film distance

1.4 Scattered radiation to direct radiation intensity ratio

Scattered direct radiation intensity ratio n can be obtained from the following formula.

$$n = (k_s I_s)/(k_a I_a) \quad \text{................} \quad (1.3)$$

where,

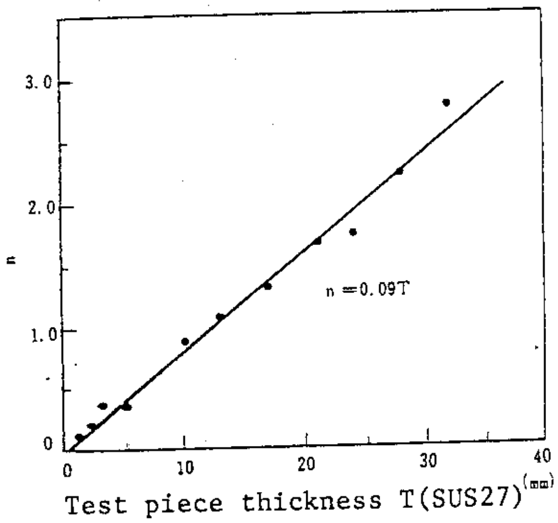
k_s: Sensitivity coefficient of X-ray film as against quality of scattered radiation

I_s: Scattered dose rate

k_a: Sensitivity coefficient of X-ray film as against quality of penetrating radiation

I_a: Penetrating dose rate

Fig. 1.8 shows the scattered direct radiation intensity ratio of SUS304 stainless steel measured by using X-ray film.



WELTES 260D
RR+Pb 0.03
F·F·D·60 cm
Diaphragm Lead 75 mm dia.
Radiation field 350 mm dia.
Cassette and sample are
in intimate contact.

Fig. 1.8 Scattered direct radiation intensity ratio when sensitivity coefficient of X-ray film is considered

2. Radiographic Conditions and Image Quality of Radiograph

2.1 Radiation quality and influence of scattered radiation

In formula (1.1) which represents radiographic contrast ΔD, μ represents the radiation quality. It shows that the greater μ and the smaller n, the greater the radiographic contrast. In radiography, therefore, the image quality is affected by how the radiation quality is selected and how the scattered radiation is eliminated.

(1) Quality of X-rays and dose rate

In practical applications of normal radiographic examination, the tube voltage and tube current are used as a guide to express the radiation quality and dose rate, where the difference in the radiation quality is expressed by the difference in the tube voltage and the difference in the dose rate is expressed by the difference in the tube current. However, the difference in the tube voltage represents not only the radiation quality but also the difference in the dose rate. Comparison of the dose rates per 1 mA of tube current at different tube voltages at a distance of 1 m using 11 types of X-rays units from A through K shows that the dose rate differs widely at the same tube voltage and tube current if the X-ray unit differs as shown in Fig. 2.1. It has also been revealed by measuring the half value layer (HVL) that the radiation quality also differs from one X-ray unit to another. To select a right type of X-ray unit, rough judgement can be made by preparing a correct exposure chart and checking the penetrameter sensitivity.

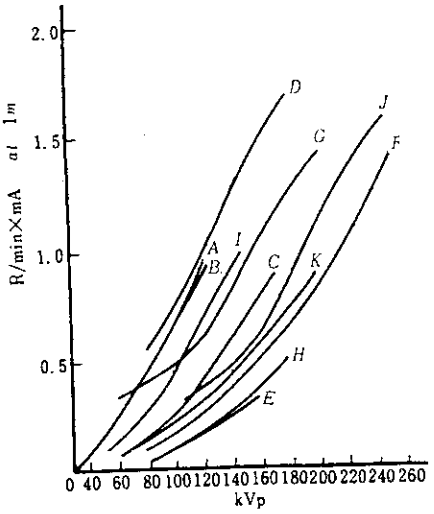


Fig. 2.1 Comparison between various tube voltages and radiation dose rates

(2) Change in radiographic contrast by radiation quality

Radiographic contrast ΔD for a small defect whose thickness is ΔT is as shown in formula (1.1). To detect very small defects whose thickness is ΔT, it is necessary to increase ΔD. To do so, it is necessary to increase γ, μ, and σ and decrease n, as shown in formula (1.1). Of these factors, μ and n change greatly depending on the type of the source used for radiographic inspection, that is, the radiation quality.

Regarding X-rays, it is obvious that the absorption coefficient of X-rays is greater than those of ^{60}Co, ^{137}Cs and ^{192}Ir sources as shown in Fig. 1.5. when absorption coefficient μ (Fe) is considered as the radiation quality corresponding to the tube voltage. Fig. 2.2 shows the relationship between the effective energy and the scattered direct radiation intensity ratio with respect to a steel plate of constant thickness. If there is no change in the type of the X-ray film, density of the radiograph, and photographic arrangement, the radiographic contrast of a very small defect whose thickness is ΔT is proportional to μ/(1 + n), and this can be calculated. Table 2.1 shows the result of μ/(1 + n) calculated for an X-ray unit and gamma ray units (^{192}Ir and ^{60}Co) Table 2.1 shows that μ/(1 + n), that is, radiographic contrast ΔD is greater with the X-ray unit (tube voltage 175 kVp) and decreases in order of ^{192}Ir and ^{60}Co sources. The solid lines in Fig. 2.3 represent the absorption curves for a soft X-ray unit. The broken lines represent the absorption curves for portable X-ray units which are commonly used for steels. To obtain the same dose rate of penetration for an aluminum plate of the same thickness, it is necessary for the X-ray unit to increase the tube voltage of Normal X ray unit for steel inspection, thus resulting in low radiographic contrast.

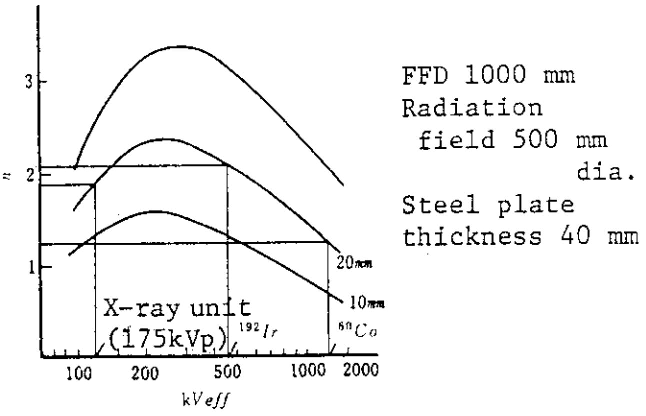


Fig. 2.2 Relationship between effective energy and scattered direct radiation intensity ratio

Table 2.1 Relationship between Type of source and μ/(1 + n) (Test piece 20-mm-thick steel plate)

Source	μ(Fe) (cm^{-1})	kVeff	n	$\frac{\mu}{1+n}$(cm^{-1}
X-ray unit (175 kVp)	2.2	120	1.9	0.76
^{192}Ir	0.67	450	2.1	0.22
^{60}Co	0.42	1,250	1.2	0.19

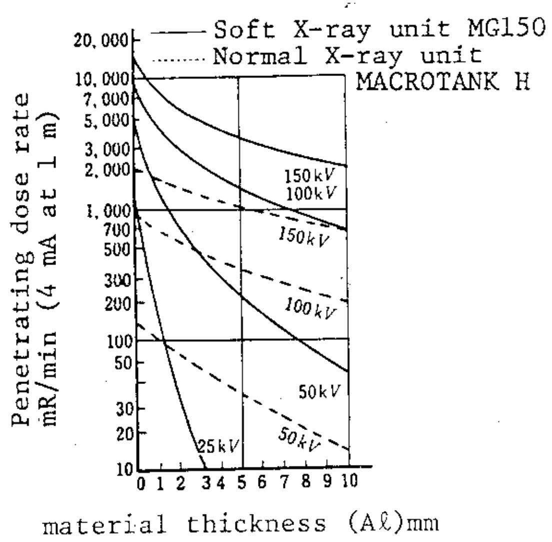


Fig. 2.3 Comparison of absorption curves by two types of X-ray units

(3) Change in radiographic contrast due to scattered radiation

Factors that affect the scattered direct radiation intensity ratio include the profile of the test object, besides the radiation quality. For example, when the reinforcement of a weld is high, X-rays that penetrate the base metal are much more intense than the X-rays that penetrate the weld and the scattered radiation emitted by X-rays that irradiate the base metal are much more intense than those emitted by X-rays that irradiate the weld, so that the scattered radiation from the base metal adjacent to the weld join the X-rays that have penetrated the weld and the scattered direct radiation intensity ratio at the center of the weld increases as shown in Fig. 2.4, resulting in low quality of the radiographic image.

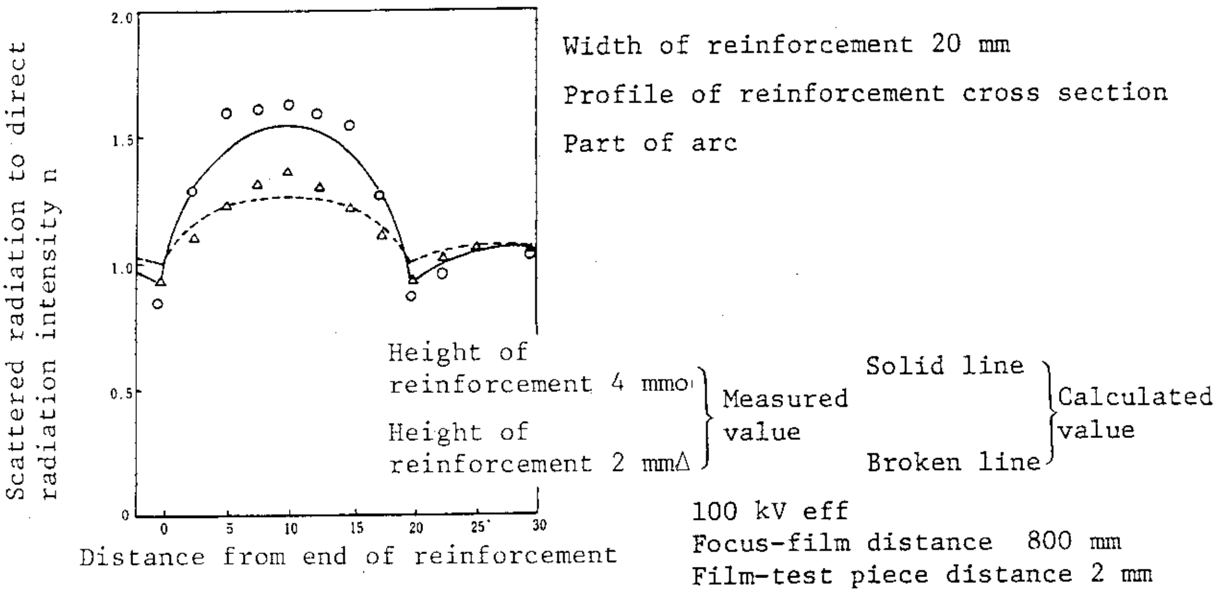


Fig. 2.4 Scattered radiation to direct radiation intensity ratio at different positions of weld

100 kV eff
Focus-film distance 800 mm
Film-test piece distance 2 mm
Field of radiation: 200 mm dia.
Thickness of test piece: 12 mm
Test piece: Steel

If X-rays are generated with the radiation port fully opened with no diaphragm and no mask, the scattered radiation is emitted from portions other than the necessary area of the test piece, resulting in an unsharp image.

2.2 Influence of photographic density

Radiographic contrast ΔD when the density of a radiograph has changed is proportional only to film contrast γ.
As shown in Fig. 1.2, with no-screen X-ray film (low sensitivity, ultra-fine grain film), γ increases almost linearly with increase in density. This means that ΔD increases with increase in density.

The relationship between the density and minimum perceptible contrast ΔDmin of the wire image is as shown in Fig. 2.5. Here, as long as ΔD corresponding to wire diameter d is above ΔDmin corresponding to wire diameter d, a wire with a diameter of d is perceptible. That is, in the low density range where γ is small, radiographic contrast ΔD is smaller than ΔDmin. Thus the wire is not perceptible. On the other hand, in the high density range where increase in ΔDmin due to density is greater than increase in ΔD, the wire is not perceptible.
It is normal that the reinforcement height of a weld is not uniform and the density of the radiograph corresponding to the base metal differs from that corresponding to the weld.

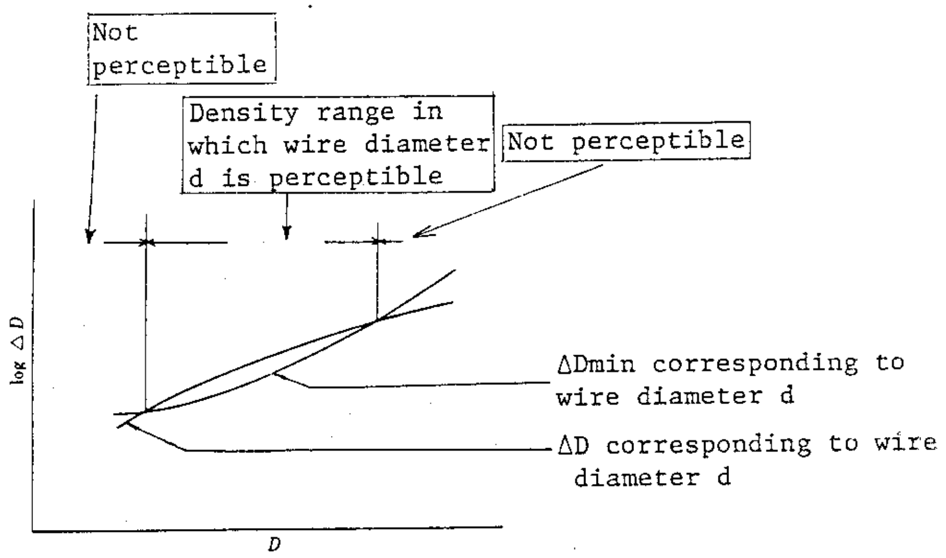


Fig. 2.5 Relationship between density, ΔD and ΔDmin

2.3 Influence of geometrical conditions

Since various factors such as exposure time, photographic density, influence on the penetrameter sensitivity are related to each other in radiography, the geometrical arrangement of radiography cannot be determined in general term. Geometrical facctors to be considered include the following.

(1) Dimensions of focus and source

In actual radiography with X-rays, the effective focus size differs depending on the direction of the beam even in the same radiation field, as can be seen from Fig. 2.6, making it necessary to identify the size of the effective focus size in each direction of the beams when rigorous inspection is required.
Regarding the size of the gamma ray source, the dimensions are known from the source manufacturer and its indication is used as it is.

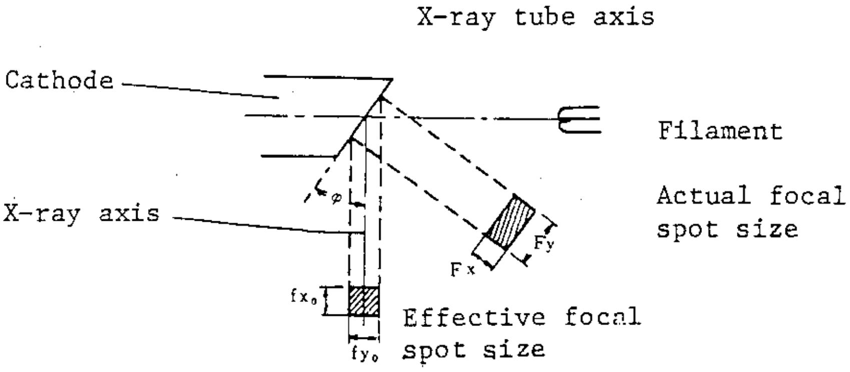
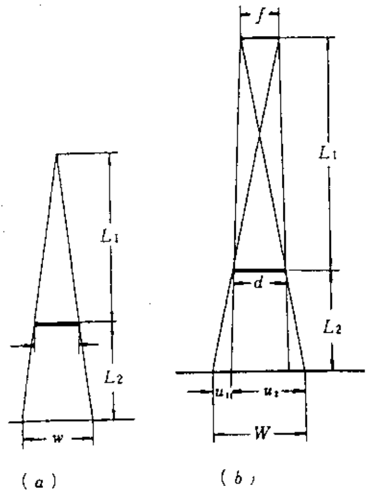


Fig. 2.6 Focal spot size of X-ray tube

(2) Radiographic unsharpness and enlarged image due to focal spot size and geometrical arrangement

One of the influences by geometrical conditions is the radiographic unsharpness due to the focal spot size of the X-ray unit or the size of the gamma ray source.
Given that the focal spot size is f, the distance between the focus and defect is L_1, the distance between the defect and X-ray film is L , and the size of the defect is d, the relationship between the radiographic image and geometrical arrangement is as shown in Fig. 2.7.



(a)

Enlargement of the image when the focal spot size can be ignored against the defect size

(b)

Enlargement of the image when the focal spot size is taken into consideration

Fig. 2.7 Influence of geometrical arrangement on radiographic image

In (a), in which the focus size is very small and is assumed to be a point, there is no penumbra of the image.
In (b), in which the focus has a size of f, a penumbra is produced on the outer periphery of the image, creating geometrical unsharpness of the image.
The size of this unsharpness varies with focal spot size f and the distances between focus, defect and film. Given the size of the unsharpness is u_1, it can be obtained from the following formula.

$$u_1 = f \frac{L_2}{L_1} \qquad (2.1)$$

As can be seen from Fig. 2.7, the size of defect image w is magnified more than the size of defect d.
Fig. 2.7(a) is a case in which f is regarded as a point. Given the magnifying factor at that time is m_0, it can be obtained from the following formula.

$$m_0 = \frac{w}{d} \fallingdotseq \frac{L_1 + L_2}{L_1} \qquad (2.2)$$

When the focal spot size is f as in Fig. 2.7 (b), defect image W is $u_1 + u_2$. Here, u_2 can be obtained from the following formula.

$$u_2 = d \times \frac{L_1 \times L_2}{L_1} \qquad (2.3)$$

Therefore,

$$W = (f \times \frac{L_2}{L_1}) + (d \times \frac{L_1 + L_2}{L_1})$$

Here, given the magnifying factor at this time is mf, the following formula derive.

$$m_f = \frac{W}{d} = \frac{f}{d} \cdot \frac{L_2}{L_1} + \frac{L_1 + L_2}{L_1}$$

$$m_f = m_0 (\frac{f}{d} + 1) - \frac{f}{d} \qquad (2.4)$$

However, the magnifying factor in this case involves the geometrical unsharpness of the image, and the greater the magnifying factor of the image m_f, the less perceptible the image.
Fig. 2.8 shows the magnifying factor m_f with respect to different values of f/d, using magnifying factor m_0 as a parameter when the focal spot size is such a small point as can be ignored.
Therefore, the smaller the size of defect d, the more the image tends to be magnified even with the same geometrical arrangement.

(3) Focal spot size and radiographic contrast

As the focal spot size f increases as against the defect size d, the image magnifying factor m_f tends to increase, but at the same time radiographic contrast of the defect is affected.

Generally, the minimum perceptible contrast decreases with increase in the image width, and the image becomes more easily perceptible. However, if the image is magnified when the focal spot size is large in comparison with the defect size, the value of d' in Fig. 1.6 increases, resulting in large value of d'/d, so that the correction factor σ tends to decreases abruptly, as is evident from Fig. 1.7, while radiographic contrast ΔD decreases and, consequently, the perceptibility decreases. Therefore, the geometrical requirement is such that the correction factor σ becomes nearly equal to 1.

(4) Influences of focal spot size in the exposure area and magnifying factor

Because of the X-ray tube design, the focal spot size and X-ray intensity distribution of an industrial X-ray unit within a radiation field are not uniform. The focal spot size on the anode side and that on the cathode side differ in the axial direction of the X-ray tube, as shown in Fig. 2.9. Assuming that radiography is made at a distance of 60 cm from the focus, with the weld line arranged in the axial direction of the X-ray tube, the magnifying factor on the radiograph differs for the same size of defect because of the difference between the focus size on the anode side

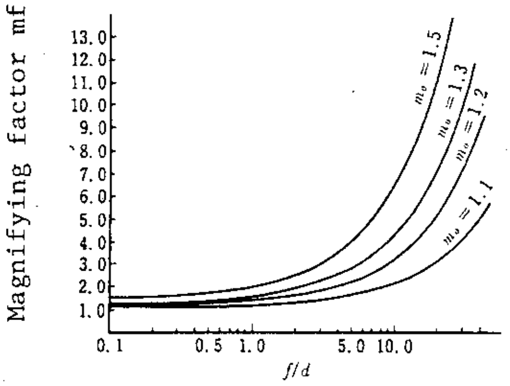


Fig. 2.8 Magnifying factor Mf when focal spot size is taken into consideration

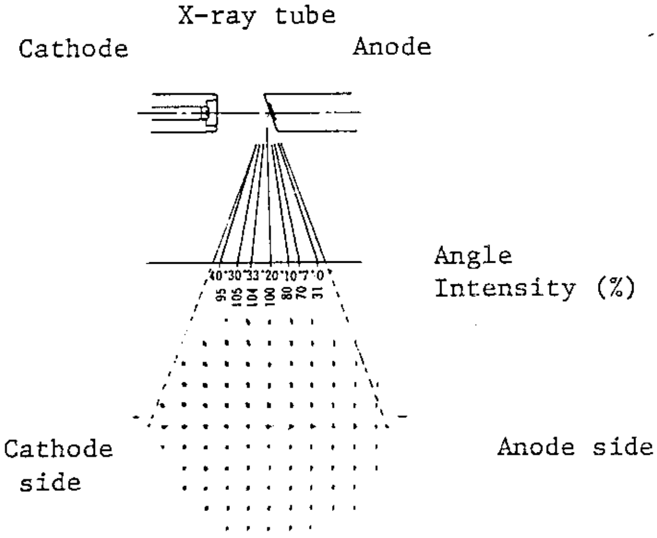


Fig. 2.9 An example of intensity distribution and change in focal spot size and in focus shape in the radiation field

and that on the cathode side. For example, if the ratio of the focal spot size between the anode side and the cathode side is 1 : 4, the magnifying factor differs 20% to 40% between the anode side and the cathode side. Furthermore, the X-ray intensity distribution in the radiation field being not uniform, the density of the radiograph taken is ununiform and the required perceptibility may not be obtained on the radiograph.

To take a radiograph with a uniform magnifying factor and within a uniform intensity distribution, it is recommended to use only the center portion of X-rays and to take a radiograph in the direction that intersects the X-ray tube axis at right angles.

2.4 Influence of combination of radiographic screen and X-ray film

If there is no change in the thickness of a test piece, tube voltage and radiographic arrangement, μp, σ and n in formula (1.1) are constant irrespective of the combination of the X-ray film and intensifying screen. Therefore, radiographic contrast ΔD when the combination of the X-ray film and intensifying screen has changed is proportional only to film contrast γ.

Fig. 2.10 shows the relationship between the density and γ for combinations of different types of X-ray films and intensifying screens. With the no-screen type X-ray film (#50, #80, and #100) used in combination with a lead foil or metal fluorescent intensifying screen, γ increases linearly with increase in density. The value of γ of the screen type X-ray film (#400) used in combination with a fluorescent intensifying screen or metal fluorescent intensifying screen increases with increase in density in the low density range, and it becomes maximum in the neighborhood of 1.5 to 2.0 density but decreases thereafter.

To detect very small defects, it is necessary to increase radiographic contrast ΔD for very small defects. To do so, combination of an X-ray film of large γ at the same density and intensifying screen should be selected.

Fig. 2.11 shows the relationship between the width of the wire image and minimum perceptible contrast ΔDmin for different combinations of X-ray films and intensifying screens. ΔDmin at the same width is maximum when the screen type X-ray film (#400 + KZ-SF) is combined with a fluorescent intensifying screen, and decreases with improvement in

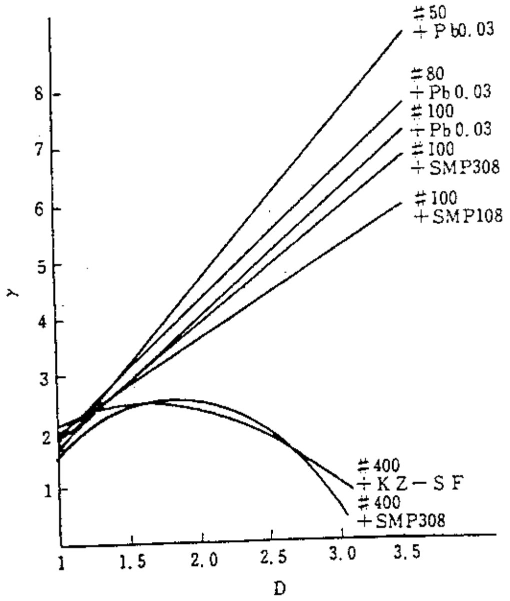


Fig. 2.10 Relationship between density and film contrast for different combinations of X-ray films and intensifying screens

the graininess of the no-screen type X-ray film combined with a lead intensifying screen.

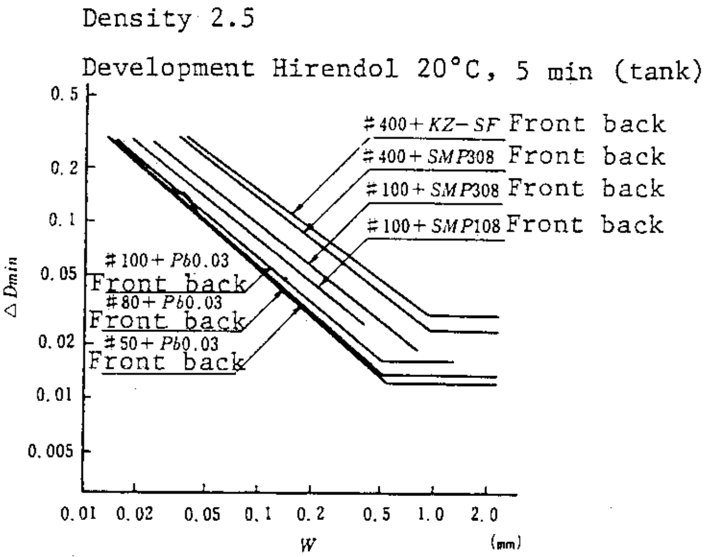


Fig. 2.11 Relationship between wire image width and ΔDmin for different combinations of X-ray films and intensifying screens

Table 2.2 shows a comparison of the number of cracks that can be detected when the combination of the X-ray film and intensifying screen is changed. To make the exposure time equal, it is necessary to increase the tube voltage with ultra-fine grain X-ray films (#50), and the difference in the number of cracks that can be detected is obvious, particularly in contrast to the combination of #400 film and KZ - SF. The better the graininess is, the higher the perceptibility is. It is also to be noted that there is a great difference in the number of cracks that can be detected though there is not much difference in the penetrameter sensitivity. Therefore, in selecting a radiographic screen it is necessary to select an X-ray film and intensifying screen suited to the purpose.

Table 2.2 Number of perceptible cracks depending on the combination of X-ray film and intensifying screen

Film	Intensifying screen	Tube voltage	Photographic density		Radiographic contrast ΔD - A - B	Penetrameter sensitivity			Detectability of cracks			
			Base metal (maximum) A	Contrast meter 1 mm B		No. of cracks	ϕ mm	%	Clear	Normal	Not clear	Impossible
Fuji # 50	Lead foil	220 kVp	2.04	1.90	0.14	4	0.20	1.1	14	7	5	0
Fuji # 80	Front back both 0.03 mm	212 "	2.08	1.92	0.16	4	0.20	1.1	12	6	5	3
Fuji #100		182 "	2.03	1.86	0.17	4	0.20	1.1	9	8	6	3
Fuji #100	SMP 108	158 "	1.96	1.70	0.26	4	0.20	1.1	7	10	4	5
Fuji #100	SMP 308	150 "	1.96	1.72	0.24	3	0.25	1.4	6	10	3	7
Fuji #150	Lead foil	160 "	2.04	1.86	0.18	3	0.25	1.4	7	7	5	7
Fuji #200	Front back both 0.03 mm	138 "	1.95	1.81	0.14	3	0.25	1.4	4	3	8	11
Fuji #400	SMP 308	112 "	1.48	1.28	0.20	3	0.25	1.4	4	8	6	8
Fuji #400	KZ-SF	107 "	1.76	1.51	0.25	3	0.25	1.4	4	3	7	12

3. Determination of exposure conditions

3.1 How to determine exposure conditions

The exposure conditions can be determined conveniently by using an exposure chart.
The following paragraphs concern the method of determining the exposure conditions using an exposure chart and method of correcting the radiographic density.

(1) Method of determining the exposure conditions (using exposure chart)

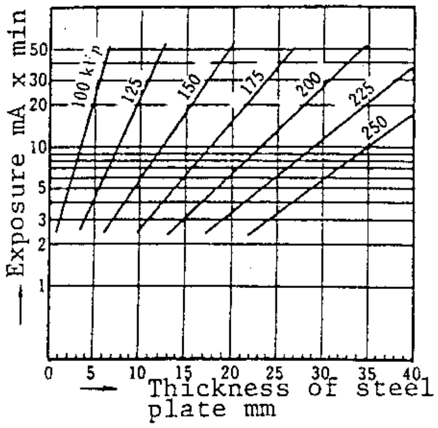
Let us assume that a 15.0 mm thick steel plate is radiographed. Given that the focus-film distance is 60 cm when X-ray film #100 and intensifying screen 0.03 F & B are used, the following exposure conditions can be obtained from the expousure chart in Fig. 3.1:
① 3[mAxmin] at 200 kVp, ② 6[mAxmin] at 175 kVp, and
③ 18[mAxmin] at 150 kVp
This means that the radiographic density of the 15.0 mm thick steel plate is 1.50 in any case if radiography is carried out at the above-mentioned tube voltage and tube current. Since the tube current (mA) is normally 4 to 5 mA, the exposure conditions when the tube voltage is 175 kVp is 1.5 min, and 4.5 min when it is 150 kVp if the tube current is 4 mA.
If radiography to be conducted at 150 kVp and 4.5 min takes too long a time, the exposure time can be reduced by making the focus-film distance shorter than 60 cm. In that case, the exposure factor is utilized. For example, when the focus-film distance is 40 cm, the following relation holds.

$$\frac{18[\mathrm{mA\cdot min}]}{60^2[\mathrm{cm}]^2} = \frac{x[\mathrm{mA\cdot min}]}{40^2[\mathrm{cm}^2]}$$

$$\therefore x = 18\mathrm{mA\cdot min} \times 0.44$$

$$x = 7.92 \fallingdotseq 8\mathrm{mA\cdot min}$$

And the exposure time can be 2 min at a tube current of 4 mA.



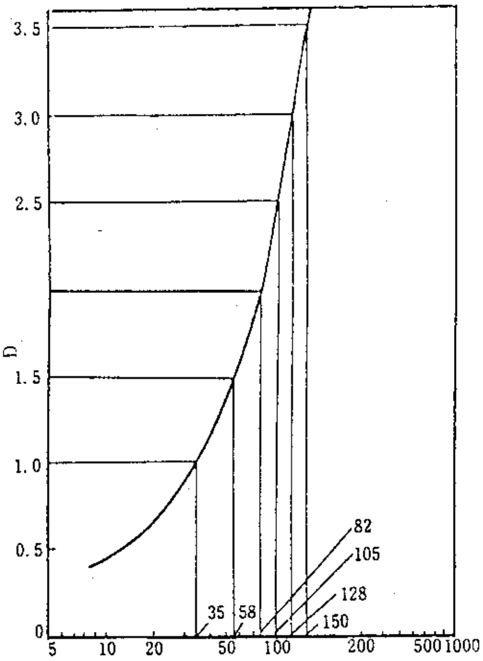
X-ray film: Fuji #100
Intensifying screen: lead foil
(front, back 0.03 mm)
X-ray unit: EX250-5A
Focus-film distance: 60 cm
Density: 1.5
Development: Fuji Hirendol, 20°C,
5 min (tank)

Fig. 3.1 Exposure chart
(tube voltage is a parameter)

(2) Correction of radiographic density (utilization of characteristic curve)

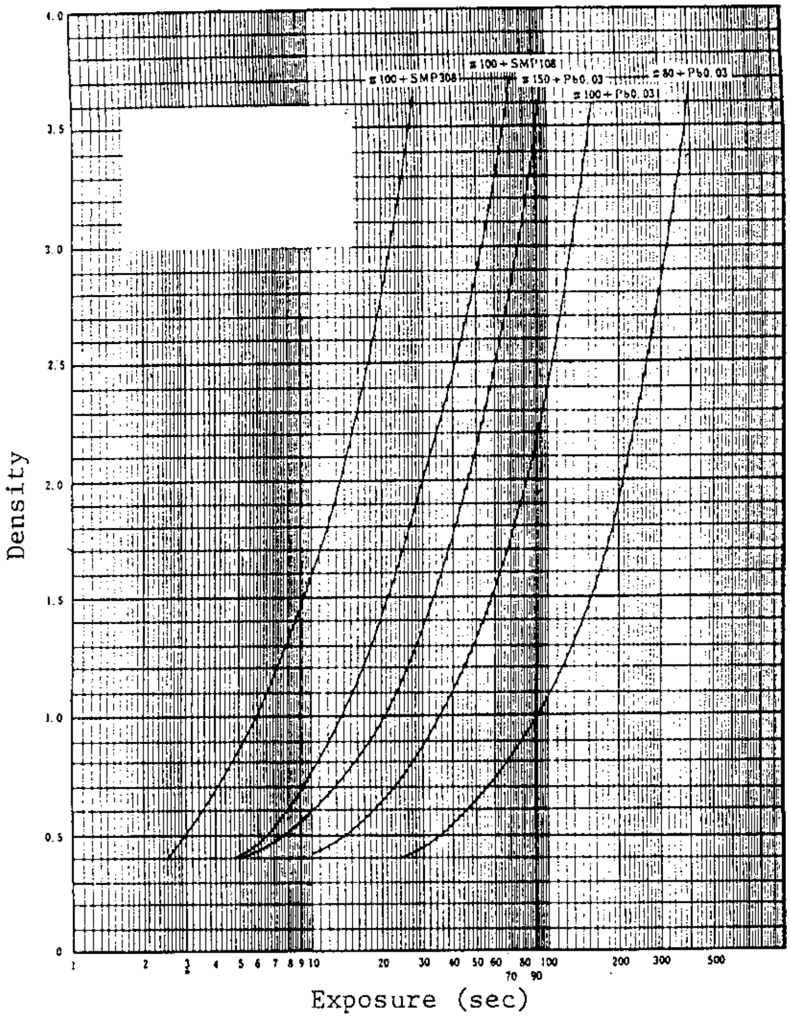
In actual radiographic operation, it is often difficult to work under exactly the same conditions as when the exposure chart was prepared. Thus it sometimes happen that a radiograph with the intended density cannot be obtained by making radiography under the conditions determined from the exposure chart because of the differ-

ent condition, such as scattered radiation. This makes it necessary to take another radiograph after correcting the radiographic conditions. This correction of the radiographic conditions is usually done by judgement based on experience. The following concerns the method of correcting the radiographic density by utilizing the characteristic curve of the X-ray film.
For example, correction of density 1.00 to density 1.50 is done in the following manner.
Fig. 3.2 shows the characteristic curve of X-ray film. From this figure, the exposure time corresponding to density 1.00 is 35 seconds and the exposure time corresponding to density 1.50 is 58 seconds. That is, the exposure for density 1.50 is $\frac{58}{35}$ or approximately 1.66 times the exposure for density 1.00. This means that given the exposure when a radiograph with a density of 1.0 is taken is E_1, the density of the radiograph will be 1.50 if a radiograph is taken with an exposure of E_1 x 1.66. Thus the magnifying factor of exposure for correcting density D_1 to D_2 can be obtained by utilizing the characteristic curve shown in Fig. 3.3 when the type of the X-ray film differs.



Film #100
Intensifying screen Pb 0.03 front, back 5 min tank
Development: Hirendol 20°C
X-ray unit: MAKROTANK H
Tube voltage 200 kVp
Tube current: 4 mA
Test piece: Steel plate 16 mm
Focus-film distance 600 mm

Fig. 3.2 Characteristic curve of X-ray film



Development: Hirendol 20°C
5 min tank
X-ray unit: MAKROTANK H
Tube voltage: 200 kVp
Tube current: 4 mA
Test piece: 16 mm thick
steel plate
Focus-film distance: 600 mm

Fig. 3.3 Characteristic curve of X-ray film

4. Viewing Conditions and Image Quality of Radiograph

4.1 Apparent radiographic contrast

If the viewing room is well lighted, the light coming into the eyes includes the penetrating light of intensity L from the radiograph and the light of Ls_1. Also, if a fixed mask adjusted to the film size is not used, the light of Ls_2 around the edge of the radiograph is further added. Given $(Ls_1 + Ls_2)/L = n'$, the apparent radiographic contrast ΔD_a can be obtained from the following formula.

$$\Delta D_a = \frac{\Delta D}{1 + n'} \quad \cdots\cdots\cdots\cdots\cdots\cdots\cdots \quad (4.1)$$

Addition of Ls_1 and Ls_2 to L reduces the apparent radiographic contrast, ΔD_a, to $\frac{1}{1+n'}$ of ΔD.
The symbol n' in equation (4.1) is the ratio of the intensity L_s (the sum of Ls_1 and L_{s2}) other than the penetrating light to the intensity L of the penetrating light. Therefore, if L_s is constant, n' becomes larger as the density increases. Namely, the viewing of a high-density radiograph is influenced by the brightness of the room and the fixed mask of the illumination. Thus, in order to prevent the apparent contrast ΔDa of the radiograph from decreasing, it is necessary to minimize light intensity L_s other than the penetrating light.

4.2 Influence of the brightness of film illuminator

The relationship between ΔD and ΔDmin corresponding to wire diameter d when a film illuminator of a fixed brightness L'_0 is used is shown by the solid lines in Fig. 4.1

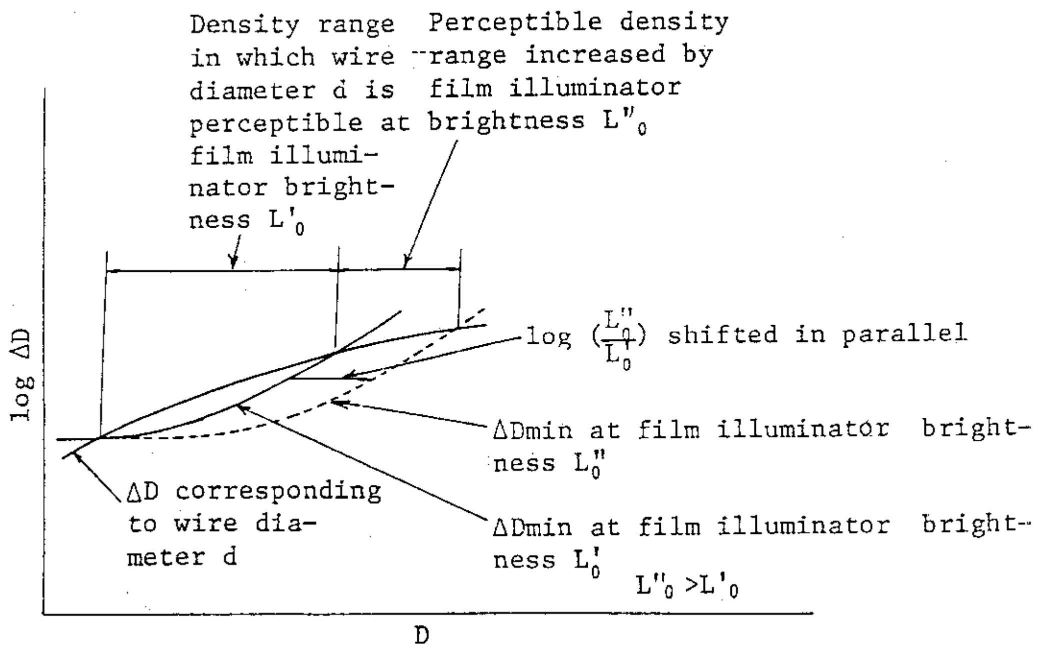


Fig. 4.1 Relationship between density and penetrameter sensitivity (influence of film illuminator brightness)

Next, suppose we observe a radiograph, using a film illuminator of brightness L''_0 ($L''_0 > L'_0$). When a radiograph of density D_1 is observed with a film illuminator of brightness L'_0 and when a radiograph of density D_2 is observed with a film illuminator of brightness L''_0, the following relationship holds between radiograph densities D_1 and D_2 which make equal the intensities of the beams of the penetrating light:

$$D_2 - D_1 = \log \left(\frac{L''_0}{L'_0}\right) \quad \ldots\ldots\ldots\ldots\ldots\ldots \quad (4.2)$$

If both beams of the penetrating light have the same intensity when the minimum perceptible contrast ΔD_{min} is the same, ΔD_{min} with the film illuminator of brightness L''_0 as calculated from equation (4.2) will be as shown by the broken line in Fig. 4.1, which can be obtained by shifting the solid curve for ΔD_{min} by $\log \left(\frac{L''_0}{L'_0}\right)$ in parallel sideways. If L''_0 is four times as bright as L'_0, ΔD_{min} corresponding to L''_0 is obtained by shifting the curve in parallel to the right by $\log 4 \fallingdotseq 0.6$ in density.

4.3 Influence of room brightness

The relationship between ΔD and ΔD_{min} corresponding to wire diameter d in dark room observation is shown by a solid line in Fig. 4.2. Now suppose that besides the penetrating light, light of a constant intensity L_{S1} comes into the eyes during observation in a room. At low density, n' is small because of the high intensity of the penetrating light and, as is clear from equation (4.1), ΔD does not decrease appreciably. At high density, however, n' is large because of the low intensity of the penetrating light and apparently ΔD decreases considerably. The above relationship is shown by the broken line in Fig. 4.2.

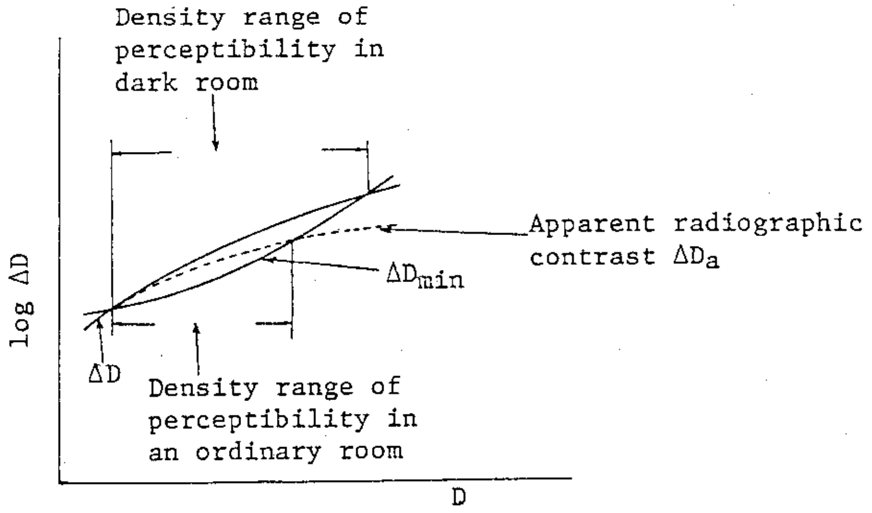


Fig. 4.2 Relationship between density, D and ΔD_{min} (influence of room brightness)

Therefore, when observation is made in an ordinary room, the density range in which wire diameter d is perceptible is narrow as compared with that in a dark room, as shown by Fig. 4.2. This indicates that when viewing a radiograph, it is necessary to exercise care that no light other than the penetrating light comes into the observer's eyes.

5. Improvement of Image Quality of Radiograph

5.1 Detection of defect

Whether a defect can be identified on a radiograph or not is determined by the relationship between the density difference shown by the defect image, namely, the radiographic contrast ΔD corresponding to the defect and the minimum density difference that allows the defect to be identified, namely, the minimum perceptible density difference ΔD_{min}.

$$|\Delta D| \geqq |\Delta D_{min}| \quad \ldots\ldots\ldots\ldots\ldots\ldots \quad (5.1)$$

$$|\Delta D| < |\Delta D_{min}| \quad \ldots\ldots\ldots\ldots\ldots\ldots \quad (5.2)$$

The density difference is perceptible in the case of equation (5.1), and not perceptible in the case of equation (5.2).
Radiographic contrast, ΔD, is related to the material of the object to be radiographed, absolute value of its thickness and the difference in thickness, quality of the penetrating radiation, dose of scattering radiation which depends on the geometrical arrangement of irradiation, source size and intensity distribution, quality of X-ray film (including intensifying screen), and dose characteristics.
Minimum perceptible density difference ΔD_{min} is related to the image size and density distribution, graininess of X-ray film (intensifying screen, quality of radiation), density of the radiograph, viewing conditions for the radiograph (brightness of the film illuminator, brightness of the observation room, use or non-use of the mask, and observation distance), and human factors.
To discuss the perceptibility of a defect quantitatively, therefore, it is necessary to obtain the values of ΔD and ΔD_{min} quantitatively.

5.2 Minimum perceptible contrast

Minimum perceptible contrast ΔD_{min} is related to various factors such as those mentioned above.
Fig. 5.1 shows the relationship between the density of a radiograph observed in a dark room using a KS-3 type film illuminator and minimum perceptible contrast ΔD_{min}.

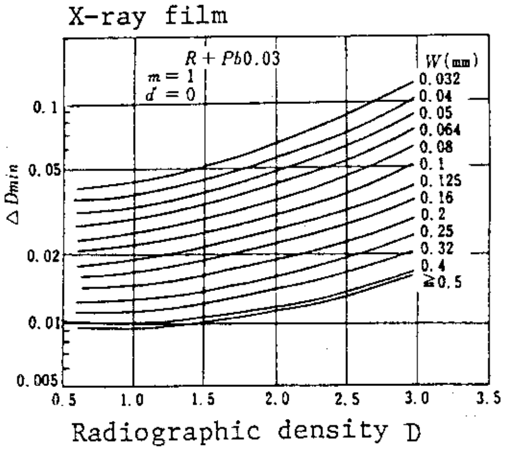


Fig. 5.1 Relationship between radiographic density and minimum perceptible contrast (viewing conditions: dark room, KS-3 type film illuminator)

As shown in Fig. 5.1, D_{min} of the wire image increases with increase in density, and the smaller the width of the wire image, the more remarkable the rate of increase. Fig. 5.2 shows the relationship between the width of the wire image and ΔD_{min} as obtained from Fig. 5.1.

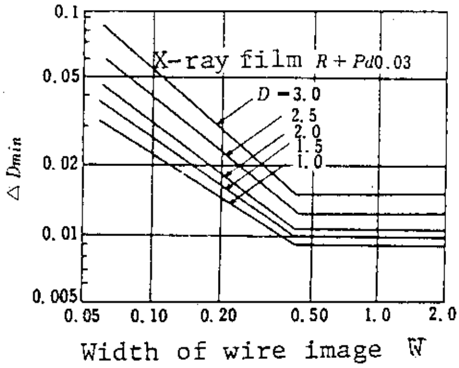


Fig. 5.2 Relationship between the width of wire image and minimum perceptible contrast (obtained from Fig. 2.9)

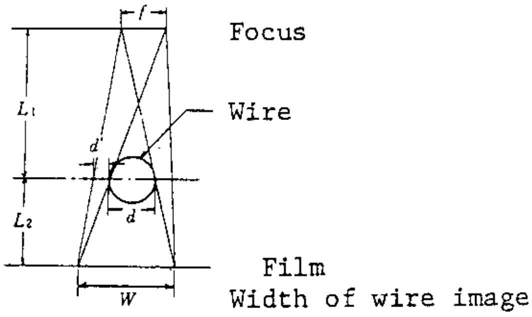


Fig. 5.3 Width of wire image

Here the image width W of a wire of diameter d as shown by Fig. 5.3 is given by the following formula.

$$W = m(d + d') \quad \ldots\ldots\ldots\ldots\ldots\ldots \quad (5.3)$$

where m : Magnifying factor

d' : Apparent focal spot size at the position of a penetrameter wire.

The value m is given by the following formula.

$$m = \frac{L_1 + L_2}{L_1} \quad \ldots\ldots\ldots\ldots\ldots\ldots \quad (5.4)$$

where L_1 : Focus-penetrameter distance

L_2 : Penetrameter-film distance

So long as the width of the wire image is large, ΔD_{min} is constant, but when the width of the wire image is small it increases with decrease in width. The rate of this increase varies with the density, and the higher the density, the higher the rate of increase.

5.3 Method of improving the image quality of radiograph

Fig. 5.4 shows the relationship between the radiographic density and minimum perceptible contrast.
Point A in the figure is not perceptible because it is in a range below ΔD_{min}. However, the defect can be detected if the density

difference at Point A is increased to Point B or C. Point D shows the density difference of the defect image in a high-density radiograph, which is in an undetectable range. It can be made perceptible, however, by lowering the density of the radiograph to Point B, while keeping the density difference at Point D unchanged. Fig. 5.5 shows the relationship between the width of the image and ΔD_{min}. In the figure, Point E is not perceptible because it is in a range below ΔD_{min} (solid line). If the image is enlarged, however, Point E shifts to Point F, which is perceptible. Also, if a combination of X-ray film of a small ΔD_{min} value and an intensifying screen is used, Point E becomes perceptible because it shifts to a range above ΔD_{min} (broken line), as shown in the figure.

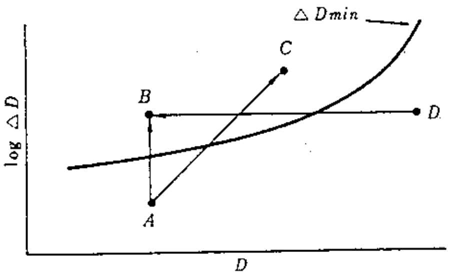
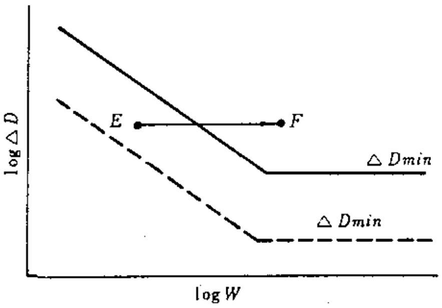


Fig. 5.4 Method of improving the image quality (by increasing the density difference and decreasing the density)



ΔD_{min} smaller than that indicated by the solid line

Fig. 5.5 Method of improving the image quality (by enlarging the image and reducing ΔD_{min})

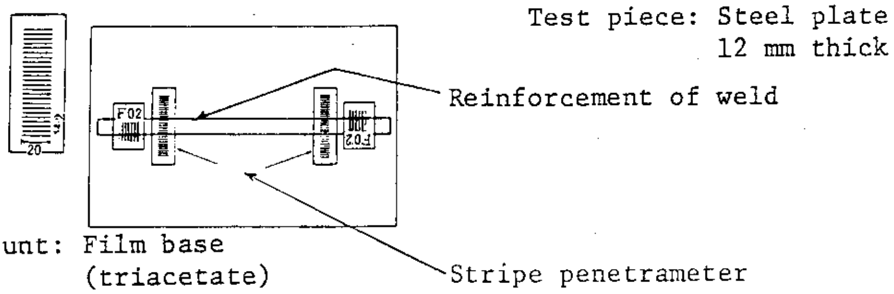
5.4 Methods of improving the image quality by enhancing the radiographic contrast

5.4.1 Improvement of image quality by reduction of scattered direct radiation intensity ratio

(1) Removal of reinforcement of weld

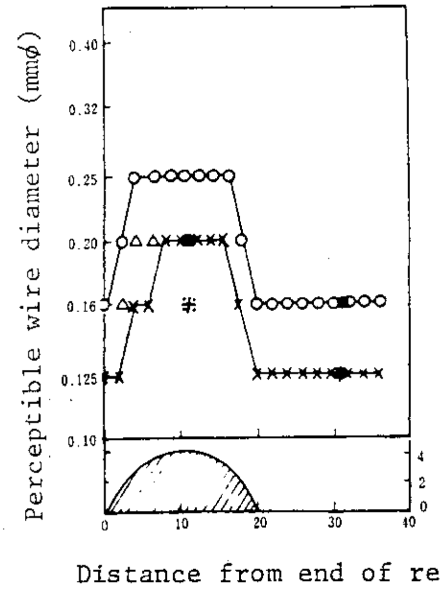
The intensity of the scattered radiation generated by X-rays passing through the base material is much higher than that of the scattered radiation generated by X-rays passing through the weld. Therefore, scattered X-rays from the base material in the vicinity of the weld are added to the X-rays that have penetrated the weld, thus increasing the scattered direct radiation intensity ratio in the center of the weld as shown in Fig. 2.4 and lowering the image quality of the radiograph.
Some experimental results are given below. In order to measure the image quality at different positions on a reinforcement of weld, penetrameters, each consisting of wires of the same diameter, are arranged as shown by Fig. 5.6 (a) (hereinafter

referred to as stripe penetrameters), and radiographs are taken using them with the photographic arrangement such as shown by Fig. 5.6 (b). The reinforcement of weld has a height of 4 mm and a width of 20 mm, with a semicircular cross section, and is of the same material as the base material. Also, a penetrameter (F02) which has been in wide use is used simultaneously for comparison. If a wire image can be clearly distinguished by an observer, it is given two marks, and if the image can be distinguished though vaguely, it is given one mark. If the total marks given by five observers are seven marks or more, the image is classified as perceptible, and if the total number of marks is two or less, the image is classified as imperceptible. The viewing conditions for the radiographs are as follows: Place of observation, dark room; film illuminator, KS-3 with the highest brightness; viewing distance, 20 cm. Fig. 5.7 shows the results. With strip penetrameters, a wire with a diameter of 0.16 mm is perceptible at the base material, but only a 0.25-mm-dia. wire is perceptible at the center portion of the reinforcement of weld, indicating the deterioration of the image quality. With the F02 penetrameter, the same wire diameter as that perceived on the strip penetrameter is perceptible at the base material, but at the center portion of the reinforcement of weld, wires of smaller diameter down to 0.20 mm are perceptible as compared with the strip penetrameter.
From the above, it is expected that the removal of the reinforcement of weld allows the scattered direct radiation intensity ratio at the base material, making it possible to improve the image quality of radiographs of welds to the same level as that of the base material.



Mount: Film base
(triacetate)
Wire diameter (mm)
0.10, 0.125, 0.16
0.20, 0.25, 0.32
0.40
(a) Strip penetrameter
(b) Photographic arrangement

Fig. 5.6 Strip penetrameters and photographic arrangement



Strip penetrameter F02

o: Perceptible } stripe pemetrameter
x: Not perceptible }
●: Perceptible } F02
※: Not perceptible }

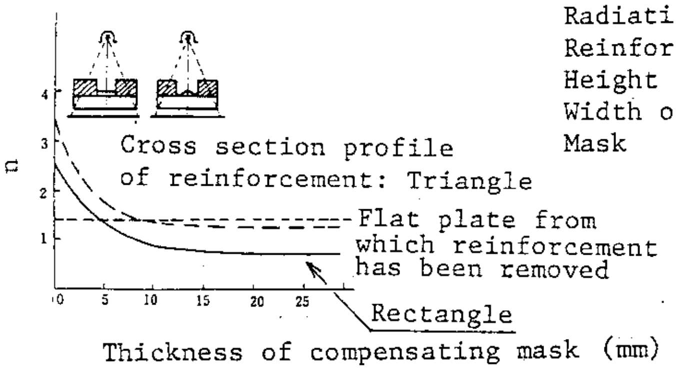
Width of reinforcement 20 mm
Height of reinforcement 4 mm
Fixed mask
(Film size)

X-ray unit:	Weltes 150S
Tube voltage:	120 kV_p
Exposure:	40 mA·min
Focus-film distance:	800 mm
Film-test piece distance:	2 mm
Radiation field:	300 mm dia.
Test piece:	12-mm-thick steel plate
Film:	Fuji #100
Intensifying screen:	Pb 0.03FB
Developing:	Hirendol 20°C, 5 min.

Fig. 5.7 Penetrameter sensitivity at different position on reinforcement of weld

(2) Utilization of thickness compensating mask

After placing an absorber (hereinafter referred to as a thickness compensating mask or simply as a mask) on the base metal, the relationship between the mask thickness and the scattered direct radiation intensity ratio at the center portion of a weld was obtained where the cross section profile of the reinforcement a rectangle or isosceles triangle. The measurement results are given in Fig. 5.8.



100 kVeff
FFD = 800 mm
Thickness of base metal : 20 mm Fe
Test piece-film distance : 2 mm
Radiation field : 200 x 200 mm
Reinforcement : Source side
Height of reinforcement : 4 mm
Width of reinforcement : 5 mm
Mask : Source side Fe

Fig. 5.8 Relationship between the thickness of compensating mask and scattered direct radiation intensity ratio n

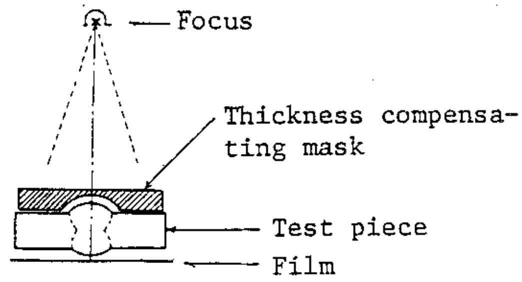


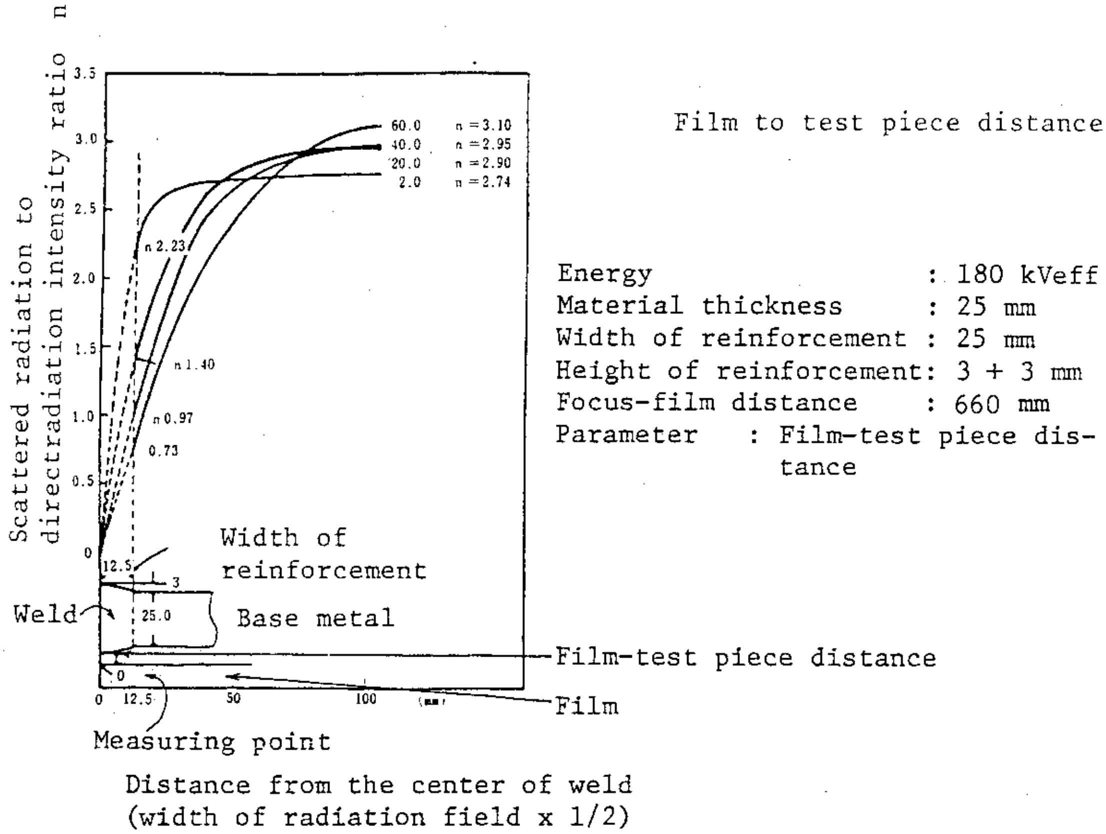
Fig. 5.9 How to use thickness compensating mask

In any case, the scattered direct radiation intensity ratio sharply decreases with increase in the mask thickness. Also, when a sufficiently thick mask is used, the scattered direct radiation intensity ratio is smaller than when a reinforcement is removed. This is because the mask acts as a shielding mask, markedly reducing the dose rate of the scattered radiation reaching the measuring point on the film from the base metal located under the mask.
Consequently, if a thickness compensating mask such as shown in Fig. 5.9 is used on a butt weld of plates having a reinforcement, the dose of the base metal and that of the weld are equalized, as a matter of course, and radiographs that satisfy the density range requirement can be taken more easily. Moreover, contrast of such radiographic contrast is markedly enhanced over the radiographs taken without using the thickness compensating mask, resulting in improved image quality of the radiograph.

(3) Utilization of shielding mask

Only the scattered direct radiation intensity ratio is influenced by the size of the radiation field; other factors are unrelated to the size of the radiation field so long as the photographic arrangement and the density remain the same.

In radiography, the film is usually placed close to the test piece. Fig. 5.10 shows the relationship between the width of the radiation field (the distance from the center of the weld x 2) and the scattered direct radiation intensity ratio in such a photographic arrangement. Fig. 5.10 also shows the relationship between the width of the radiation field and the scattered direct radiation intensity ratio for a test piece film-distance larger than normal. Fig. 5.11 illustrates the relationship between the film-test piece distance and the intensity ration of the scattered direct radiations from the weld and the base metal.



Energy : 180 kVeff
Material thickness : 25 mm
Width of reinforcement : 25 mm
Height of reinforcement: 3 + 3 mm
Focus-film distance : 660 mm
Parameter : Film-test piece distance

Fig. 5.10 Relationship between the width of radiation field and scattered direct radiation intensity ratio

When the film is placed close to the test piece, the scattered direct radiation intensity ratio increases sharply with increase in the width of the radiation field. In other words, so long as the width of the radiation field agrees with that of the reinforcement of weld, the scattered direct radiation intensity ratio does not much differ from that from a sufficiently wide radiation field, and the intensity ratio of the scattered direct radiations from the base metal does not increase so much even if the radiation field becomes wider. In normal photography, therefore, decrease in the scattered direct radiation

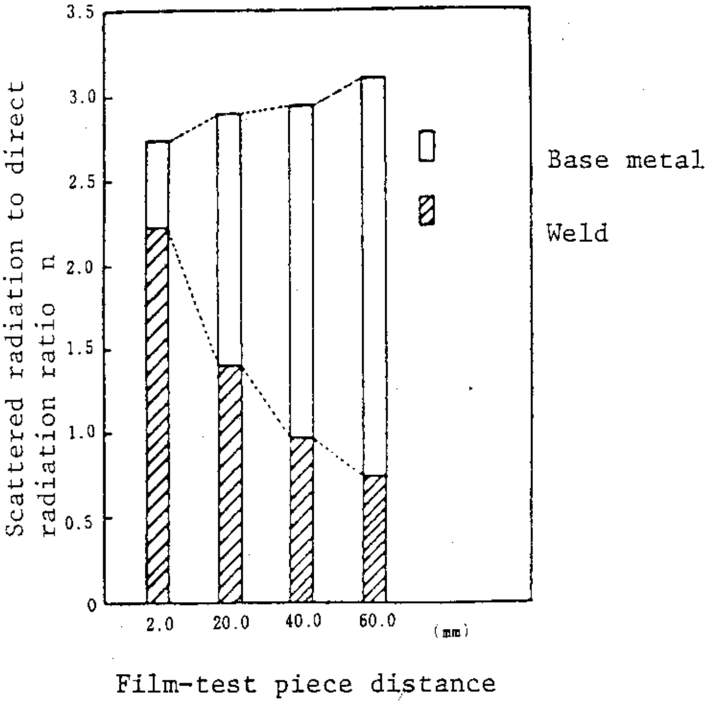


Fig. 5.11 Relationship between film-test piece distance and scattered direct radiation intensity ratio (measurement conditions are the same as in Fig. 5.10)

intensity ratio cannot be expected even when a diaphragm is used, unless the size of the radiation field is made equalized to or smaller than the width of the reinforcement.
However, as is clear from Fig. 5.11, the scattered direct radiation intensity ratio from the weld (shaded portion) decreases sharply with increase in the film-test piece distance.
In addition to the conventional radiographic method of irradiating a large field, another method is known, as shown in Fig. 5.12, whereby a radiograph is taken of a small area by irradiating only an area of interest, keeping the film properly away from the test piece and using an adequate shielding material. This method is called narrow radiation field method.
When the same type of X-ray film, the same density and the same X-ray quality are selected from equation (1.1), radiographic contrast, ΔD, is proportional to $\sigma/(1 + n)$. Now, in the narrow radiation area method, increasing the film-test piece distance reduces not only the scattered direct radiation intensity ratio, but also σ. Fig. 5.13 shows plotting of $\sigma/(1 + n)$ by calculation when the film-test piece distance is varied in different ways, with a shielding mask placed on the radiation source side.
The figure reveals that there exists an optimum photographic arrangement where $\sigma/(1 + n)$ or the radiographic contrast is maximum.

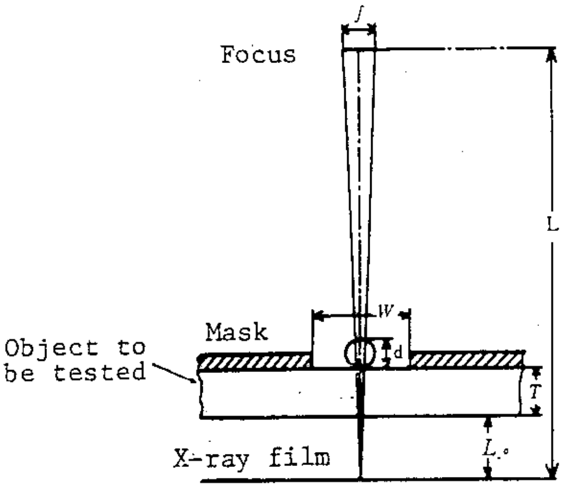


Fig. 5.12 Photographing arrangement

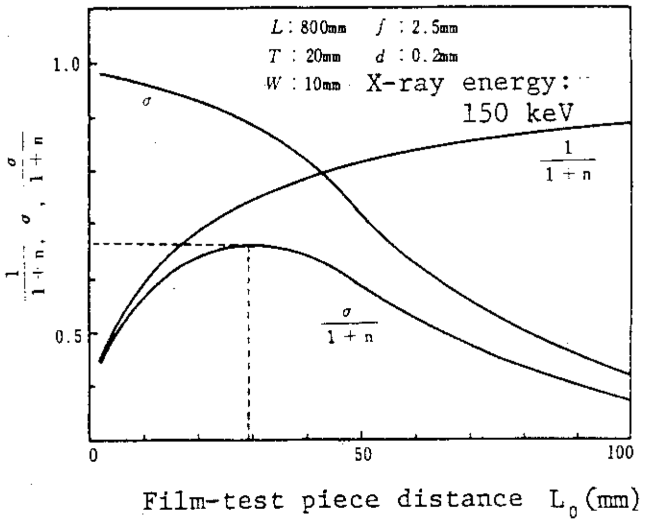


Fig. 5.13 Relationship between the film-test piece distance and $\sigma/(1 + n)$

5.4.2 Improvement of image quality by selection of optimum X-ray quality

Fig. 5.14 shows, by solid lines, the variation of the scattered direct radiation intensity ratio n_1 for a weld with a base metal thickness (T_2) of 15 mm and a reinforcement width of 20 mm, at different reinforcement heights.

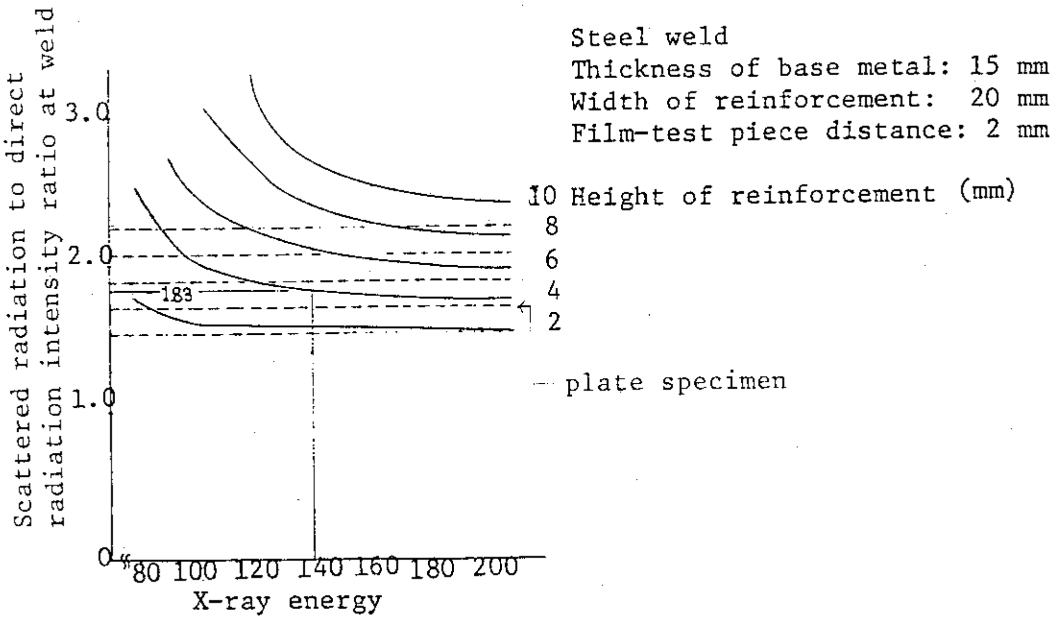


Fig. 5.14 Influence of reinforcement height and X-ray energy on scattered direct radiation intensity ratio

As is clear from the figure, the scattered direct radiation intensity ratio increases with decrease of the effective energy. This tendency is more remarkable as the height of the reinforcement increases. The broken lines in the figure indicate, for reference, the scattered direct radiation intensity ratios for a plate specimen having the same thickness as the material thickness (the sum of the base metal thickness and reinforcement height) at different reinforcement heights. They show a tendency that the scattered direct radiation intensity ratio of the reinforced test piece approaches these values with increase in effective energy.

On the other hand, Fig. 5.15 shows the optimum densities and minimum perceptible wire diameters for various X-ray energies used in radiography of a reinforced weld. As is clear from the figure, the optimum density of the base metal increases and that of the weld decreases with decrease in X-ray energy. The minimum perceptible wire diameter decreases until the X-ray energy falls to a certain level, but after that point the diameter increases even if the X-ray energy continues to fall. This indicates that there exists an optimum X-ray quality in a reinforced test piece.

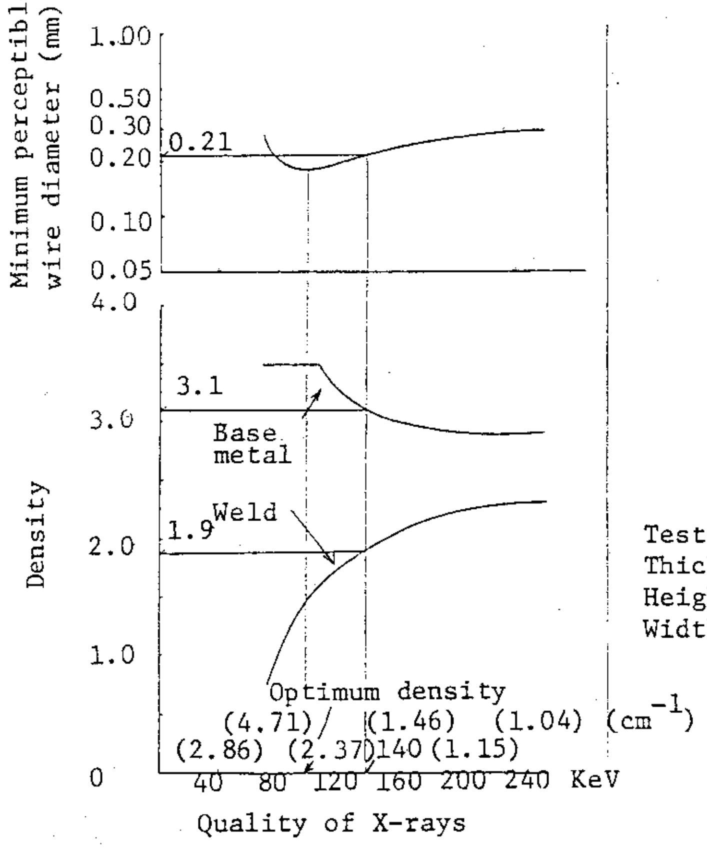


Fig. 5.15 Relationship between X-ray quality and minimum perceptible wire diameter

Test piece:	Steel
Thickness of base metal:	15 mm
Height of reinforcement:	4 mm
Width of reinforcement :	20 mm

Fig. 5.16 shows the relationship between the X-ray quality, optimum density and minimum perceptible wire diameter, obtained by using the reinforcement height as a parameter as in Fig. 5.15.

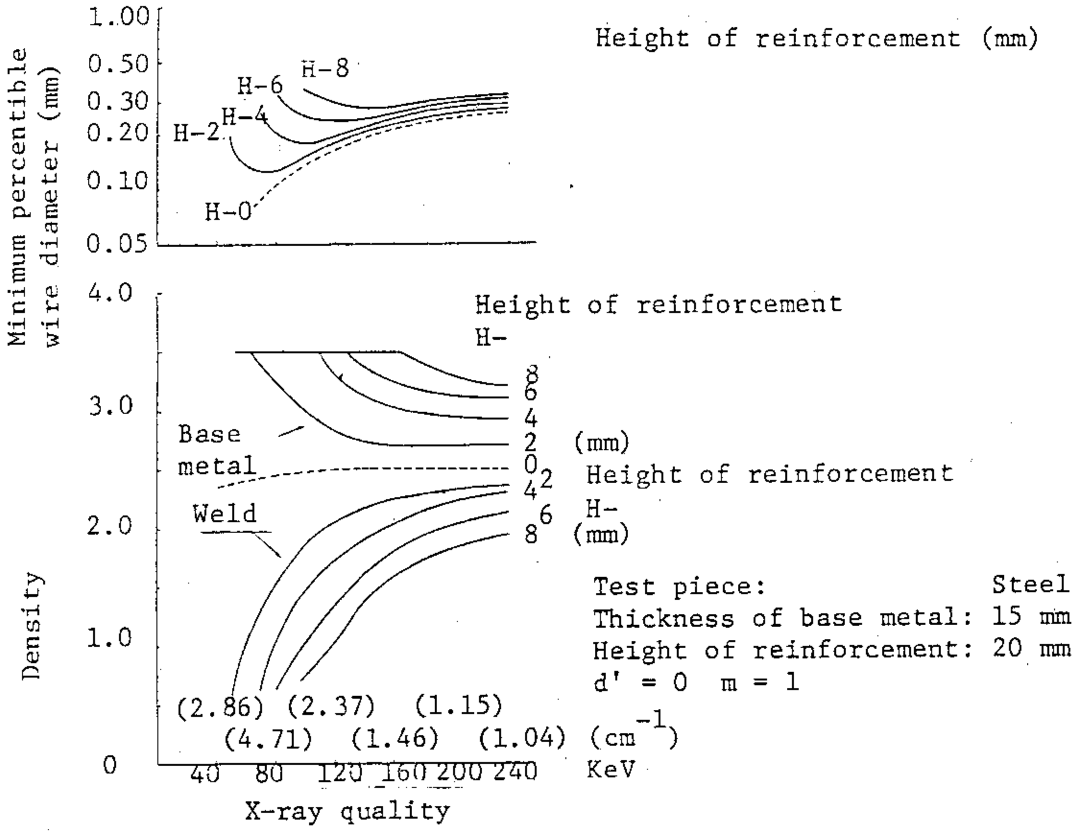


Fig. 5.16 Relationship between reinforcement height and optimum X-ray quality

5.5 Methods of improving the image quality by lowering minimum perceptible contrast

5.5.1 Improvement of image quality by selection of proper radiographic screens

Minimum perceptible contrast of the penetrameter, ΔD_{min}, varies with the type of photosensitive materials used. Fig. 5.17 shows the measurement results of ΔD_{min}, which indicate that a combination of X-ray film of good graininess and intensifying screen gives a smaller ΔD_{min} value than a combination of those having poor graininess, for wire images of the same width. This means that the image quality can be improved by properly selecting the type of radiographic screens.

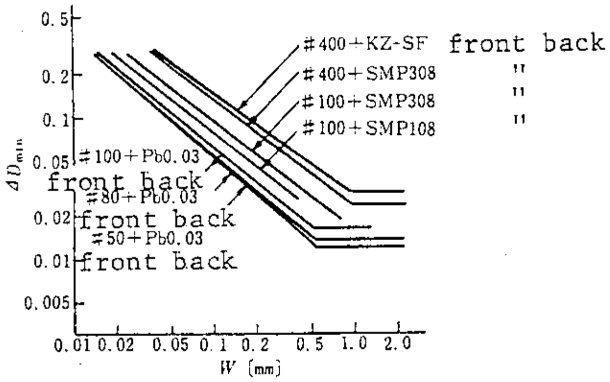
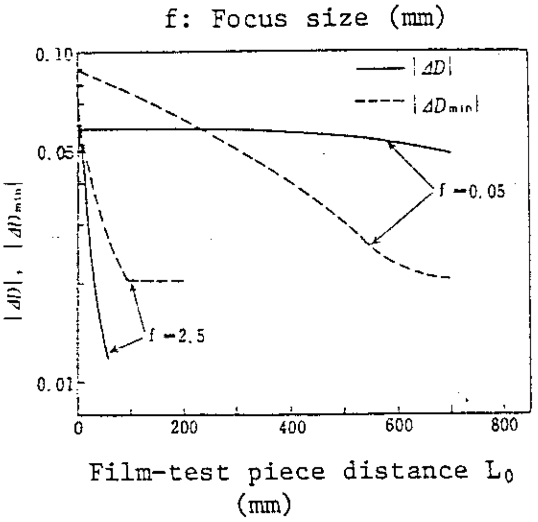


Fig. 5.17 Relationship between the width of wire image and ΔD_{min} for various combinations of film and intensifying screen (density 2.5, developing Hirendol 20°C, 5 min. (tank))

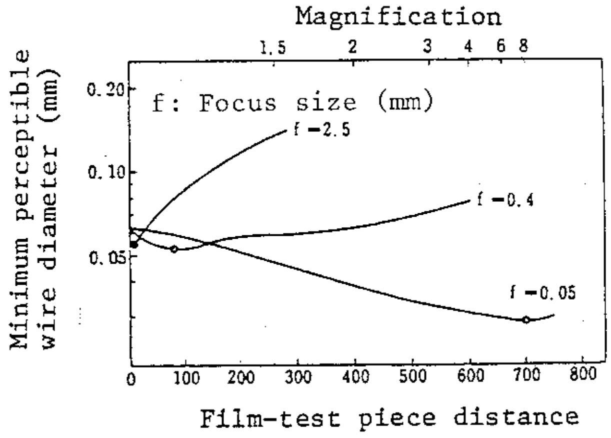
5.5.2 Enlarging radiography

Improvement of the image quality of radiographs can be expected if the defect image can be enlarged by placing the test piece away from the film, using a microfocus X-ray unit, without lowering the radiographic contrast.
Fig. 5.18 shows the relationship between the film-test piece distance and $|\Delta D|$ and $|\Delta D_{min}|$ when the focus size (f) is 2.5 mm and 0.05 mm. When f = 2.5 mm, $|\Delta D_{min}|$ decreases with the increase in the film-test piece distance. However, since $|\Delta D|$ decreases more than $|\Delta D_{min}|$ does, $|\Delta D|$ is smaller than $|\Delta D_{min}|$, making it impossible to perceive a wire of 0.05 mm diameter. When f is 0.05 mm, on the other hand, $|\Delta D_{min}|$ decreases with increase in the film-test piece distance, but as $|\Delta D|$ decreases slightly, $|\Delta D|$ is equal to, or greater than, $|\Delta D_{min}|$ at a film-test piece distance of more than 240 mm, making it possible to perceive a 0.05 mm wire. From the above results, it can be seen that it is necessary to use a small focus in enlarging radiography. Namely, it is necessary to select a focal spot size that allows minimizing decrease in the σ value in enlarging radiography, keeping in mind that σ is one of the factors that determine the radiographic contrast.
Fig. 5.19 shows the relationship between the film-test piece distance and the minimum perceptible wire diameter for different focus sizes.
The figure indicates that when a microfocus (f = 0.05 mm) is used, enlarging radiography, in which the film-test piece distance is made larger than in ordinary radiography (contact radiography), is more effective for the improvement of the image



Test piece: Aluminum plate
Material thickness: 5 mm
Focus-film distance: 800 mm
Absorption coefficient: 0.5
Density: 2.5
Film: Fuji #100 Pb 0.03 F&B
Wire diameter of penetrameter: 0.05 mm

Fig. 5.18 Relationship between film-test piece distance and $|\Delta D|$ and $|\Delta D_{min}|$



Test piece: Aluminum plate
Material thickness: 5 mm
Focus-test piece distance: 800 mm
Absorption coefficient: 0.6
Density: 2.5
Film: Fuji #100 Pb 0.03 F&B

Fig. 5.19 Relationship between film-test piece distance and minimum perceptible wire diameter

quality. On the other hand, the effectiveness of enlarging radiography is not so high if a large focal spot size (f = 2.5 mm, f = 0.4 mm) is used because the geometrical correction factor σ sharply decreases with increase in the film-test piece distance due to the influence of the focal spot size.

6. Conversion of Penetrameter Sensitivity

6.1 Conversion of the sensitivity of penetrameters differing in material

The penetrameter sensitivity is widely utilized as a criterion to indicate the image quality of the radiograph. It is generally considered necessary to use a penetrameter made of the same material as the test piece or having a similar X-ray absorption to that of the test piece. It is, however, difficult to satisfy these conditions in all radiographic tests of welds of various types of metals, alloys and castings. Thus it is desirable that radiographic tests be conducted using a penetrameter consisting of a few types of materials.

(1) Conversion of penetrameter sensitivity

When two wires of different types of materials (different absorption coefficients) placed on a test piece are simultaneously radiographed as shown in Fig. 6.1, the following relationship holds simultaneously from equations (1.1) and (5.1), given the penetrameter wire diameters which are the perceptible limits on the radiograph are d_1 and d_2 respectively.

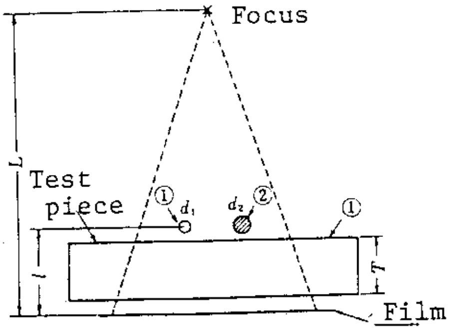
$$\left.\begin{aligned} \Delta D_1 &= (\Delta D_{min})_1 = -\frac{0.434\gamma\mu_{\rho 1}\sigma_1 d_1}{1+n} \\ \Delta D_2 &= (\Delta D_{min})_2 = -\frac{0.434\gamma\mu_{\rho 2}\sigma_2 d_2}{1+n} \end{aligned}\right\} \quad \cdots\cdots\cdot \ (6.1)$$

where ΔD_1, ΔD_2 = Density differences for d_1 and d_2

$(\Delta D_{min})_1$, $(\Delta D_{min})_2$ = Minimum perceptible contrast for d_1 and d_2

μ'_1, μ_2 = Absorption coefficients of X-rays for individual materials (when sensitivity cofficients are taken into consideration)

σ_1, σ_2 = Correction factors for d_1 and d_2, which depend on the focal spot size and the geometrical conditions of radiography



Circled number denote the type of wire material.
L: Focus-film distance
ℓ: Penetrameter-film distance

Fig. 6.1 Radiographic arrangement

The minimum perceptible contrast is related to the radiographic density, image size, combination of X-ray film and intensifying screen, and the viewing conditions in radiography. The relationship between the width of the wire image and the minimum perceptible contrast shown by using logarithmic section paper is given by the diagram in Fig. 6.2.

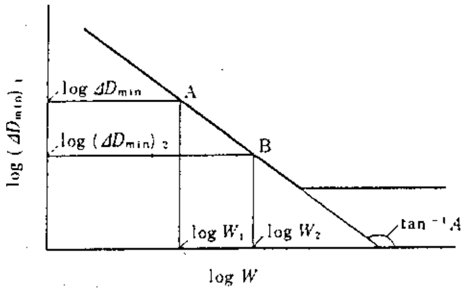


Fig. 6.2 Relationship between the width of wire image W and minimum perceptible contrast ΔD_{min} (when the radiographic density is constant and the influence of focus size is negligible)

For simplicity, let us consider a case where the influence of the focal spot size is negligible, then σ_1 and σ_2 in equation (6.1) are 1, and the following relationship holds between d_1 and d_2:

$$\frac{d_1}{d_2} = \frac{(\Delta D_{min})_1}{(\Delta D_{min})_2} \frac{\mu_{\rho 1}}{\mu_{\rho 2}} \quad \cdots\cdots\cdots\cdots\cdots\cdots\cdots \quad (6.2)$$

In Fig. 6.2, the gradient A of the line connecting Point A and Point B corresponding to d_1 and d_2, respectively, can be obtained from the following equation:

$$A = \frac{\log(\Delta D_{min})_1 - \log(\Delta D_{min})_2}{\log d_1 - \log d_2} \quad \cdots\cdots\cdots \quad (6.3)$$

Therefore, the following equation can be obtained:

$$\frac{(\Delta D_{min})_1}{(\Delta D_{min})_2} = \left(\frac{d_1}{d_2}\right)^A \quad \cdots\cdots\cdots\cdots\cdots\cdots\cdots \quad (6.4)$$

From equations (6.2) and (6.4) the following equation derives:

$$\frac{d_1}{d_2} = \left(\frac{\mu_{\rho 1}}{\mu_{\rho 2}}\right)^{-1/(1-A)} \quad \cdots\cdots\cdots\cdots\cdots\cdots\cdots \quad (6.5)$$

As is clear from equation (6.5), to convert the diameter of wires of different types of materials, it is necessary to measure the ratio of the absorption coefficients for each wire material, $\mu_{\rho 1}/\mu_{\rho 2}$, and gradient A in Fig. 6.2.
So long as the test piece thickness is large, μ_ρ may be considered almost equal to $\bar{\mu}_T$. Within such a large-thickness range, the ratio μ_1/μ_2 in equation (6.5) is expressed approximately as follows.

$$\frac{\mu\rho_1}{\mu\rho_2} = \frac{\bar{\mu}_{T1}}{\bar{\mu}_{T2}} \quad \dots\dots\dots\dots\dots\dots \quad (6.6)$$

On the other hand, the relationship between effective energy and $\bar{\mu}_{T1}/\bar{\mu}_{T2}$ is given by Fig. 6.3. Therefore, the value of $\bar{\mu}_{T1}/\bar{\mu}_{T2}$ can be known from the effective energy kV_{eff} of X-rays which have penetrated the test piece.

Thus, from Fig. 6.2, Fig. 6.3, the effective energy of the X-rays used, and equation (6.5), the diameter of wires of differing materials can be converted.

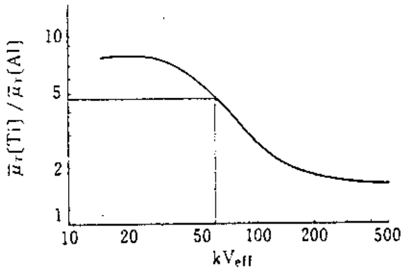


Fig. 6.3 Relationship between effective energy and the ratio of absorption coefficients

(2) X-ray quality meter

When the material of the penetrameter wire is different from that of the test piece, measurement of the quality of X-rays is needed for conversion of the penetrameter sensitivity.
The quality of X-rays can be known by measuring the half-value layer from the absorption curve as an absorption coefficient or effective energy. Here, even if the same tube voltage and tube current are used, the quality of X-rays varies with the type of X-ray unit used. It is, therefore, necessary to know the absorption curve for each X-ray unit. This has posed a problem in converting the penetrameter sensitivity in practical use. To solve this problem, the X-ray quality meter has recently developed as a means of measuring the quality of X-rays directly from a radiograph. As a result, a new X-ray quality meter has come to be used in practical application, which combines a penetrameter of material different from the test price and X-ray quality meter.
As shown by Fig. 6.4, two sheets of different types of material put on a test piece are radiographed simultaneously. Here, the combination of the two thin plates differing in the type of material is called an X-ray quality meter. Incidentally, the material of the X-ray quality meter should be different from those of the test piece and penetrameter. The radiographic contrasts ΔD_3 and ΔD_4 for the two thicknesses t_3 and t_4 are given from equation (1.1) as follows ($\sigma \fallingdotseq 1$):

$$\Delta D_3 = -\frac{0.434\gamma\mu_{\rho 3}t_3}{1+n} \quad \dots\dots\dots\dots\dots\dots \quad (6.7)$$

$$\Delta D_4 = -\frac{0.434\gamma\mu\rho_4 t_4}{1+n} \quad \dots\dots\dots\dots\dots\dots \quad (6.8)$$

Therefore, if the densities of the portions corresponding to t_3 and t_4 are equal, the following equation is obtained from equations (6.7) and (6.8) as a condition for $\Delta D_3 = \Delta D_4$.

$$\frac{\mu_{\rho 3}}{\mu_{\rho 4}} = \frac{t_4}{t_3} \quad \cdots\cdots\cdots\cdots\cdots\cdots \quad (6.9)$$

Here, if the thickness of the test piece is within a wide range, equation (6.9) is approximately given below.

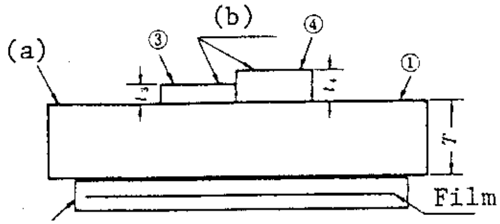
$$\frac{t_4}{t_3} = \frac{\overline{\mu T_3}}{\overline{\mu T_4}} \quad \cdots\cdots\cdots\cdots\cdots\cdots \quad (6.10)$$

Namely, if we measure the density of the radiograph of the X-ray quality meter taken in that test piece thickness range for the two types of materials to obtain the thickness ratio t_4/t_3 that makes both densities equal, the ratio of absorption coefficients, $\frac{\mu T_3}{\mu T_4}$, for various radiographic conditions can be obtained.

In applying the conversion of the penetrameter sensitivity, we can consider, for simplicity, an X-ray quality meter one of which materials is the same material as that of the test piece and the other is of the same as that of the penetrameter.
In this case, suffix 3 in equation (6.9) is 1 and suffix 4 is 2, and the following equation can be obtained from equations (6.5) and (6.9)

$$\frac{d_1}{d_2} = \left(\frac{t_1}{t_2}\right)^{1/(1-A)} \quad \cdots\cdots\cdots\cdots \quad (6.11)$$

Given that d_1 and t_1 are the diameter of a wire of the same material as the test piece and the thickness of a sheet of that material, respectively and that d_2 and t_2 are the diameter of a wire of a material different from the test piece and the thickness of a sheet of that material, respectively. By knowing the thickness ratio t_1/t_2 that gives the same radiographic density and the gradient A of wire diameter in Fig. 6.2, we can obtain minimum sensitivity d_1 from the value of d_2, using equation (6.11). That is, the penetrameter sensitivity obtained by using a penetrameter of the same type of material as that of the test piece can be obtained by using a penetrameter of a material different from that of the test piece.



(a) Test piece
(b) X-ray quality meter

Circled number indicate
the type of material

Fig. 6.4 Radiography using
X-ray quality meter

6.2 Conversion of penetrameter sensitivity when the penetrameter profile differs

For example, penetrameter sensitivity is converted between a wire type penetrameter and a hole type penetrameter.

In order that the penetrameter wires can be perceived on a radiograph in a radiographic test, it is necessary that the relationship represented by equation (5.1) be satisfied.

On the other hand, minimum perceptible contrast ΔD_{min} is given in Fig. 5.2 and expressed approximately by the following equations:

$$\Delta D_{min} = C\, W^{-A} \qquad \ldots\ldots\ldots\ldots\ldots (6.12)$$

where W is the width or diameter of an image, and C and A are constants determined by the density.

When the influence of the focus size can be ignored, namely, when the apparent focal spot sizes at penetrameter position are $d' \fallingdotseq 0$ and $\fallingdotseq 1$, the penetrameter minimum size which determines the minimum perceptibility is determined from the values of density D and $\mu p/1 + n$ from equations (1-1) and (6.12) because C and A can be known if the density is determined.

Fig. 6.5 shows the relationship between the radiographic density and the minimum perceptible wire diameter, which was obtained for a wire type penetrameter, where $\mu p/(1 + n)$ is a parameter. Fig. 6.6 shows the relationship between $\mu p/(1 + n)$ and d_{min}, where density D is a parameter.

As is clear from this figure, the wire diameter which is perceptible at a density of approximately 2.5 is the minimum diameter. This density is called the optimum density. Here, it should be noted that the optimum density is not related to the material of the test piece.

Fig. 6.7 shows the relationship between the density and the minimum perceptible thickness with a hole type penetrameter. Fig. 6.8 shows the relationship between $\mu p/(1 + n)$ and the minimum perceptible thickness of the penetrameter. The hole diameter of the plate is one time the plate thickness (1T-Hole). The above-mentioned relationship is also obtained with hole diameters which are twice (2T-Hole) and four times (4T-Hole) the plate thickness. Fig. 6.9 shows the relationship between $\mu p/(1 + n)$, minimum perceptible wire diameter d_{min}, and minimum perceptible thickness T_{min} when D is 2.5. Now, in Fig. 6.9, the minimum perceptible wire diameter d_{min} and the minimum perceptible thickness T_{min} under the radiographic conditions of $\mu/[1 + n] = k$ are d_1 and T_1, T_2 and T_3, respectively. This relationship is shown in Fig. 6.10 as a penetrameter sensitivity conversion diagram for the two types of penetrameters.

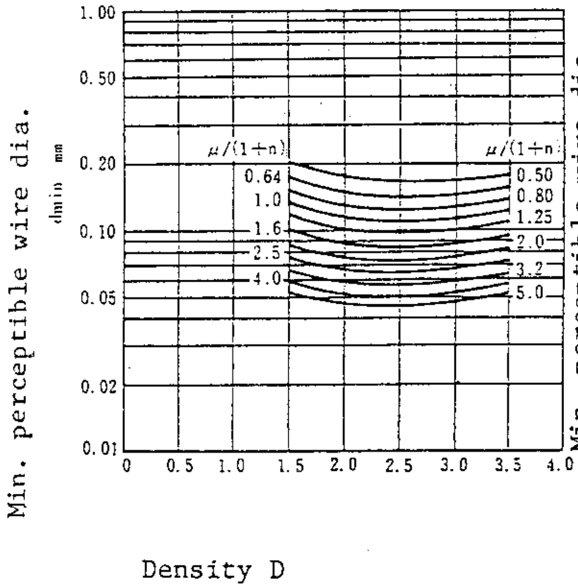


Fig. 6.5 Relationship between density and perceptible wire diameter

Source: X-rays
Film: KODAK M+PbO.03 F&B

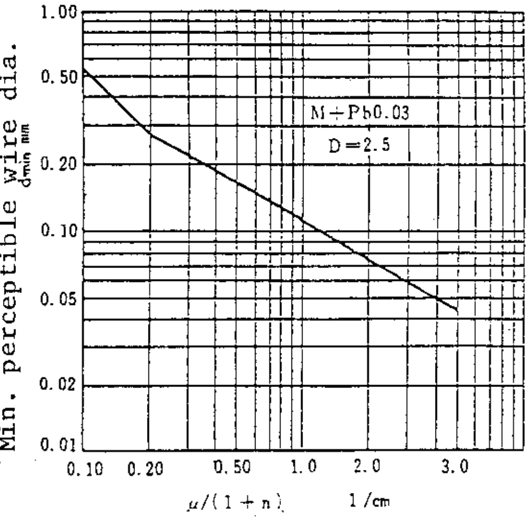


Fig. 6.6 Relationship between $\mu/(1+n)$ and d_{min} (wire type penetrameter)

Source: X-rays
Film: KODAK M+PbO.03 F&B
Density: D = 2.5

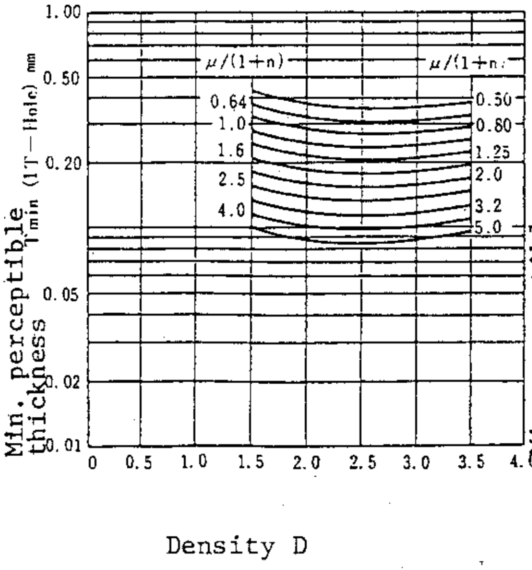


Fig. 6.7 Relationship between density and minimum perceptible thickness T_{min} (1T-Hole) of hole type penetrameter

Source: X-rays
Film: KODAK M+PbO.03 F&B

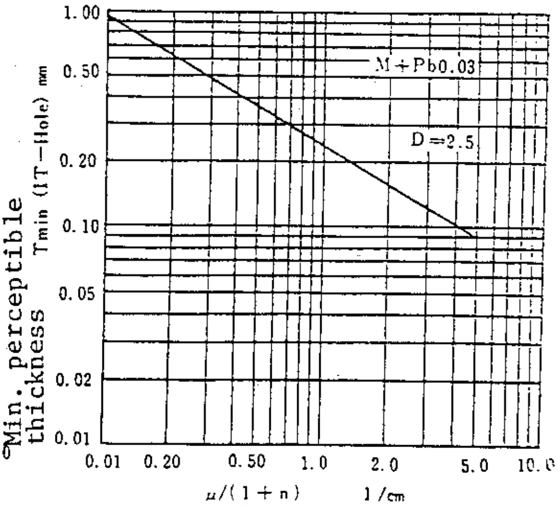


Fig. 6.8 Relationship between $\mu/(1+n)$ and T_{min} (hole type penetrameter, 1T-Hole)

Source: X-rays
Film: KODAK M+PbO.03 F&B
Density: D = 2.5

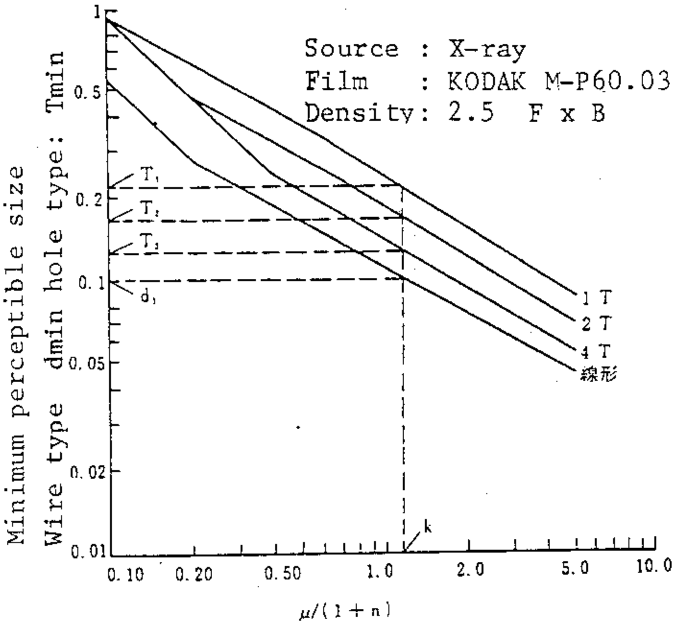


Fig. 6.9 Relationship between μ/(1 + n), minimum perceptible wire diameter d_{min} and minimum perceptible thickness T_{min}

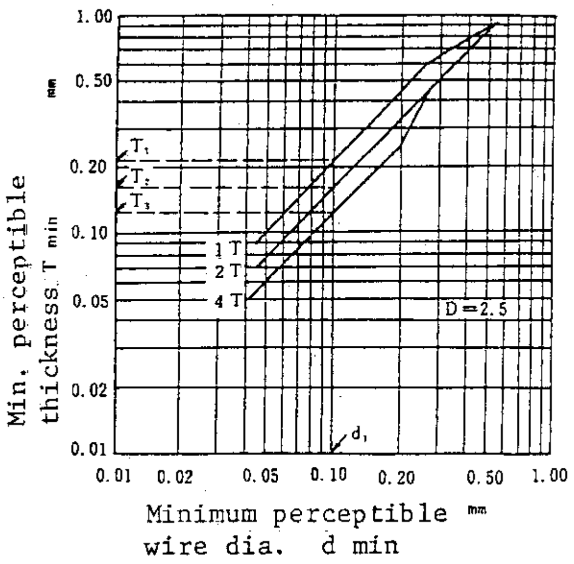


Fig. 6.10 Sensitivity conversion diagram

Source: X-rays
Film: KODAK M+PbO.03 F&B
Density: D = 2.5

Acknowledgement

It would be said that the work reported here has been supported by the Radiographic Testing educational subcommittee of the Japan Society for Nondestructive Inspection.

The author would express here special thanks to Professor T.Senda, chairman of subcommittee, of Faculty Engineering at Osaka University as well as to members of the Radiographic Testing educational subcommittee as follows; j.Sekita of Engineering Co., Ltd., k.Hirayama of Faculty of Engineering at Osaka University, I.Matsuyama of Tokyo Metropolitan Industrial Technology Center, Y.Maruyama of Nippon Kokan K.K and K.Yokoyama of Sakai Iron Works Co., Ltd..

References

1) T. Senda; Studies on Radiographic Contrast, Report of the Institute of Industrial Science University of Tokyo, Vol. 11. (6), 297, (1962)

2) Radiographic Testing Text B (1981)
The Japanese Society for Nondestructive Inspection

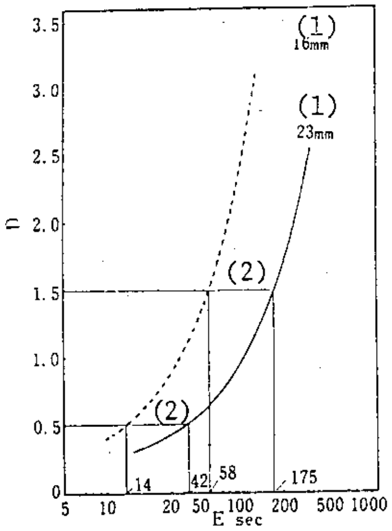
3) Radiographic Testing Procedure of Welds
The Japanese Society for Nondestructive Inspection

4) T. Senda, K. Hirayama, Study on X-ray Quality Meter,
The Japanese Society for Nondestructive Inspection,21-12 (1972),
p. 719-722

5) K. Ooka, Experiments on the Radiographic Contrast of Heat Resisting Materials, Journal of Nondestructive Inspection, Vol. 31. (5), 308-317 (1982)

Appendix A Characteristic Curves

Fig. A-1 shows the characteristic curves of X-ray films used for 16.0-mm and 23.0-mm thick test pieces, respectively. As is clear from the figure, the exposure for a density of 0.50 is 14 seconds on the broken line and 42 seconds on the solid line. Namely, if the test piece thickness is increased from 16.0 mm to 23.0 mm, it requires 3.0 times the exposure required for the former type of test piece to take a radiograph with a density of 0.50. Likewise, for a density of 1.50, the thicker test piece requires an exposure 3.0 times as much. Consequently, if the exposures for each point on the broken line are multiplied threefold and shifted in parallel sideways, the broken line overlaps the solid line. This indicates that the ratio between the exposure for a density of 0.50 and that for a density of 1.5, for example, is constant irrespective of the test piece thickness. Also, it is proved experimentally that in the practical exposure range, the exposure ratio is constant irrespective of the type of the X-ray unit, tube voltage (type of the line source), material of the test piece, and the distance between the focus and film.
From the characteristic curves for various X-ray films used in combination with the intensifying screen (shown in Fig. 3.3), it can be seen that the exposure time required to take a radiograph with a density of 1.50 is 58 seconds with #100+Pb0.03, and 150 seconds with #80+Pb0.03. In other words, when the type of X-ray film is changed from #100 to #80, taking a radiograph with a density of 1.50 requires 150/58 times the exposure required by the former type of X-ray film. When the sensitivity of #100+Pb0.03 is set at 1.00, the relative sensitivity of #80+Pb0.03 is 58/150 ≒ 0.39.



Film: #100
Intensifying screen: Pb 0.03 F&B
Development: Hirendol 20°C 5-min tank
X-ray unit: MACROTANK H
Tube voltage: 200 kVp
Tube current: 4 mA
Source-film distance: 600 mm
Test piece: Steel plate

(1) Test piece thickness
(2) Three times

Fig. A-1 Characteristic curves of X-ray films

Appendix B Method of preparing exposure chart when the amount of scattered X-rays is negligibly small

As shown by Fig. B-1, radiography is performed using a small diaphragm and with an absorber in intimate contact with the irradiation port, to make the amount of scattered X-rays negligibly small. Prior to radiography, absorbers differing in thickness (for example, 2, 4, 6, 8, 10, 14, 18, 22, 26 mm) should be provided and different tube voltages (for example, 120 and 140 kVp) be selected. Using absorbers of different thicknesses for each tube voltage, obtain characteristic curves for X-ray films by plotting the exposure (sec. or min.) on the abscissa and the density on the ordinate, as shown by Fig. B-2. Next, obtain characteristic curves by changing the tube voltage.
In preparing characteristic curves for the X-ray film, what is necessary is to obtain only an exposure that gives D = 1.50 if an exposure chart for D = 1.50 is needed. However, as the exposure charts for D = 1.0 to D = 3.5 can be obtained by knowing the characteristics up to the dotted line region, it is recommended to obtain characteristic curves covering the dotted-line regions.

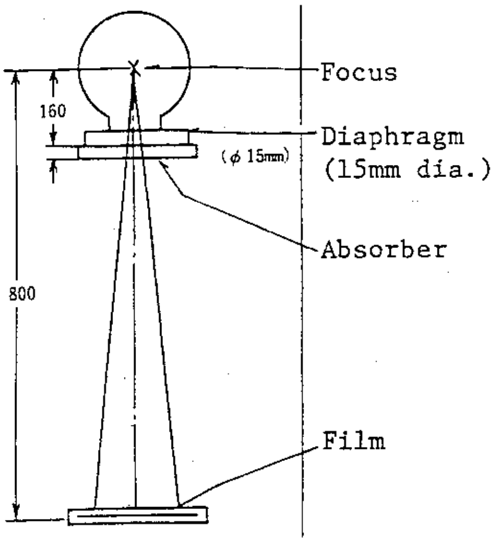


Fig. B-1 Radiographic arrangement

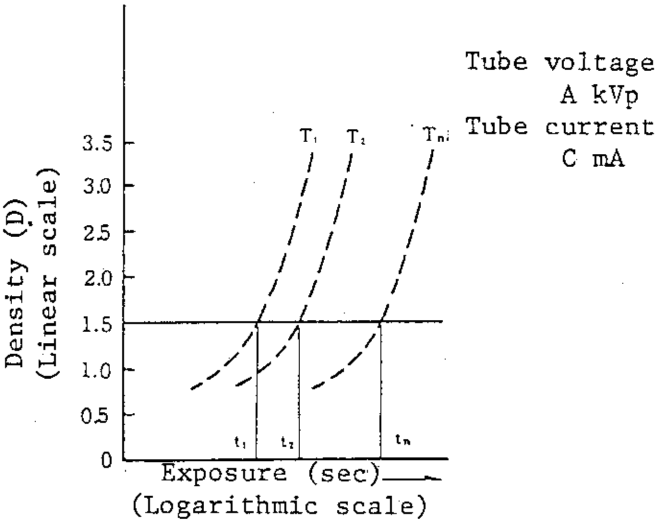


Fig. B-2 Characteristic curves for X-ray film

Now, let us obtain exposures e_1 and e_2 from the points where a horizontal straight line showing a constant density (in this case, D = 1.50) intersects the curves in Fig. B-2. Then an exposure chart for the absorber thickness and exposure can be obtained by plotting the points of the absorber thickness (mm) on the abscissa (linear scale) and the exposure (mA min) on the ordinate (logarithmic scale) to connect these points, as shown in Fig. B-3. By repeating the above procedure for different tube voltages, an exposure chart can be obtained where the amount of scattered X-rays is negligibly small, as shown by Fig. B-4.

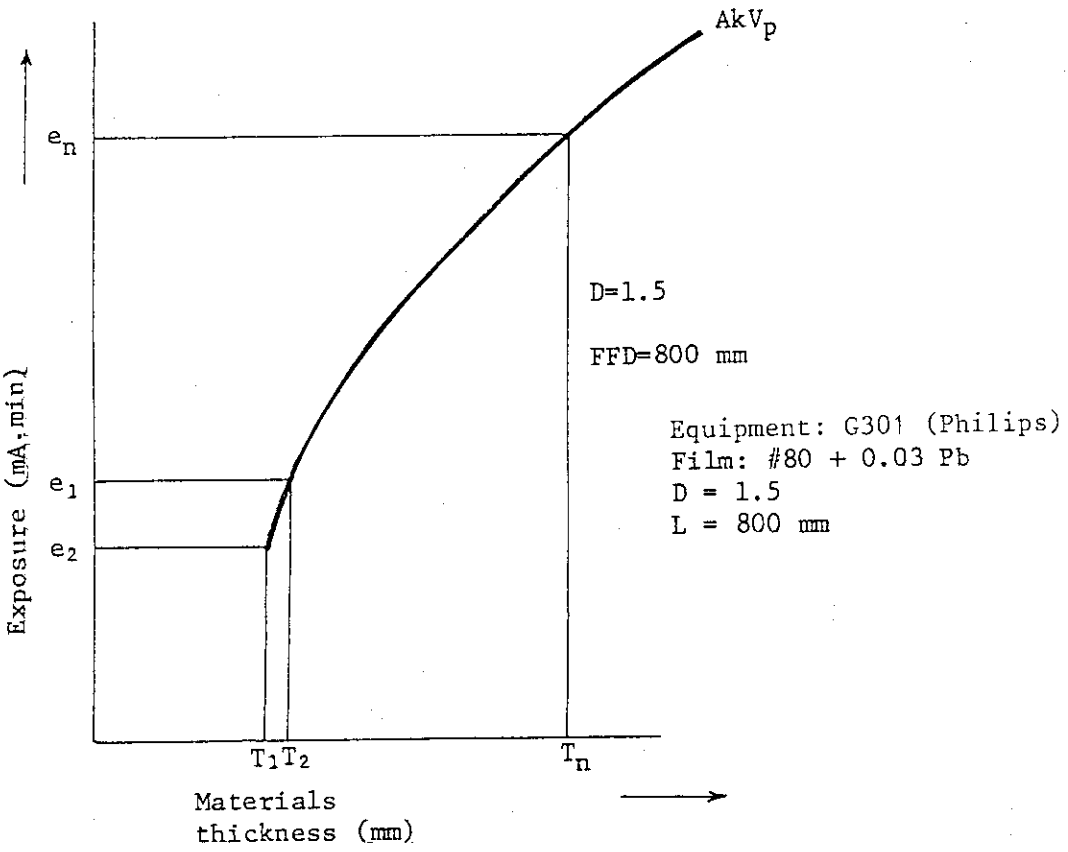


Fig. B-3 Typical exposure chart

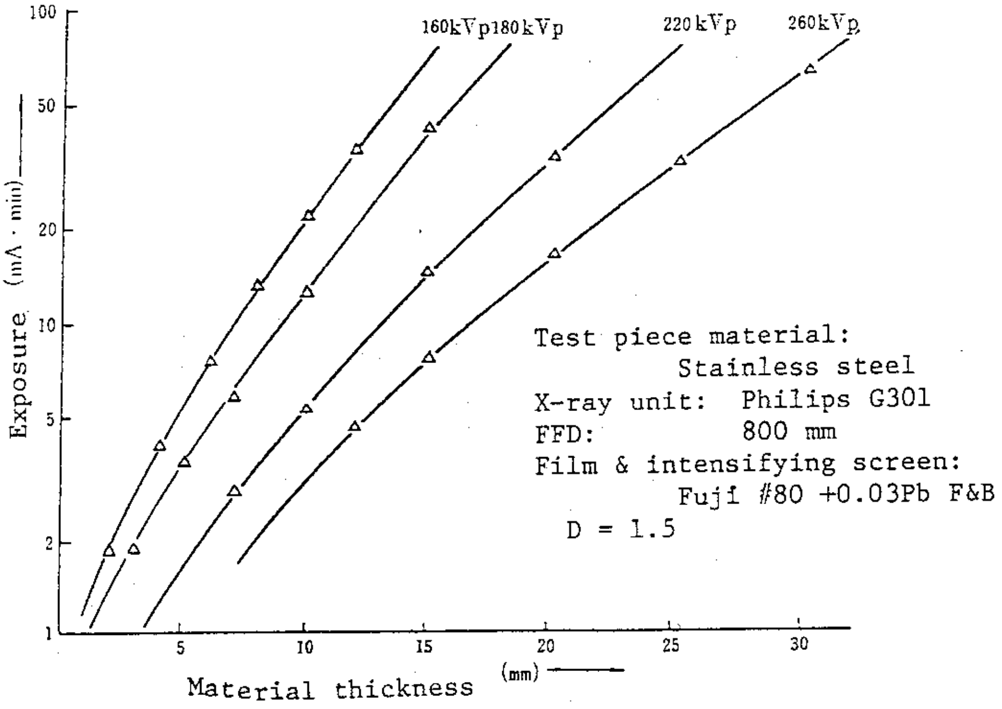


Fig. B-4 An example of exposure chart

Appendix C Method of Preparing Exposure Chart When There are Scattered X-Rays

When an X-ray film is exposed for t_1 min to X-rays of A kVp, C_1 mA at a distance of L_m after penetrating a test piece having thickness T_1, the X-ray dose is $I_1C_1t_1/L^2$(where I_1 is the dose rate of X-rays that have penetrated T_1). Given the sensitivity coefficient of the film for the quality of X-rays is k_1, the condition for the density of the X-ray film becoming D_0 is expressed by the following equation:

$$\frac{k_1I_1C_1t_1}{L^2} = k_0R_0 \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots \quad (2)$$

where R_0 is the dose for the density D_0 on the X-ray film dose characteristic curve, and k_0 is the sensitivity coefficient of the film for the quality of X-rays with which the dose characteristic curve of the film was obtained.

On the other hand, if there exist scattered X-rays of I_1' for test piece thickness T_1, equation (2) for obtaining the density D_0 can be represented by equation (3).

$$\frac{(k_1I_1 + k_1'I_1')\ C_1't_1'}{L^2} = k_0R_0 \quad \ldots\ldots\ldots \quad (3)$$

where k_1' is the sensitivity factor of X-ray film against the quality of scattered X-rays.

Therefore, the relationship between a case with a negligibly small amount of scattering X-rays and a case with scattering X-rays is represented by the following equation:

$$C_1't_1' = \frac{c_1t_1k_1I_1}{k_1L_1+k_1'L'} \quad \ldots\ldots\ldots\ldots\ldots\ldots \quad (4)$$

If we put $C_1t_1 = e_1$, $C_1't_1' = e_1'$ and $k_1'I_1'/k_1I_1 = n$, the above equation can be expressed as follows.

$$e_1' = \frac{e_1}{1 + n} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \quad (5)$$

Regarding the scattered direct radiation intensity ratio n, it has been verified by experiments and calculations that n can be known from the relationship shown in Fig. C-1 for different thickness T and that it is almost proportional to the varying thickness T of the absorber within the practical range.2), 3)

An exposure chart for a case of a negligibly small amount of scattered X-rays is shown by Fig. C-2. An exposure chart for a case of scattered X-rays which has been obtained from Fig. C-1 against Fig. C-2 is shown by Fig. C-3.

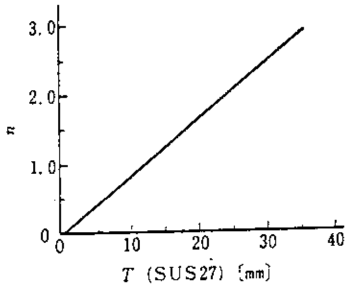


Fig. C-1 Measurement result of the scattered direct radiation intensity ratio obtained by taking the sensitivity factor of X-ray film into consideration. (X-ray unit Weltes 260 D, X-ray film RR, intensifying screen Pb 0.03 front pack, film-focus distance 60 cm, diaphragm 75 mm dia., radiation field 350 mm, cassette and test piece in intimate contact)

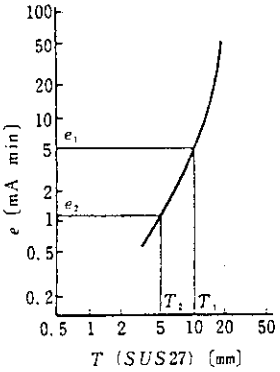


Fig. C-2 An exposure chart obtained by a new preparation method. (160 kVp, X-ray unit Weltes 260 D, X-ray film RR, intensifying screen Pb 0.03 front pack, Konidol X 20°C 5 min. (tank), film-focus distance 60 cm, D = 1.5)

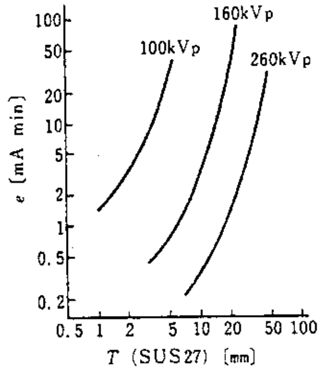


Fig. C-3 An exposure chart for a case where scattered X-rays are present. (X-ray unit Weltes 260 D, X-ray film RR, Intensifying screen Pb 0.03 front pack, Konidol X 20°C 5 min., film-focus distance 60 cm, D = 1.5)

Appendix D Method of Obtaining Absorption Coefficient and Scattered radiation to Direct Radiation Intensity Ratio

(1) Method of obtaining absorption coefficient using exposure chart 4)

Absorption coefficient μ_1 for material thickness T_1 can be obtained by using the exposure chart for a negligibly small amount of scattered X-rays (see Fig. B-4). In this case, T_2 is obtained from e_2 which is twice as large as exposure e_1 for T_1 by using the following equation, as shown by Fig. D-1.

$$T_2 - T_1 = \bar{h}_1 \quad \cdots\cdots\cdots\cdots\cdots\cdots \quad (6)$$

$$\bar{\mu}_1 = \frac{0.693}{\bar{h}_1} \quad \cdots\cdots\cdots\cdots\cdots\cdots \quad (7)$$

The relationship between the absorption coefficient and the test piece thickness which has been obtained from the exposure chart and equation (7), is shown in Fig. D-2.

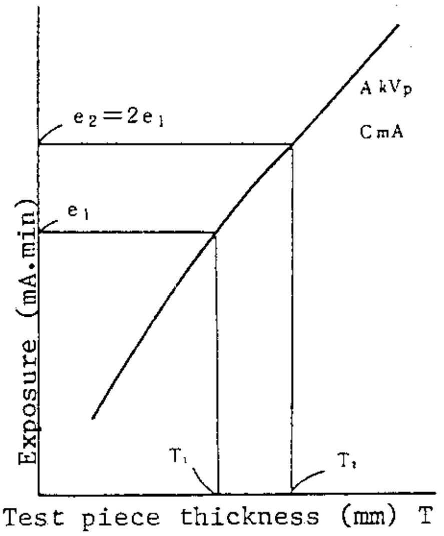


Fig. D-1 Exposure chart

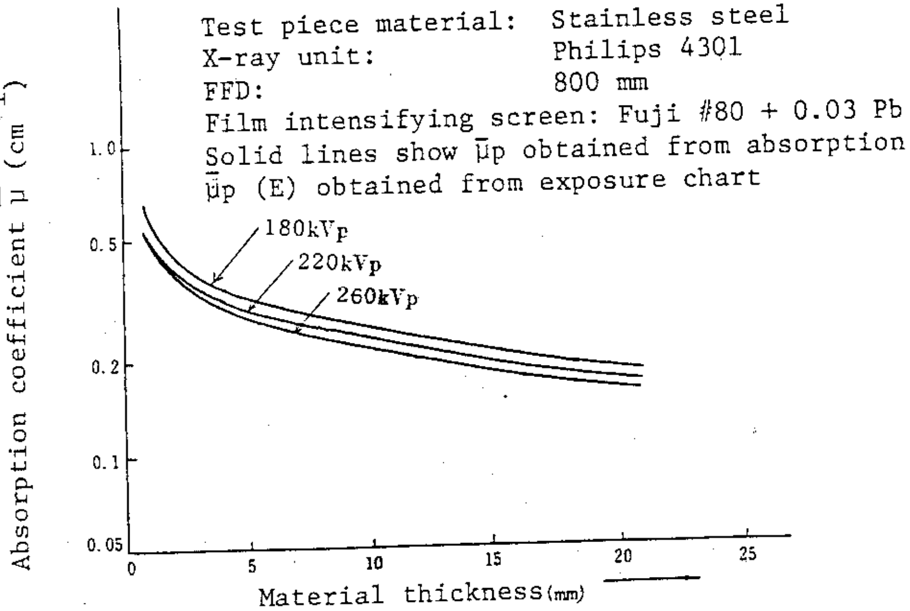


Fig. D-2 Relationship between material thickness and absorption coefficient

(2) Measurement of scattered direct radiation intensity ratio with X-ray film

(a) Measurement by characteristic curves

Fig. D-3 shows the ordinary radiographic arrangement used in conducting a radiographic test (exposure of a large radiation field). The density of a radiograph taken with the radiographic arrangements shown by Fig. B-1 is denoted by D_1 and that of a radiograph taken with the radiographic arrangement shown by Fig. D-4 is denoted by D_2, both under the same conditions. Then R_1 and R_2 against respective densities can be obtained from the X-ray dose characteristic curve shown by Fig. D-4. (R_1 and R_2 can be relative exposures.) The scattered direct radiation intensity ratio n can be obtained from R_1 and R_2 by using the following equation.

$$n = \frac{R_2}{R_1} - 1 \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots \quad (8)$$

Fig. D-5 shows a scattered direct radiation intensity ratio curve.

(b) Measurement by exposure chart

Radiographs are taken with the radiographic arrangements shown by Fig. B-1 and Fig. D-3, and then an exposure chart such as shown by Fig. D-6 is prepared. If the exposure for a narrow radiation field where the amount of scattered X-rays is negligibly small is denoted by e_1' and that for a wide radiation field by e_1, the scattered direct radiation intensity ratio n can be obtained from the following equation:

$$n = \frac{e_1'}{e_1} - 1 \quad \dots\dots\dots\dots\dots\dots\dots\dots \quad (9)$$

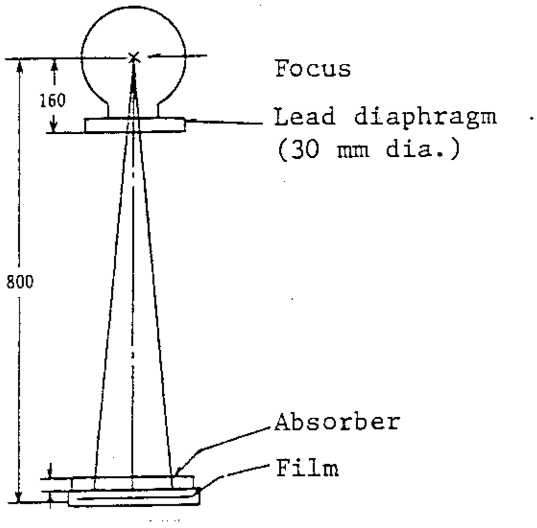


Fig. D-3 Radiographic arrangement

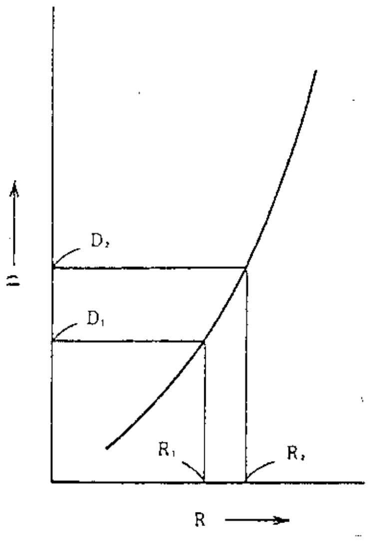


Fig. D-4 X-ray film dose characteristic curve

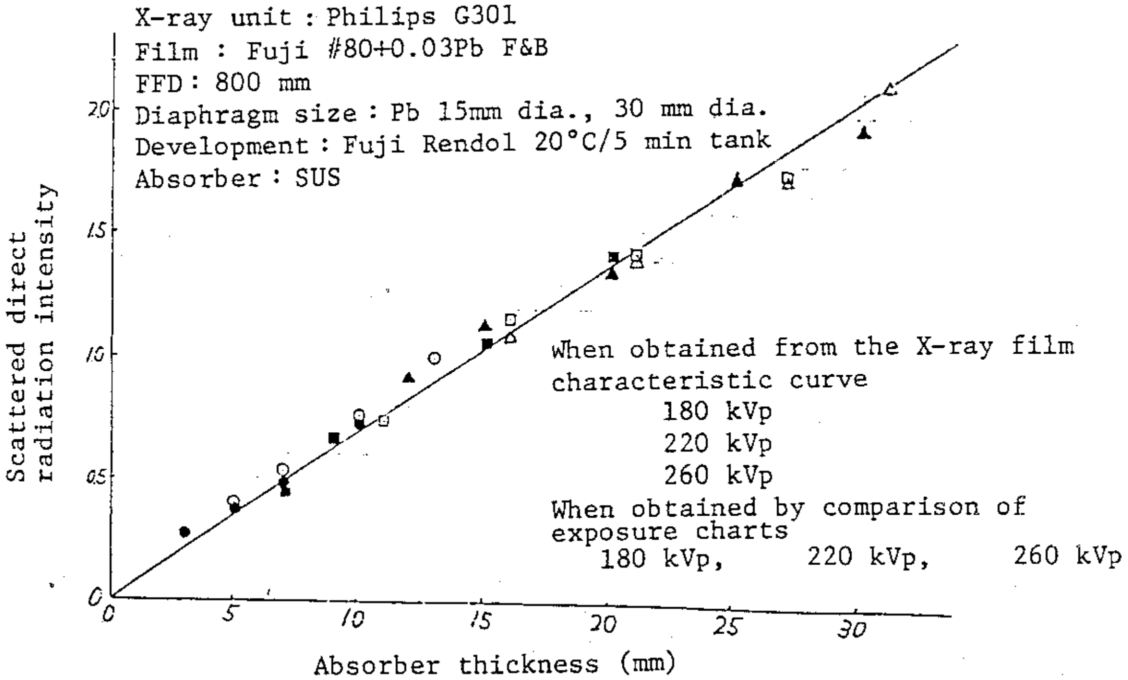


Fig. D-5 Relation between scattered direct radiation intensity and absorber thickness

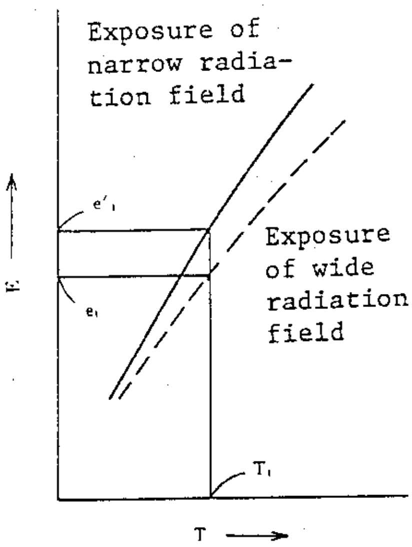


Fig. D-6 Exposure chart