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CONSTANT EXPOSURE TECHNIQUE IN INDUSTRIAL RADIOGRAPHY

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August 1983

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CONSTANT EXPOSURE TECHNIQUE IN INDUSTRIAL RADIOGRAPHY

by

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1. INTRODUCTION

The advantages of a constant exposure technique were already previously explained and advertised for use in industrial radiography [1,2]. There two methods of making industrial radiographs were compared. One consisted of making radiographs at constant kilovoltage but at a variable exposure (mAmin) and the other of using variable kilovoltage at constant exposure (mAmin). The advantages of the latter method, which permits the use of faster film-screen combinations, were discussed. The comparison was made from the point of view of the quality of the radiographic image, assessed by the use of artificial and natural defects.

This paper describes the results of an investigation using the ISO wire IQI's and ASTM penetrameters for the assessment of radiographic quality. Aluminium and steel plates were subject to both exposure techniques. X-ray film of different speed as well as radiographic paper were used throughout the investigation.

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* Work performed under contract with Risø National Laboratory.

2. PRINCIPLE OF THE CONSTANT EXPOSURE TECHNIQUE

In [2] a densitometric scan was given (see fig. 1) through

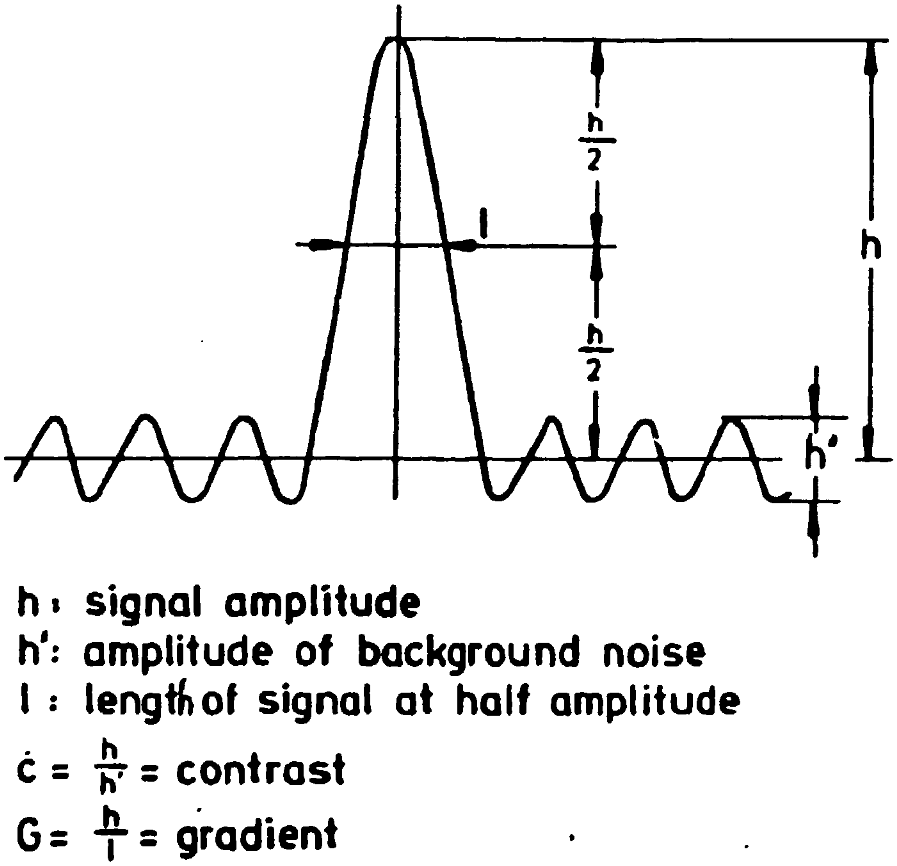

Fig. 1. Characteristics of a radiographic signal [2]

a radiogram representing a hole in a radiographed plate. It's clear that the film density signal from the hole is higher than the background density of the rest of the radiogram. The background density indicates noise fluctuations.

The quality of information obtained from a radiograph can be defined as the quotient h/h' (see fig. 1), i.e. the relation between the amplitude of the signal and the noise.

Fig. 2 shows the results obtained with both techniques: the constant kilovoltage technique and the constant exposure technique. Here a fast radiographic system (e.g. fast X-ray film) was compared with a slow one.

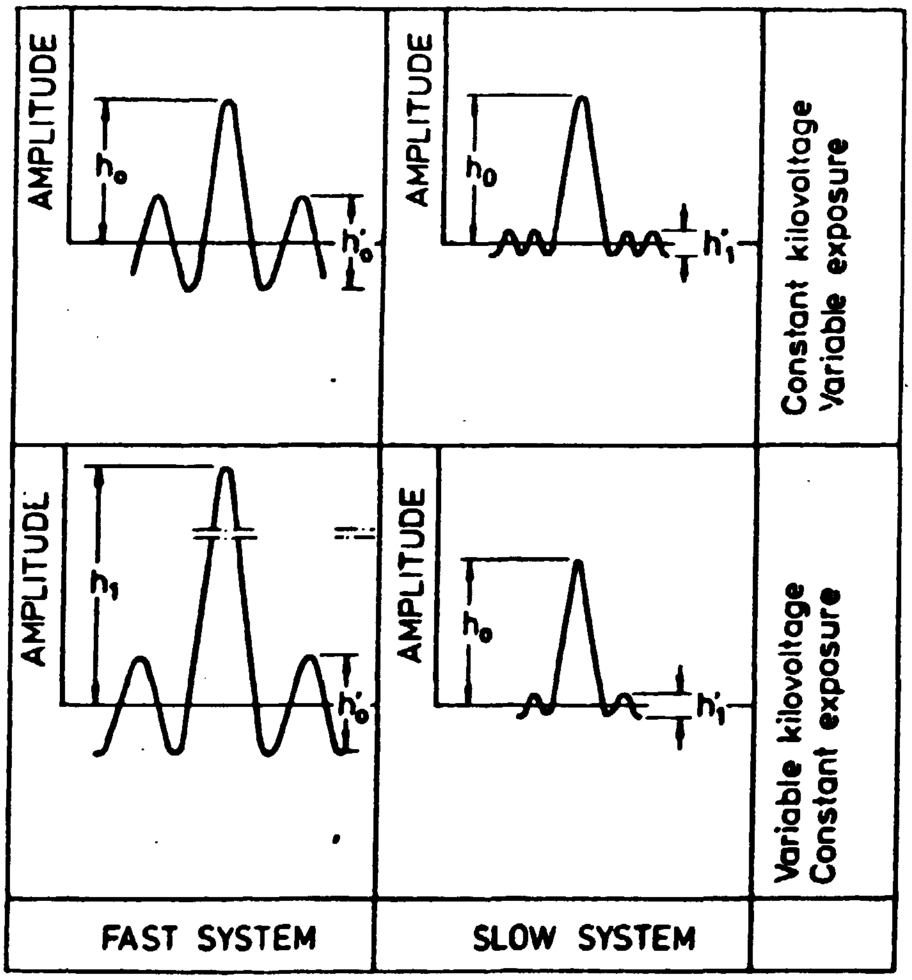

Fig. 2. Comparison between the constant kilovoltage and constant exposure techniques [2]

For the constant kilovoltage technique the signal from the defect has a constant amplitude, but the amplitude of the background noise depends on the speed of the system (it is lower for the slower system). For the constant kilovoltage technique the quality of information obtained decreases with the increasing speed of the system.

If, on the other hand, one will maintain the same exposure for the faster system the kilovoltage can be lowered, because a lower dosage is necessary for the faster system. The lowering of the kilovoltage increases the amplitude of the signal. Thus, the ratio of the signal to background noise can be relatively improved for the faster system.

3. CHOICE OF EXPOSURE FACTORS

The main exposure factors: kilovoltage, milliamperage, exposure time, and focus to film distance (FFD) depend on the object to be radiographed (its material and thickness), on the X-ray machine to be used (maximum rating, size of the focus of the X-ray tube) and on the film (or paper) and screen combination.

If one has a given X-ray machine with a X-ray tube of a given size a minimum FFD can be calculated for the given thickness of the object to be radiographed.

X-ray tubes always produce a certain geometric unsharpness (U_g) of the radiographic image (see fig. 3) because of the finite dimensions of the focus of an X-ray tube (Φ).

This can be calculated as:

$$U_g = \frac{\Phi \cdot a}{F-a} \quad \dots\dots\dots\dots\dots\dots\dots \quad (1)$$

where: Φ - the size of the focus,
a - the defect-to-film distance
F - the FFD.

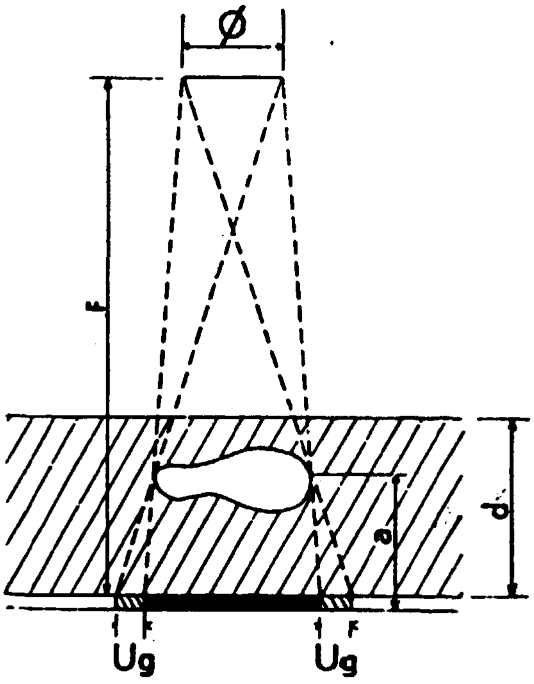

Fig. 3. Geometrie unsharpness of a radiographie image

The maximum value of U_g, for the defect located at a maximum distance from the film (a=d) can be calculated from the formula:

$$U_{g_{max}} = \frac{\Phi \cdot d}{F-d} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \quad (2)$$

where d is the thickness of the object.

Besides the geometric unsharpness the inherent unsharpness (U_i) of the film (or paper) influences the quality of the radiographic image. This inherent unsharpness depends on the film itself and radiation energy. According to [3] the inherent unsharpness of Agfa-Gevaert Structurix X-ray film exposed to X-rays (without screen) at less than 100 kV is U_i = 0.1 mm, and above 100 kV (with lead screen) U_i = 0.2 mm.

In general it is unnecessary to strive for a geometric unsharpness better than the inherent unsharpness and therefore:

$$U_g \leq U_i. \ldots\ldots\ldots\ldots\ldots\ldots\ldots \quad (3)$$

With this in mind one can calculate the minimum FFD as follows:

$$FFD_{min} = \frac{\Phi \cdot d}{U_g} + d \quad \ldots\ldots\ldots \quad (4)$$

This minimum FFD can only rarely be used in practice. For relatively small focal sizes and object thicknesses this FFD is to small. The following illustrates it well.

In the present investigation an aluminium plate, 30 mm thick, was exposed with an X-ray machine with an X-ray tube focal spot of 2.3 mm. From equation (4) the minimum FFD can be calculated as:

$$FFD_{min} = \frac{2.3 \times 30}{0.2} + 30 = 375 \text{ mm}$$

A steel plate, 10 mm thick, was investigated with an X-ray machine with a 3 mm focal spot. Here:

$$FFD_{min} = \frac{3 \times 10}{0.2} + 10 = 160 \text{ mm}$$

In both cases films with lead screens were used and the kilovoltages exceeded 100 kV therefore, it was assumed that $U_g = U_i = 0.2$ mm.

As can be seen in both instances the minimum FFD was very short. Such a short FFD cannot be used for two reasons: The irradiated area is too small and the range of radiation intensity an it is too large.

The X-ray beam is irradiated from the X-ray tube head at a certain angle, which can be different along the tube axis and perpendicular to it. With the X-ray machines used throughout this investigation the X-ray beam cone angles were the following:

A 180 - along tube axis - 60°; perpendicular - 40°
A 300 - along tube axis - 57°; perpendicular - 40°

In order to cover irradiation fields of 10x48 or 30x40 cm with those machines the following minimum FFD are necessary:

A 180: for 10 x 48 cm - FFD = 45 cm
A 180: for 30 x 40 cm - FFD = 42 cm
A 300: for 10 x 48 cm - FFD = 42 cm
A 300: for 30 x 40 cm - FFD = 42 cm

The next factor which must be taken into account in choosing the FFD is the decrease of radiation intensity reaching the film under the central point of the radiographed object and its point laying furthest from the center. This decrease of radiation intensity is due to two factors: the larger FFD at points far from the center, which decreases the radiation intensity according to the inverse square law, and the decrease of intensity due to the higher attenuation of radiation that has to pass through a thicker layer of material.

The first decrease of radiation intensity is easy to calculate. E.g. for a 60° cone of radiation the FFD at the outskirts of the cone increases by 15.5% in relation to the center of the cone, which gives a reduction of radiation intensity to 75% of that in the center.

The thickness of material which must be penetrated by the radiation on the outskirts of a 60° radiation cone increases by 15.5%, which will attenuate radiation more that at the center of the radiation cone.

For a 40° radiation cone the radiation intensity decreases to 88% and material thickness increases by 6.5%.

Both factors will reduce film densities at the outskirts of the radiation cone. This reduction of film density must be kept within some limits prescribed by the radiographic standards,however. This reduction of density depends on the attenuation coefficient of the radiographed material and on the characteristic curve of the X-ray film. It is almost impossible to calculate the first factor whereas the second one can be deducted from the appropriate characteristic curve.

As one example it can be quoted that the reduction of radiation intensity to 75% for a Agfa-Gevaert Structurix D7 film will cause the decrease of film density, e.g. from 2.5 to 1.95. This could exceed the tolerance limits.

For most of the portable, selfrectified X-ray machines the maximum milliamperage very seldom exceeds 5 mA They are usually operated at this rating.

For practical reasons the exposure time should not be too long. Most of the exposure charts are made for maximum exposures of 100 mAmin, which with 5 mA means a maximum exposure time og 20 min.

The last exposure factor, the kilovoltage, is chosen so as to give the required film density at maximum permissible exposure and minimum permissible FFD. This can be done with the help of exposure charts for the material thickness under radiography.

During this investigation two X-ray machines were used: Andrex 180 kV for aluminium and Andrex 300 kV for steel 30 mm Al was investigated at a constant exposure of 25 mAmin for different kilovoltages and at constant 170 kV for different exposures.

10 mm of Fe was investigated at 100 mAmin for different kilovoltages and at 215 kV for different exposures. For both X-ray machines 5 mA was used. In most instances the FFD was 1 m. However, for very short exposures lower milliamperages used and the FFD increased to obtain the desired mAmin in a practicable exposure time.

4. FILM, PAPER, AND INTENSIFYING SCREENS

During the investigation different X-ray films, radiographic paper and intensifying screens were used. They differed greatly in speed, contrast, and grain size.

The following X-ray films were used:

- Kodak Industrex D,C,A,M and DR (all double coated) as well as SR (single coated). They were all used with lead intensifying screens (0.05 + 0.10 mm thick).
- Agfa-Gevaert Structurix RCF with fluorometallic intensifying screens.

Radiographic papers used were:

- Kodak Industrex Instant 600 and 620 and Rapid 700 exposed with fluorescent F1 and F2 intensifying screens.
- Agfa - Gevaert Structurix IC with Structurix IC Type II fluorescent and Structurix RCF fluoremetallic intensifying screens.

All radiographic papers used with fluorescent intensifying screens were exposed through a 0.05 mm lead filter, as it was previously found [4,5] that it improves the image quality by cutting off scattered radiation.

5. FILM AND PAPER PROCESSING

All the Kodak X-ray films were normally developed in Kodak DX-developer (4 min, 20°C) and fixed in Kodak FX 40 fixer (10 min).

Although Agfa-Gevaert recommends that RCF film be developed manually in G 127 developer at 35° C for 45 s, the RCF film was processed in the same way as all other X-ray films. The reason was that it was technically impractical to heat a 60 l developing and fixing baths to 35°C and keep this temperature constant.

Therefore, while assessing the results obtained with the RCF film one must keep these processing conditions in mind. When processed according to the recommendations of the manufacturer, the RCF will probably give better results. This will be checked during the next investigation.

The Kodak 600 and 620 papers were processed in the Kodak Industrex Instant Processor Model P-1 (described in 4), whereas the Kodak 700 paper was manually processed as the X-ray film, but the developing time was 45 s (as recommended by the manufacturer).

The Agfa-Gevaert Structurix IC paper was processed in Agfa-Gevaert IC 50 processor (described in [4]).

6. EXPOSURE TECHNIQUE

Throughout the investigation a 30 mm aluminium and 10 mm steel plate were used. The first was exposed with an Andrex 180 kV self-rectified machine (2.3 mm focus) and the other with a similar Andrex 300 kV machine (3 mm focus).

The standard FFD was 1 m. For very low exposures (mAmin) the FFd had to be increased to reach a practicable exposure time.

A 5 mA current was used as standard. In some instances, for very low exposures a lower current was used.

The exposure time was chosen so as to reach a film density of $D_f = 2.5$ and paper density of $D_p = 1.0$.

First the Al plate was exposed at constant exposure of 25 mAmin and the kilovoltage was chosen so as to reach $D_f = 2.5$ and $D_p = 1.0$.

The Fe plate was exposed in the same way, but at a constant exposure of 100 mAmin.

Thereafter, the Al plate was exposed at a constant kilovoltage of 170 kV, and exposures were chosen so as to reach $D_f = 2.5$ and $D_p = 1.0$. For the Fe plate the constant kilovoltage was 215 kV.

7. IMAGE QUALITY INDICATORS

Two types of image quality indicators were used throughout the investigation. The first were the ISO wire IQI's[6,7] and the others the ASTM penetrameters [8].

Whereas, it is possible to use one set of the ISO wire IQI's for all thicknesses of radiographied material, it is necessary to have a separate set of ASTM penetrameters for each thickness.

To have penetrameters corresponding to 1,2 and 4% of the thickness of the radiographed object, penetrameters in Al and Fe were fabricated with the following thicknesses: 0.1, 0.2, 0.3, 0.4, 0.6, 0.8 and 1.2 mm.

In fig. 4 all the ISO wire IQI's and ASTM penetrameters for Al and Fe, used throughout this investigation, are shown.

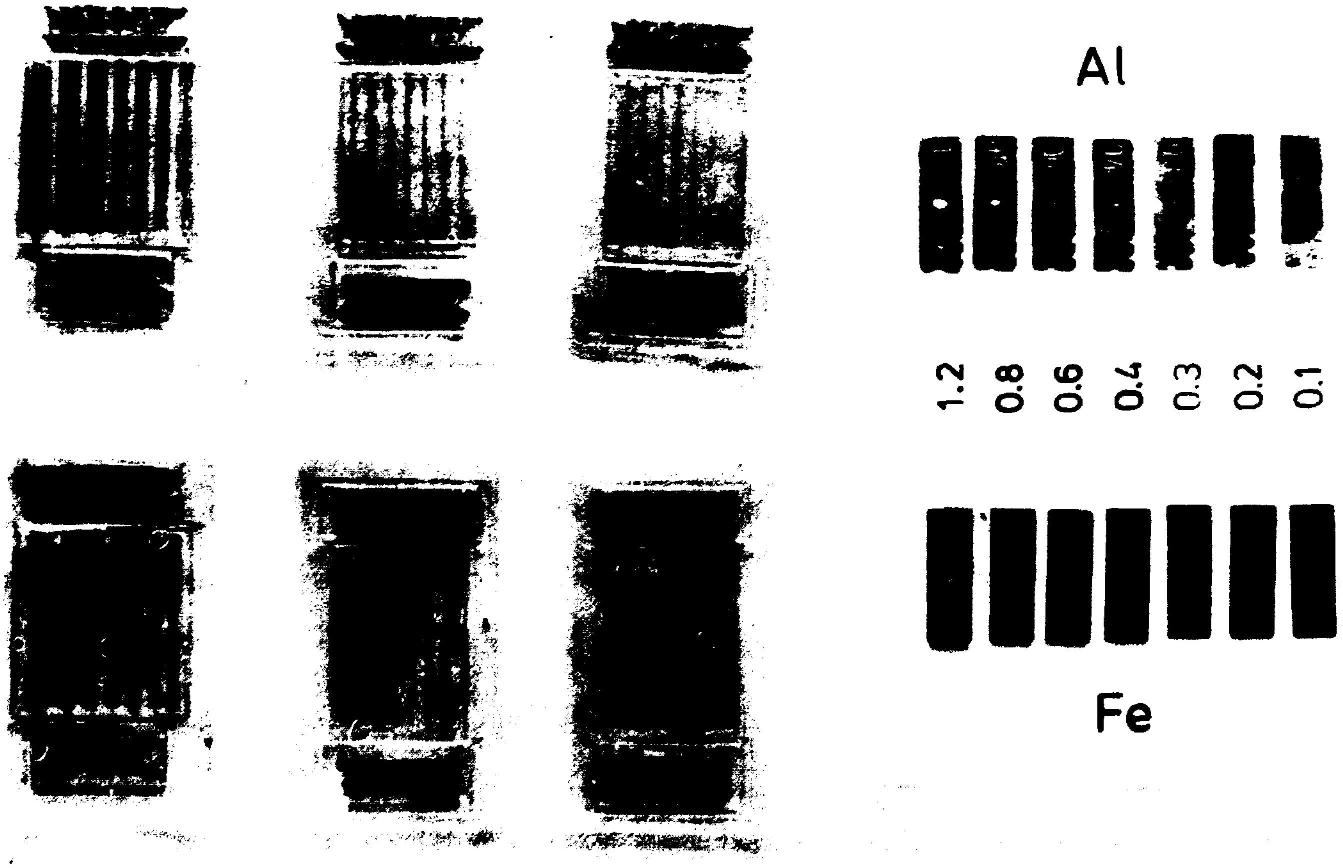

Fig. 4. ISO wire IQI's and ASTM penetrameters for Al and Fe

During the exposure one wire IQI and three penetrameters were always placed on the radiographed plate. Fig. 5 shows this arrangement for the 30 mm Al plate, whereas Fig. 6 shows the same for the 10 mm Fe plate.

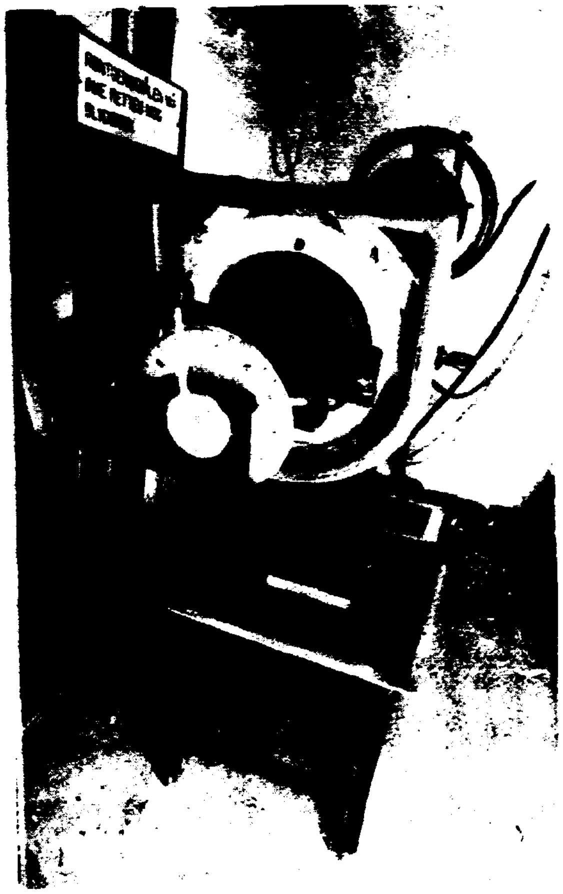

Fig. 5. Exposure of the 30 mm Al plate

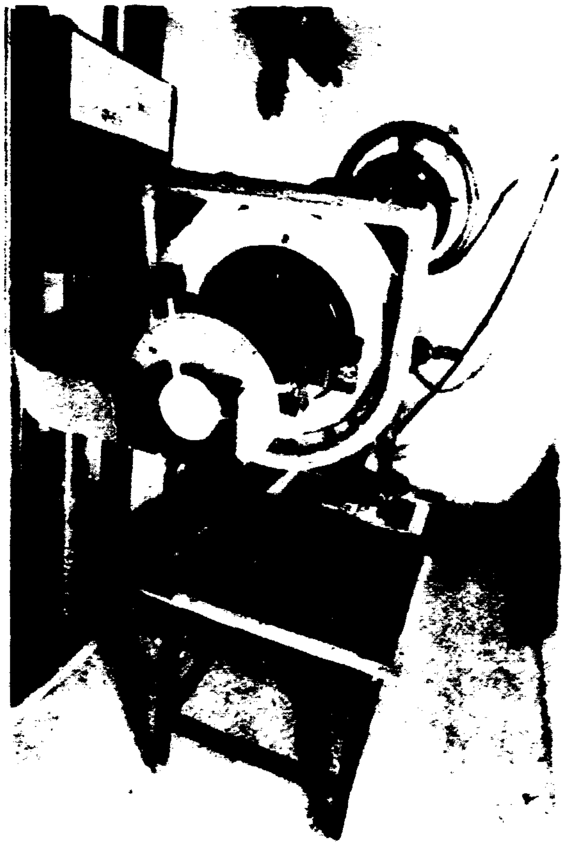

Fig. 6. Exposure of the 10 mm Fe plate

8. RADIOGRAPHIC IMAGE QUALITY

A direct comparison was made of radiographic image quality obtained by the use of the ISO wire IQI's and the ASTM penetrameters for various brands of X-ray film and radiographic paper. The results are presented in the form of diagrams as in [9] and [10] for all the X-ray film and paper described in 4 above. Fig. 6 gives the results for 30 mm of Al whereas in fig. 7 the results are given for 10 mm of Fe.

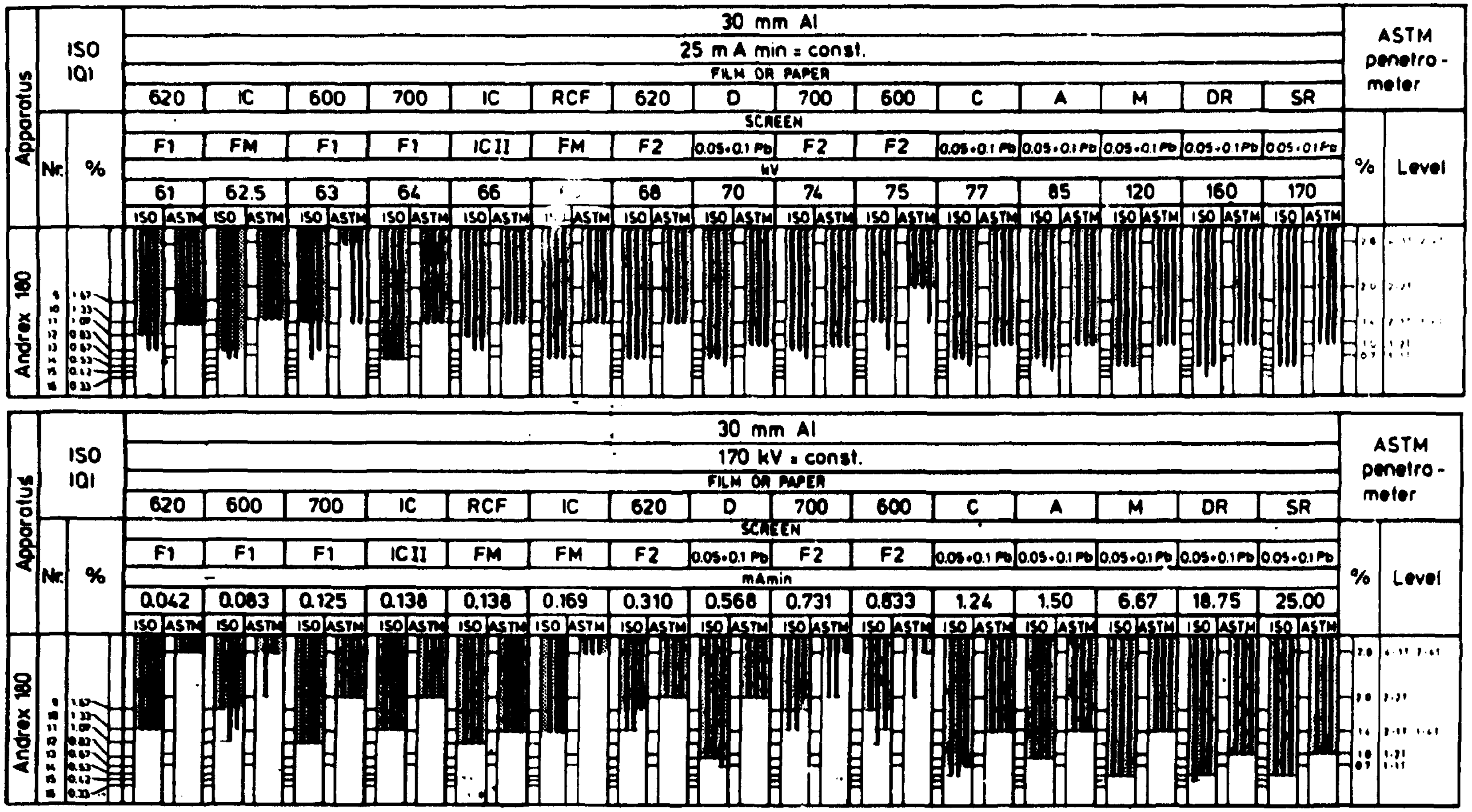

Fig. 7. ISO wire IQI and ASTM penetrameter sensitivities for 30 mm Al

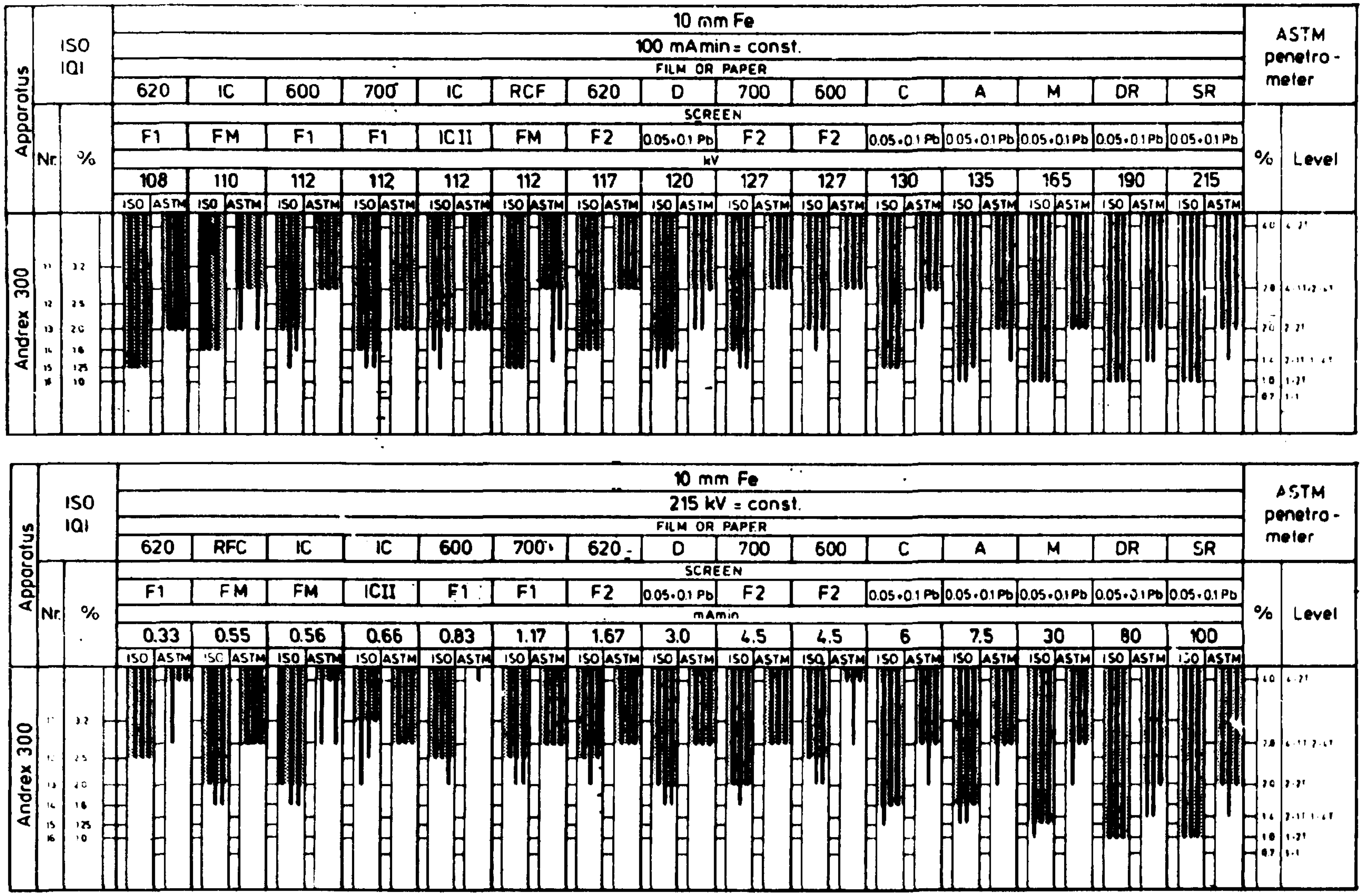

Fig. 8. ISO wire IQI and ASTM penetrameter sensitivities for 10 mm Fe

In the above diagrams the results of the assessments of three different persons were recorded. Only if all of the three had seen the same IQI wire or the penetrameter hole was this accepted for further comparison. In fig. 7 and 8 the dotted area corresponds to those three unanimous readings, whereas three lines give the three individual readings.

9. CONSTANT EXPOSURE VS. CONSTANT KILOVOLTAGE

If one wishes to compare the performance of the various film/paper-screen combinations from the point of view of their relative speed this can be done in the way shown on fig. 9 and 10.

These kilovoltages necessary to reach $D_f = 2.5$ and $D_p = 1.0$ are listed for a constant exposure (in mAmin) as well as exposures (in mAmin) necessary to reach the same film/paper densities for a constant kilovoltage.

The slowest X-ray film (single - coated Kodak Industrex SR, exposed with 0.05 + 0.10 mm Pb screens) was taken as reference. For a maximum exposure of 25 mAmin for Al and 100 mAmin for Fe, 170 or 215 kV were necessary to reach the density of $D_f = 2.5$ for the SR film. Thereafter for this exposure other film/paper-screen combinations were exposed at lower kilovoltages to reach the desired densities. Finally at constant kilovoltages mentioned before for the SR film the film/paper-screen combinations were exposed at mAmin necessary to give lthe desired densities.

The following relative speeds can be calculated from fig. 7 to 10.

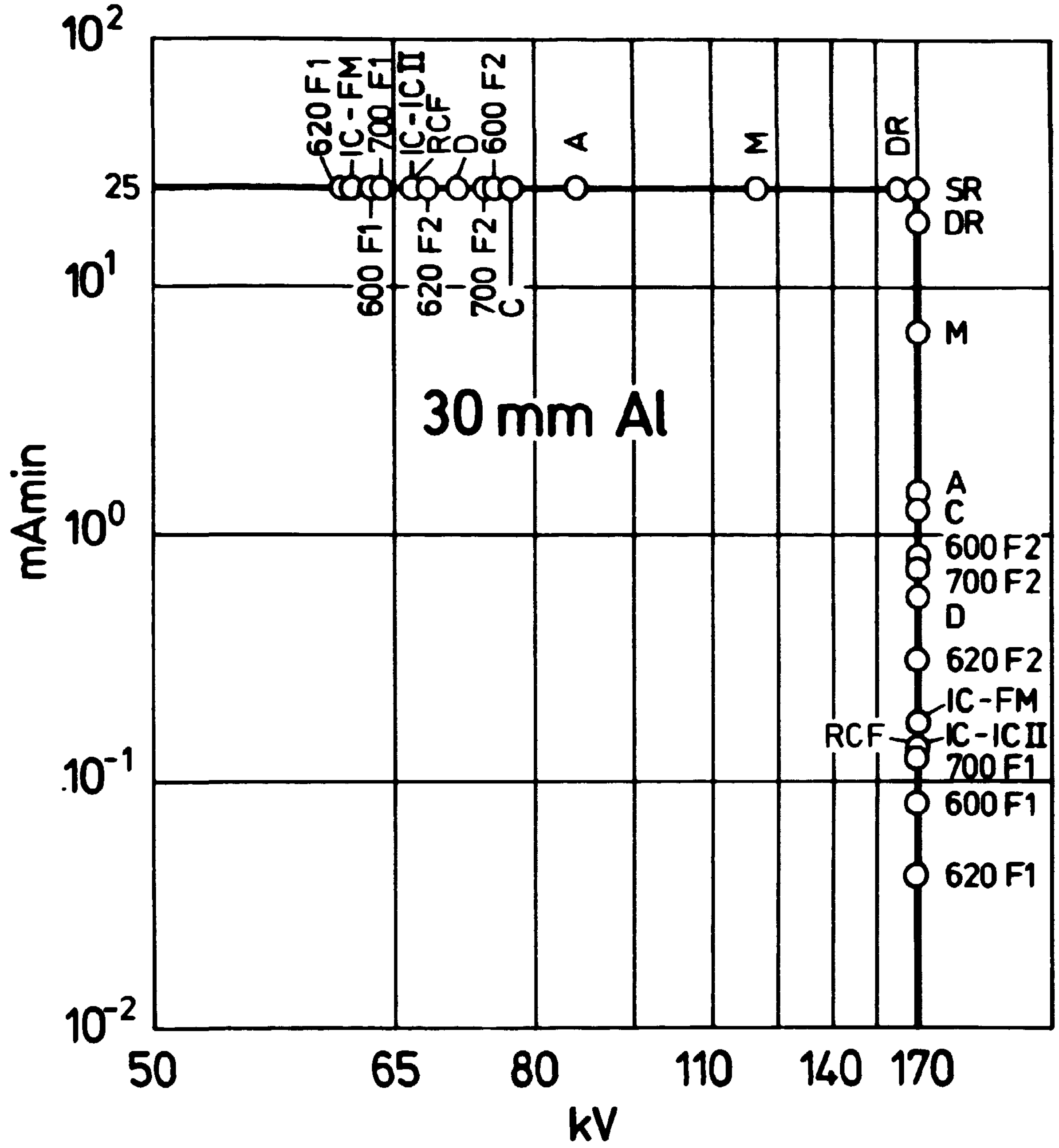

Fig. 9. Comparison of different film/paper-screen combinations for 30 mm Al at constant exposure and kilovoltage

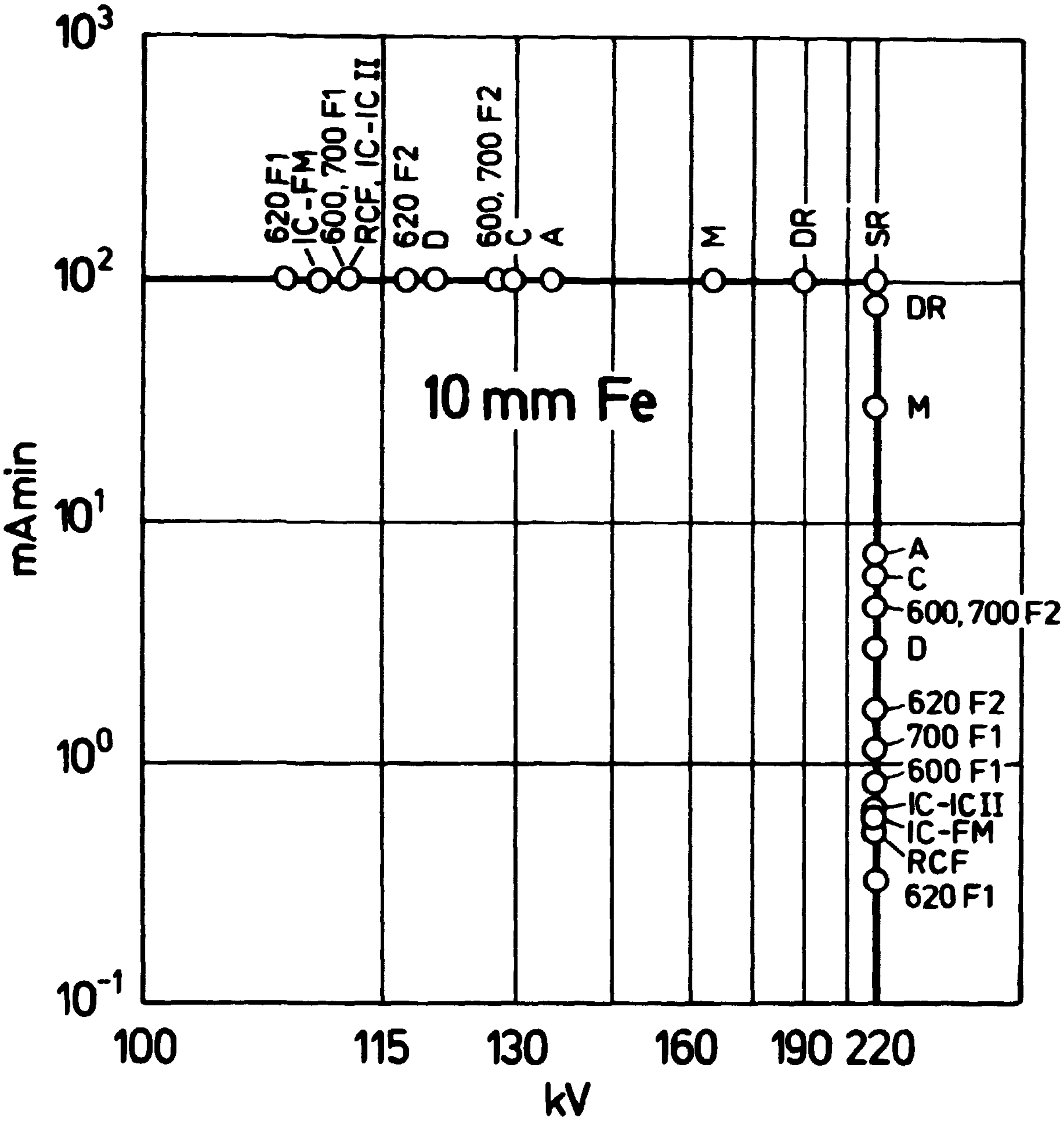

Fig. 10. Comparison of different film/paper-screen combinations for Fe at constant exposure and kilovoltage.

Table 1. Relative speed of different film/paper-screen combinations for 30 mm Al exposed at 170 kV

Film or paper	Screen	Relative speed
SR	0.05 + 0.10 mm Pb	1.00
DR	0.05 + 0.10 mm Pb	1.33
M	0.05 + 0.10 mm Pb	3.75
A	0.05 + 0.10 mm Pb	16.67
C	0.05 + 0.10 mm Pb	20.16
600	F2	30.01
700	F2	34.20
D	0.05 + 0.10 mm Pb	44.01
620	F2	80.65
1C	FM	147.93
RCF	FM	181.16
IC	ICII	181.16
700	F1	200.00
600	F1	301.20
620	F1	595.24

Table 2. Relative speed of different film/paper-screen combinations for 10 mm Fe exposed at 215 kV

Film or paper	Screen	Relative speed
SR	0.05 + 0.10 mm Pb	1 00
DR	0.05 + 0.10 mm Pb	1 25
M	0.05 + 0.10 mm Pb	3 33
A	0.05 + 0.10 mm Pb	13 33
C	0.05 + 0.10 mm Pb	16 67
600	F2	22 22
700	F2	22 22
D	0.05 + 0.10 mm Pb	33 33
620	F2	59 88
700	F1	85 47
600	F1	120 48
IC	ICII	151 52
IC	FM	178 57
RCF	FM	181 82
620	F1	303 03

The relative speed of the radiographie paper itself is given in Tables 3 and 4.

Table 3. Relative speed of different paper-screen combinations for 30 mm Al exposed at 170 kV

Paper	Screen	Relative speed	
600	F2	1.00	-
700	F2	1.14	-
620	F2	2.69	-
IC	FM	4.93	1.00
IC	ICII	6.04	1.22
700	F1	6.66	1.35
600	F1	10.04	2.04
620	F1	19.83	4.02

Table 4. Relative speed of different paper-screen combinations for 10 mm Fe exposed at 215 kV

Paper	Screen	Relative speed	
600	F2	1.00	-
700	F2	1.00	-
620	F2	2.69	-
700	F1	3.85	1.00
600	F1	5.42	1.41
IC	ICII	6.82	1.77
IC	FM	8.04	2.09
620	F1	13.64	3.55

From figs. 7 to 10 the possible decrease in kilovoltage can also be calculated when using the constant exposure technique. This percent decrease of kilovoltage is shown in Tables 5 and 6 for a constant exposure of 25 mAmin for 30 mm Al and 100 mAmin for 10 mm Fe. These 170 kV for Al and 215 kV for Fe are taken as 100%.

Table 5. Per cent decrease of kilovoltage for different film / paper-screen combinations for 30 mm Al exposed at 25 mAmin

Film or paper	Screen	Per cent decrease in kilovoltage
SR	0.05 + 0.10 mm Pb	100
DR	0.05 + 0.10 mm Pb	94,1
M	0.05 + 0.10 mm Pb	70,6
A	0.05 + 0.10 mm Pb	50,0
C	0.05 + 0.10 mm Pb	45,3
600	F2	44,1
700	F2	43,5
D	0.05 + 0.10 mm Pb	41,2
620	F2	40,0
RCF	FM	38,8
IC	ICII	38,8
700	F1	37,6
600	F1	37,1
IC	FM	36,8
620	F1	35,9

Table 6. Per cent decrease of kilovoltage for different film / paper-screen combinations for 10 mm Fe exposed at 100 mAmin

Film or paper	Screen	Per cent decrease in kilovoltage
SR	0.05 + 0.10 mm Pb	100
DR	0.05 + 0.10 mm Pb	88.4
M	0.05 + 0.10 mm Pb	76.7
A	0.05 + 0.10 mm Pb	62.8
C	0.05 + 0.10 mm Pb	60.5
600	F2	59.1
700	F2	59.1
D	0.05 + 0.10 mm Pb	55.8
620	F2	54.4
RCF	FM	52.1
IC	ICII	52.1
700	F1	52.1
600	F1	52.1
IC	FM	51.2
620	F1	50.2

10. CONCLUSIONS

While comparing the constant exposure and constant kilovoltage methods, the following conclusions can be drawn:

10.1 Relative speed. The relative speed of a certain film/ paper-screen ,combination can be determined only, when the quality of radiation is constant and different amounts of radiation of this constant quality reach the detector. This is the case for the constant kilovoltage technique.

From table 1 one can see that the relative speed can differ so much as by a factor of 600, when comparing the slowest film with the fastest paper. For the paper itself (table 3) this difference reaches a factor of 20. For higher kilovoltages and steel as attenuating material the corresponding factors are 300 and 15 as compared to these previous results for lower kilovoltage and aluminium (tables 2 and 4).

The use of the RCF film with fluorometallic screens gives the fastest X-ray film-intensifying screen combination both for Al and Fe (table 1 and 2).

The advantages of using the fluorometallic screen instead of the regular fluorescent intensifying screen are separately discussed in [11] .

10.2. Relative decrease of kilovoltage. The possibility of decreasing the kilovoltage at a constant exposure (in mAmin) was claimed as one of the main advantages of using fast film/paper-screen combinations [1,2] . This can clearly be seen from tables 1 and 2. For softer X-radiation one can decrease the kilovoltage to 35% of the former value and for harder radiation to 50%. The advantages of this decrease were discussed in detail in [1,2] .

10.3. Image quality. The advantages of higher speed and lower kilovoltage will be of a doubtful value if the radiographic image quality will decrease at the same time. Therefore the main purpose of this investigation was to investigate this factor alone. The answer to these doubts can be given while assessing the results of image quality investigations summarized on figs.7 and 8.

While analysing the results for relatively soft radiation it is surprizing to see that when using such a fast system as the 700 paper with F1 fluorescent screen, which is 200 times faster than the slowest, and with the finest grain, X-ray SR film (see table 1), can then give only slightly poorer image quality as measured by the wire IQI (0.67 % vs. 0.53 %). The highest penetrameter sensitivity of 1-2T, shown by the SR film, can also be reached for the 700 paper with the F2 screen (speed factor 35).

X-ray films M and DR show also the highest wire IQI sensitivity of 0.53%, having relative speed factors of 3.75 and 1.33 respectively. Their penetrameter sensitivity is equally good (1-2T).

Sensitivities of 0.67% (as measured by wire IQI) were also shown by the following systems: RCF-FM (speed factor 181); 620-F2(80); D(44); C(20) and A(16).

The 1.07% wire sensitivity was reached by all systems except the 600-F1(300) and 600-F2(30), whereas all the systems under examination could reach the sensitivity of 1.67%.

For radiation filtered through 10 mm of Fe, the best IQI sensitivity of 1% and the penetrameter level of 2-2T were reached only with the following films: SR(1); DR(1.25) and M(3.33).

As in the previous case (30 mm Al) the fast systems showed only slightly poorer result: 1.25% wire sensitivity corresponding to one wire less. This was reached for the 620 paper with F1 screen (speed factor 300) and RCF film with FM screens (180). Also slower films C(17) and A(13) showed the same sensitivity.

The penetrameter sensitivities showed greater discrepancies in their results. This was further discussed in [9,10] .

10.4. General conclusions. The present investigation has confirmed the theory [1,2] that by using the constant exposure technique the use of fast radiographic systems is possible and advisable as the loss of image quality is very small or nil.

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Constant exposure technique in industrial radiography	Department or group Metallurgy
	Group's own registration number(s)
30 pages + 6 tables + 10 illustrations	

Abstract

The principles and advantages of the constant exposure technique are explained. Choice of exposure factors is analyzed. Film, paper and intensifying screens used throughout the investigation and film and paper processing are described. Exposure technique and the use of image quality indicators are given. Methods of determining of radiographic image quality are presented. Conclusions about the use of constant exposure vs. constant kilovoltage technique are formulated.

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