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MELBOURNE, VICTORIA

MATERIALS REPORT 109

THE APPLICATION OF IMAGE PROCESSING TO THE DETECTION OF CORROSION BY RADIOGRAPHY

by

M. E. PACKER

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THE APPLICATION OF IMAGE PROCESSING TO THE DETECTION OF CORROSION BY RADIOGRAPHY

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SUMMARY

The computer processing of digitised radiographs has been investigated with a view to improving x-radiography as a method for detecting corrosion. Linearisation of the image-density distribution in a radiograph has been used to enhance information which can be attributed to corrosion, making the detection of corrosion by radiography both easier and more reliable. However, conclusive evidence has yet to be obtained that image processing can result in the detection of corrosion which was not already faintly apparent on an unprocessed radiograph. A potential method has also been discovered for analysing the history of a corrosion site.

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CONTENTS

1. INTRODUCTION

Radiography is a widely used method for the non-destructive examination of components. One application in which non-destructive examination is commonly required is the detection of corrosion. Unfortunately the corrosion of metals usually has little net effect on the absorption of x-rays and, except where corrosion is advanced, only low-contrast detail is obtained on a radiograph.

An investigation has been carried out to establish whether the computer processing of digitised radiographs might be able to enhance those features in an image which can be attributed to the results of corrosion. It was hoped that corrosion which would not normally be detectable on a radiograph might become readily discernible after appropriate processing, thus making radiography a more sensitive procedure for the detection of corrosion.

2. EXPERIMENTAL

2.1 Test Specimen

The material for the test specimen was an aluminium alloy, 7075-T6. Some of the material was taken from the wing spar of a Neptune aircraft which had been in service for 20 years. Pieces of this spar showing no visible signs of corrosion were riveted to a piece of the same, but unused, alloy to form the simulated component shown in Figure 1. The assembled specimen was then exposed to the external ARL site environment for two months.

2.2 Radiography

Radiographs were prepared using an Andrex 140 kVp portable x-ray generator operating at 60 kV. Kodak Industrex film, Type M, lead packed, was exposed for one minute at a distance of 1 m from the x-ray source. The exposed film was hand-processed for 7 minutes at 20°C in Kodak Type II developer.

Figure 2 shows part of an x-radiograph of the riveted aluminium-alloy component shown in Figure 1. The radiograph is dominated by features relating to gross changes in the specimen thickness. Details associated with the rivets are particularly prominent. Visual examination of the radiograph reveals lower contrast detail at "A". Experience from similar tests in the past enables this detail to be ascribed to corrosion (exfoliation) on one or both of the concealed surfaces of the riveted plates.

2.3 Digitisation and Reconstruction of Images

The radiograph was digitised at the CSIRO Wool Research Laboratories, Division of Protein Chemistry, using an Optronics International Photoscan System P-1000. Image reconstruction was also performed at the CSIRO Division of Protein Chemistry, using an Optronics International Photowrite System P-1500.

The image density was quantised into a nominal 256 uniformly spaced grey levels (8 bits). The x-ray film is believed to have sufficient grey-scale resolution to warrant this accuracy. The computer programs written to process the image use 1024 grey levels. The digitised data were linearly expanded from 256 to 1024 grey levels for greater accuracy in processing, and compressed from 1024 to 256 levels for reconstruction. The discussion that follows is in terms of these 1024 grey levels. Lower grey levels correspond to darker regions on a positive image and higher levels to lighter regions, corresponding to more and less x-ray absorption, respectively.

The image was digitised at a spatial resolution of 50 μm, but 100 μm resolution was found to be adequate for the present purposes and the raw data were reduced to this resolution by addition.

2.4 Representation of Images

For convenience, two methods were developed for the in-house representation of images. The first involves drawing the digitised traces on a graph plotter using a hidden-line plotting program.* The result is a pseudo three-dimensional map of the picture with the photographic density plotted in the vertical dimension (Fig. 3). By choosing suitable scaling parameters, this program can also be used to plot individual traces for detailed study of the effects of various image-processing procedures.

Pictures were also reproduced on a character-printing terminal (Teletype or line printer) by selecting a sequence of characters to represent various grey level ranges (Fig. 4). Overprinting of characters was necessary to achieve a sufficient spread of grey values. The resolution in Figure 4 has been reduced by a factor of 10 or thereabouts in order to fit the test image on a normal 132-character computer page; a higher resolution can be retained by restricting the area of an image to be considered. The fidelity of the pictures produced is somewhat limited because of structure in the characters representing the grey scale, and especially because of the presence of a significant unprinted area between adjacent characters, but the convenience of obtaining an immediate representation of an image outweighs these disadvantages.

The area of corrosion is just detectable in both Figures 3 and 4.

3. IMAGE PROCESSING

The area used for image-processing experiments was the lower part of Figure 2 and includes the whole of the known area of corrosion.

3.1 Contrast Manipulation

Sugg[2] has shown that poor contrast is one factor limiting the detection of defects by radiography and the main approach in enhancing the details of interest has been to increase contrast in those parts of the image corresponding to regions where corrosion may be expected to occur. In the present case, the regions immediately surrounding the rivets are considered the most likely sites.

The contrast resolution in the x-ray film (256 levels or more) is greater than that of the human visual system (up to 64 levels under ideal conditions). A radiograph can therefore be expected to contain more information than is apparent from visual examination. A human observer, moreover, will be less sensitive to low-contrast detail in close proximity to high-contrast features; corrosion detail is likely to be less visible near the rivets than in an otherwise uniform field.

It is not always possible to radiograph a component in such a way that the full tonal range in the film is used. Contrast can then be increased by the simple linear expansion of the grey scale to span the full range of grey levels. This is nominally equivalent to using higher contrast photographic materials.

A more versatile approach results from considering the distribution of grey levels within the image. A histogram of the selected part of the radiograph is shown in Figure 5; the number of image points (pixels) with a given density is plotted for each image density.† The distribution is clearly multi-modal and certain modes can be related to particular features in the image, although the degree of success with which this can be done is somewhat variable; the modes, and the boundaries between them (the anti-modes), are sometimes difficult to distinguish. This is best demonstrated by reproducing the image in restricted grey ranges. Examples are shown in Figure 6. The rivets, which are such a major feature in the test image, contribute to the grey range from about levels 165 to 327 (Fig. 6*a*). But at least two other major modes also exist within this range (Figs 6*b*, 6*c*) and, working from the histogram alone, it would be difficult to distinguish the contribution due to the rivets. The principal mode centred at grey level 320 results mainly from the largely featureless "background" surrounding the rivets (Fig. 6*c*).

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* The principle of hidden-line plotting programs is described, for example, in Reference 1.

† Although the digitisation was into 256 quantum levels, the operation of reducing the spatial resolution from 50 μm in the raw data to 100 μm in the image-processing experiments results in a smooth distribution when plotted at the higher grey-scale resolution.

The image of the corroded region gives rise to a series of minor peaks between grey levels 353 and 468 (Fig. 6*d*). These minor modes separate the corrosion area into roughly concentric rings (Fig. 7). Although the peaks are small, they appear to be real; the number of points involved in generating the histogram is sufficiently large to make it unlikely that the peaks are simply due to random fluctuations in the distribution. It is suggested that the separate modes may indicate distinct periods of active corrosion at various times during the environmental exposure. The implied ability to resolve the sequence of events at a corrosion site could prove to be a useful tool for analysing corrosion damage.

Contrast in regions of interest can be enhanced by expanding the grey scale in appropriate ranges and compressing bands of lower interest. A piecewise-linear transformation of the various grey-level bands is convenient, and usually satisfactory, although any arbitrary function can be used as the basis of a transformation.

A more useful general approach is the linearisation of the distribution, or histogram equalisation.[3,4,5,6] Information theory reveals that the "best" quantisation of the information in an image results when an equal number of image points occupy each grey level,[5,7,8] i.e. if the quantisation intervals are smaller in the more densely populated regions of the grey scale. Histogram equalisation involves redistributing the grey levels to approximate this situation. Groups of sparsely populated grey levels are combined into single levels and the more densely populated grey levels are, in principle, divided into several adjacent grey levels. The transformation is monotonic; lighter regions in the original image are lighter in the transformed image, and darker regions darker. The technique can also be modified to allow, for example, for the non-linearity of the human visual response.[9]

In redistributing the grey levels, various criteria can be employed to allocate individual pixels belonging to the more densely populated grey levels in the original image to one of several adjacent grey levels in the modified image.[5,6] In the present experiments, no attempt has been made to do this; the separation between these densely populated levels has simply been increased so that the mean occupancy is constant in any neighbourhood of adjacent levels. The gaps which result in the histogram can lead to relatively large contrast jumps in the processed image, and this can lead, in turn, to a granular appearance in the image, or to false contours in some cases.

For an image where most of the pixels are clustered into somewhat fewer than half the available grey levels (and this is true to a greater or lesser degree of most images) the result of histogram equalisation is to increase contrast over most of the area of the image. On the other hand, some parts of the image—those contributing to the "tails" of the histogram—are reduced in contrast because several originally distinct grey levels are combined into one. But, by the converse argument, only a small proportion of the total image is normally involved. Care must be taken in any particular case to ensure that contrast in the areas of interest is enhanced and not degraded.

In the test image, the greatest and lowest grey levels are 1020 and 165 (it is not normally practicable to adjust the digitising apparatus so that the density range in the image coincides exactly with the full range of instrumental grey levels). In the following discussion of the effects of histogram equalisation, it is most realistic to regard these 856 grey levels as comprising the full dynamic range; simple linear expansion as described above can be used to expand these 856 grey levels to the full range of 1024 levels. The computer program written to linearise the grey-level histogram simultaneously expands the grey scale to fill the whole range, but this is better regarded as a separate enhancement operation.

There are a total of 512,000 points in the test image and the information would be displayed most efficiently if there were 598 points in each of the 856 grey levels (512,000/856 = 598). There are 219 grey levels which contain more than 598 points and these 219 levels contain a total of 477,201 points. This means that 93·2% of the points occupy only 25·6% of the available grey range. Contrast should therefore be improved to some extent over about 93% of the image area as a result of histogram equalisation. (Including the additional effect of expanding the grey scale to 1024 levels, the optimum number of image points in each grey level would be 500. A further 1% of the image should be enhanced in contrast as a result.)

Those parts of the image which are clearly associated with the corroded area lie approximately in the range of grey levels from 353 to 468 (Fig. 6*d*). Most of these levels contain more than 598 points and those at the lower end of the range, which represent those parts of the corroded region least distinguishable from the background, contain substantially more than

598 points each. This means that contrast in the corrosion region will be enhanced as a result of histogram equalisation, with greater enhancement occurring in those regions which are least different from the background. Loss of contrast on the other hand should be restricted mainly to the very dark and very light parts associated with the rivets.

Figure 8 is a map of the image showing those areas where the grey value falls in a band containing fewer than the optimum number of grey levels. The areas thus defined are those where histogram equalisation will cause a compression of the contrast. These positions coincide closely with the positions of the rivets. The map is only approximate because of the greatly reduced spatial resolution used in producing it.

The modified histogram is shown in Figure 9. The increase in spacing between occupied levels gives a quantitative measure of the increase in contrast in terms of image density. Contrast in the background areas has been increased by a factor of up to 16 and, in the corrosion region, by a factor which varies from 1 in the lighter regions to 4 in the darker regions. Contrast between the corrosion area and the background, as measured by the separation between the most densely populated grey levels in each field, has been increased by a factor of 6.

The image after histogram equalisation is shown in Figures 10, 11 and 12. The corroded area is much more clearly defined than in the corresponding unprocessed images (Figs 3, 4 and 2, respectively).

3.2 Background Correction

It will be seen in Figure 12 that the density of the background (Fig. 6*c*) varies across the field. This is not apparent in the original radiograph (Fig. 2) and could be due to slight non-uniformity in the intensity of the x-ray beam or to the variation in the angle at which the beam passes through the specimen. An attempt was made to process the image to correct for this non-uniform exposure. An average image density was determined in a specified local area about each image point and this average value was subtracted from the actual density at that point. Ideally the array of correction terms should represent what would be left of the image if all the "features" were absent. In this particular case, the images of the rivets were sufficiently prominent and extensive to distort the local averages from what was required. But because the grey levels contributed by the rivets were largely distinct from those of the background, it was possible to set thresholds so that these features did not contribute unduly to the averaging process.

The corrosion patch itself forms a large bright area within the image and, although thresholding was of some benefit, no completely satisfactory criterion has yet been determined for distinguishing density changes associated with the principal corrosion site from a variation in the background. Some degree of compromise was necessary in selecting an averaging window which would correct for the uneven exposure without simultaneously degrading the information due to the corrosion.

The method is empirical and still falls somewhat short of the ideal proposed above.

The background correction was applied to the test image using an averaging window approximately 40 mm × 10 mm (400 points horizontally × 100 points vertically). The density distribution was then linearised as described above. Figure 13 shows the results for a single trace. Figure 13*a* represents the density variation along a trace through the centre of the upper line of rivets in Figure 2, Figure 13*b* the corresponding values of the background correction term and Figure 13*c* the result of applying this correction to the original trace. Changes in the background density have been largely removed without affecting the fine detail.

The reconstructed image is shown in Figure 14. The field has been reduced with respect to Figure 12 by omitting the dark band at the top of the original test area (Fig. 6*b*). Much of the additional contrast in Figure 14, compared with Figure 12, is a consequence of removing the associated mode from the distribution of image densities (Fig. 5), making additional grey levels available in which to display the rest of the information. The effect of the background correction can not therefore be properly assessed for the reconstructed image using the results obtained so far.

4. DISCUSSION

Figure 14 represents the best effort so far at enhancing corrosion detail for the radiograph shown in Figure 2. The boundaries of the corroded region are now clearly defined and contrast in the area of corrosion now covers almost the whole black/white density range; even the most cursory examination could not fail to detect it. There is some tendency to graininess in certain areas, as anticipated above, but this is not considered sufficiently severe to be objectionable.

The corrosion information has been enhanced by manipulating the contrast. Histogram equalisation is a convenient method for achieving this because it manages the redistribution of contrast over the whole image in terms of a single criterion which is determined automatically; no operator intervention is required. Other methods, such as the linear expansion of selected grey ranges, require some degree of judgment in specifying the transformation. However, histogram equalisation would not have been satisfactory in the present case for detecting corrosion of the rivets themselves. The applicability of a particular procedure needs some consideration in each case. However, histogram equalisation is expected to be beneficial in enhancing other similar radiographs since it usually results in some degree of contrast enhancement over *most* of an image.

While the main corroded area is clearly visible in Figure 14, it was already moderately visible in the original radiograph. One aim of the exercise was to detect areas of corrosion which were not apparent (or would normally be missed) in the original. There are no clear examples in the radiograph examined here, although the small features marked "A" in Figure 14 suggest possible sites of early corrosion. The specimen has not yet been disassembled to assess whether corrosion had also occurred in any other areas, but (unprocessed) radiographs of the same specimen after an additional month of exposure to the environment showed no new features indicative of other corrosion sites. Further experiments will be needed to establish whether these techniques can reveal corrosion which would not otherwise be detected on a radiograph.

Correction of the image for uneven exposure appears to have been successful when applied to individual traces (Fig. 13), but further work is needed to assess the effect on a complete image. The selection of optimum parameters (dimensions of averaging window, threshold parameters) also requires further consideration.

5. CONCLUSIONS

It has been shown that computer-processing of digitised radiographs can be used to enhance the contrast of those details associated with corrosion. The detection of corrosion by radiography has been made much easier as a result. The relatively simple technique of histogram equalisation was well-suited to enhancing corrosion detail in the particular image examined. Local averaging methods were also used to correct for uneven exposure of the radiograph. Both methods should be applicable to enhancing corrosion detail in other radiographs of similar type.

No positive indication has yet been obtained of corroded areas which were not at least faintly visible in the original radiograph. It is clear, however, that the techniques described would make the detection of corrosion much more reliable.

In the example studied, the image of a known corroded area could be divided into distinct density bands whose existence is believed to indicate separate stages in the corrosion process. Further work on the significance of these bands may lead to a method for determining the sequence of events in regions where corrosion has occurred.

ACKNOWLEDGMENTS

The test specimen and the radiographs were prepared by Mr D. A. Olley.

The author is grateful to Mr R. J. Rowlands and the CSIRO Wool Research Laboratories, Division of Protein Chemistry, for providing facilities for digitising and recreating images. Appreciation is also expressed to Dr M. Stewart of the CSIRO Division of Computing Research for discussions while setting up this project.

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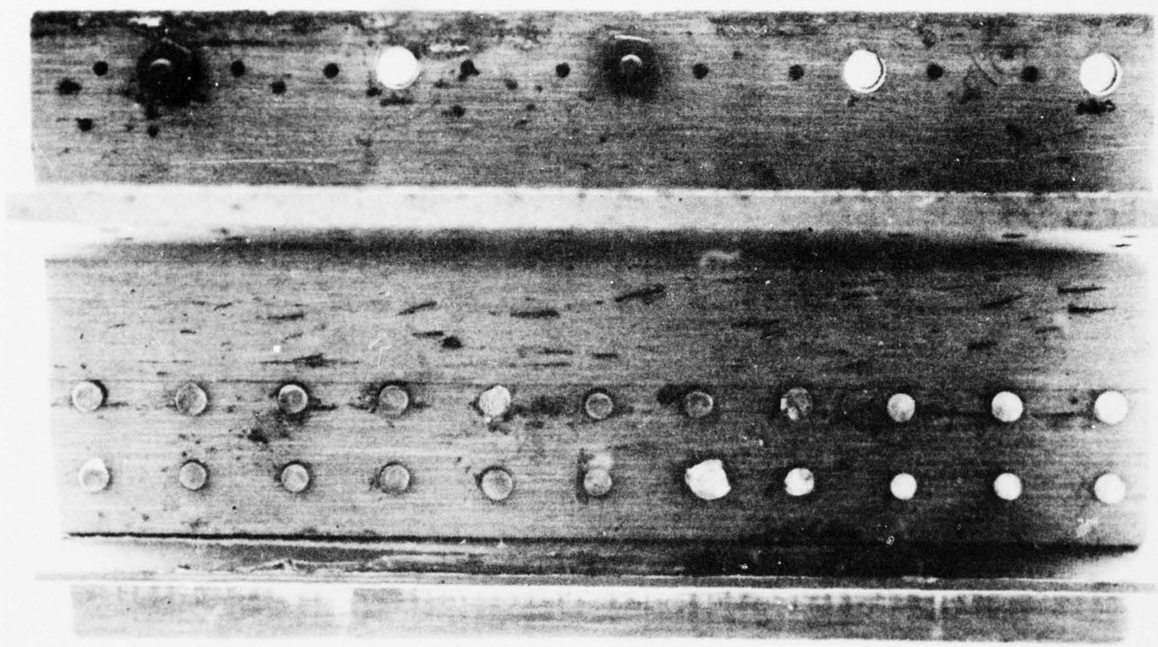


FIGURE 1. RIVETED ALUMINIUM-ALLOY COMPONENT USED AS TEST SPECIMEN.

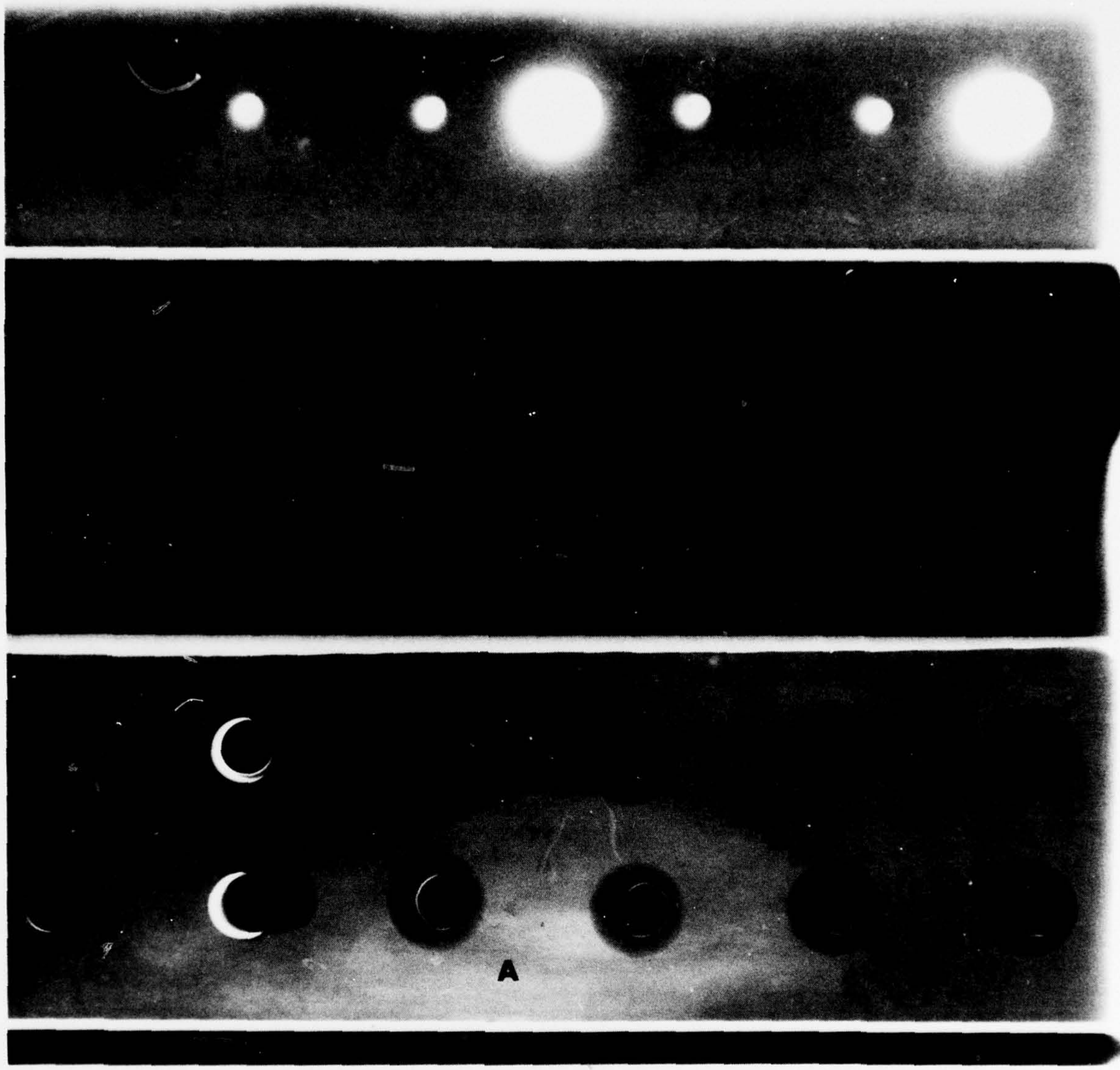


FIGURE 2. PART OF AN X–RADIOGRAPH OF THE RIVETED ALUMINIUM COMPONENT SHOWN IN FIGURE 1. THE LOWER PART OF THIS FIGURE WAS USED FOR IMAGE-PROCESSING EXPERIMENTS.

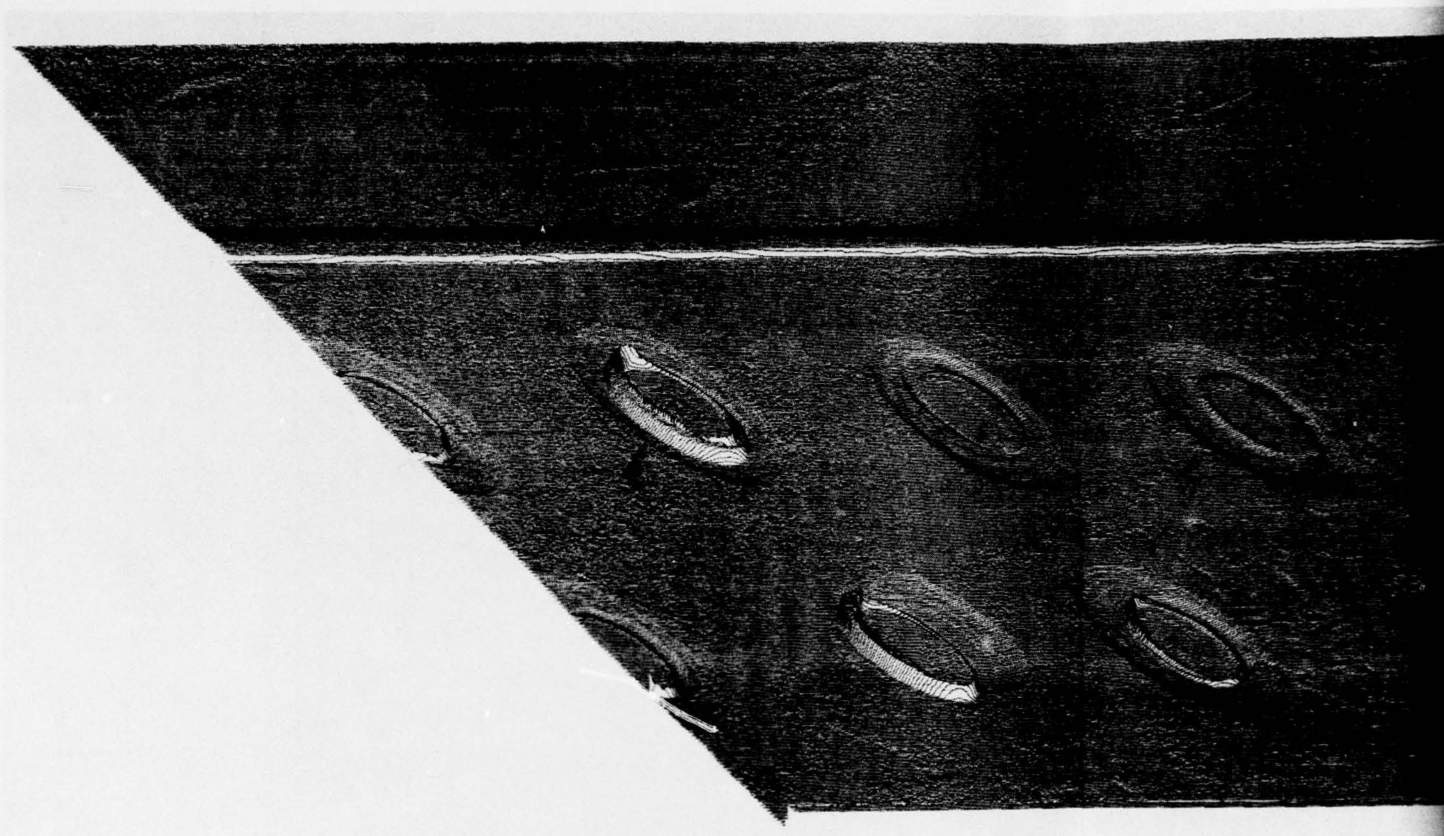
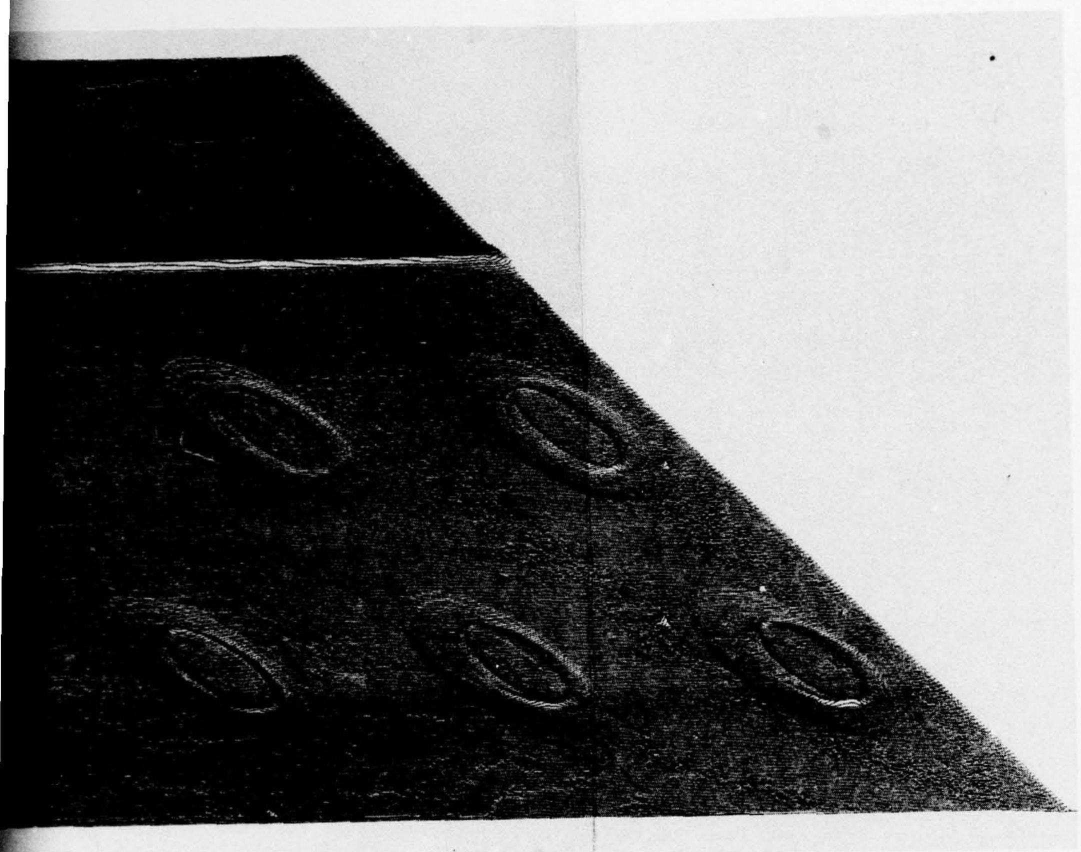


FIGURE 3. SELECTED AREA OF RADIOGRAPH AS REPRESENTE
PLOTTING PROGRAM. THE IMAGE DENSITY IS PLOTTED IN TH
DIRECTION. THE CORROSION AREA IS JUST DETECTABLE.



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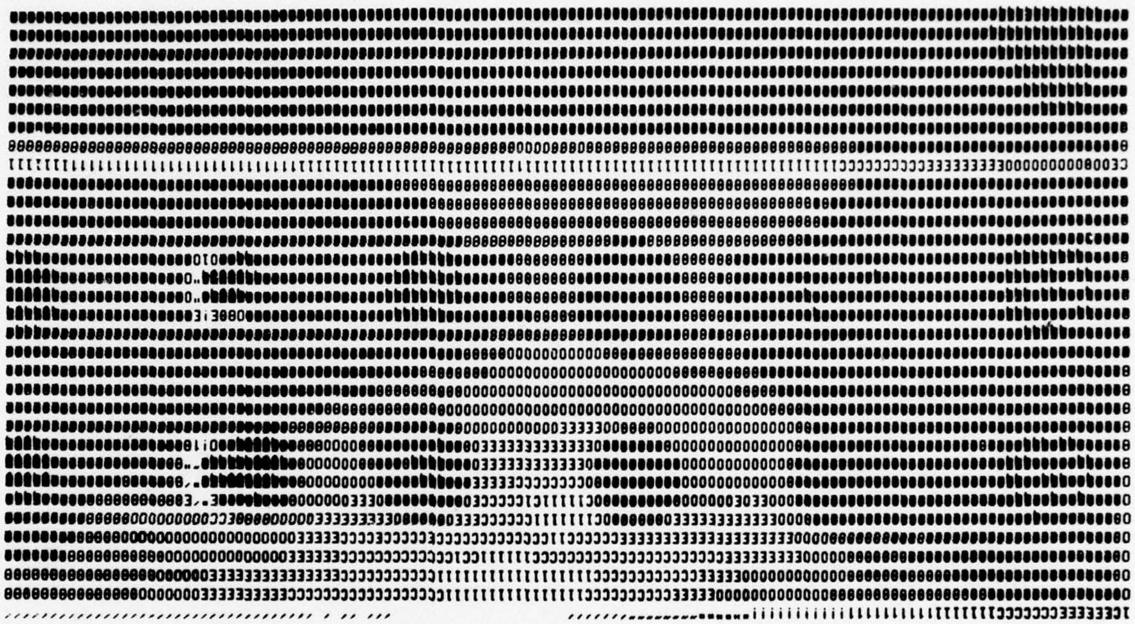


FIGURE 4. SELECTED AREA OF RADIOGRAPH AS REPRODUCED ON A TELETYPE MODEL 43 TERMINAL USING A 16-LEVEL GREY SCALE.

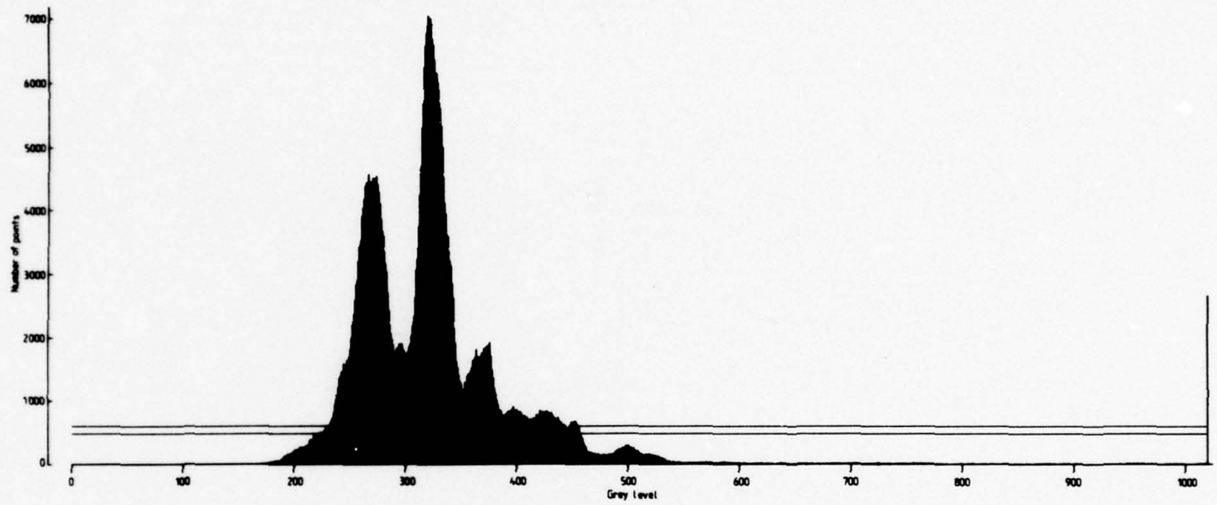
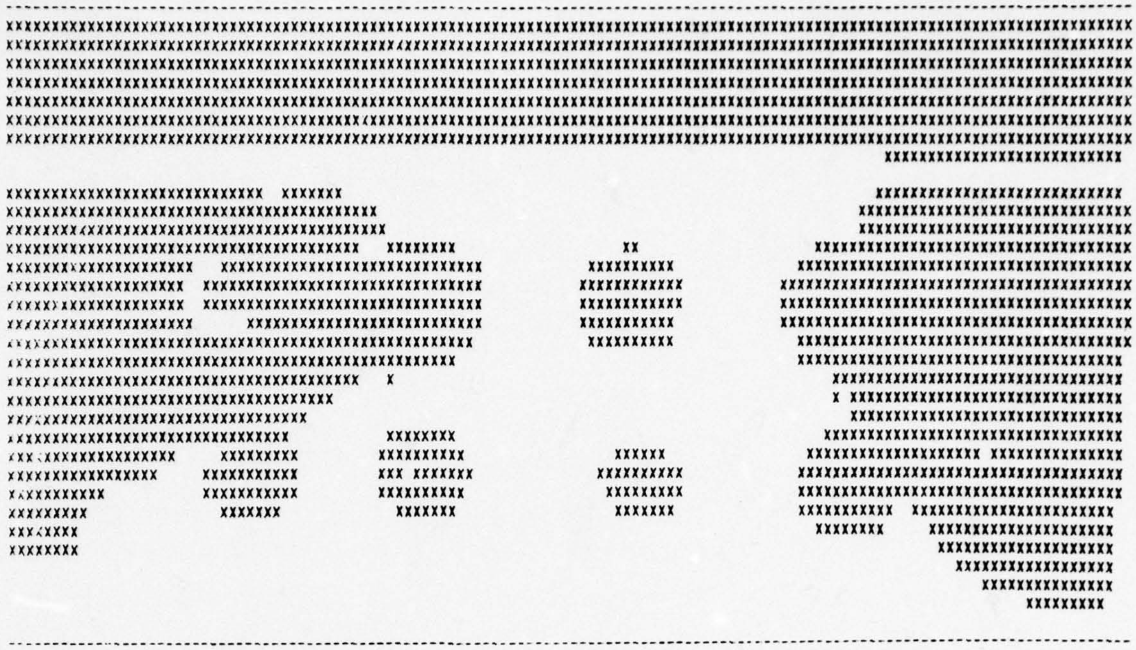
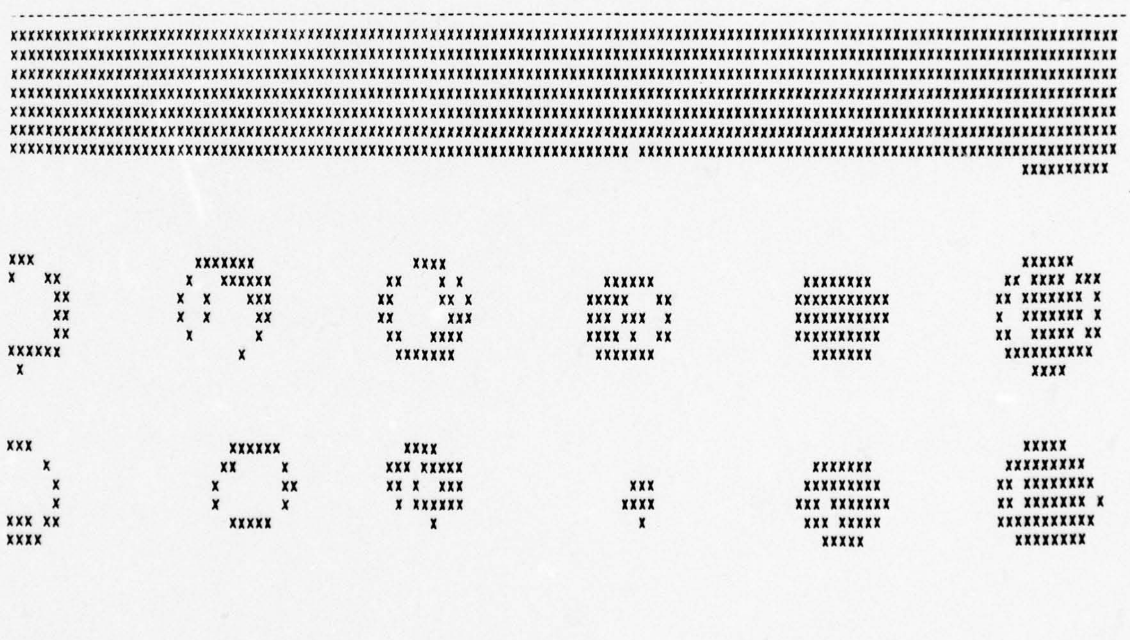


FIGURE 5. HISTOGRAM OF IMAGE DENSITIES FOR THE SELECTED AREA OF FIGURE 2.



(a)

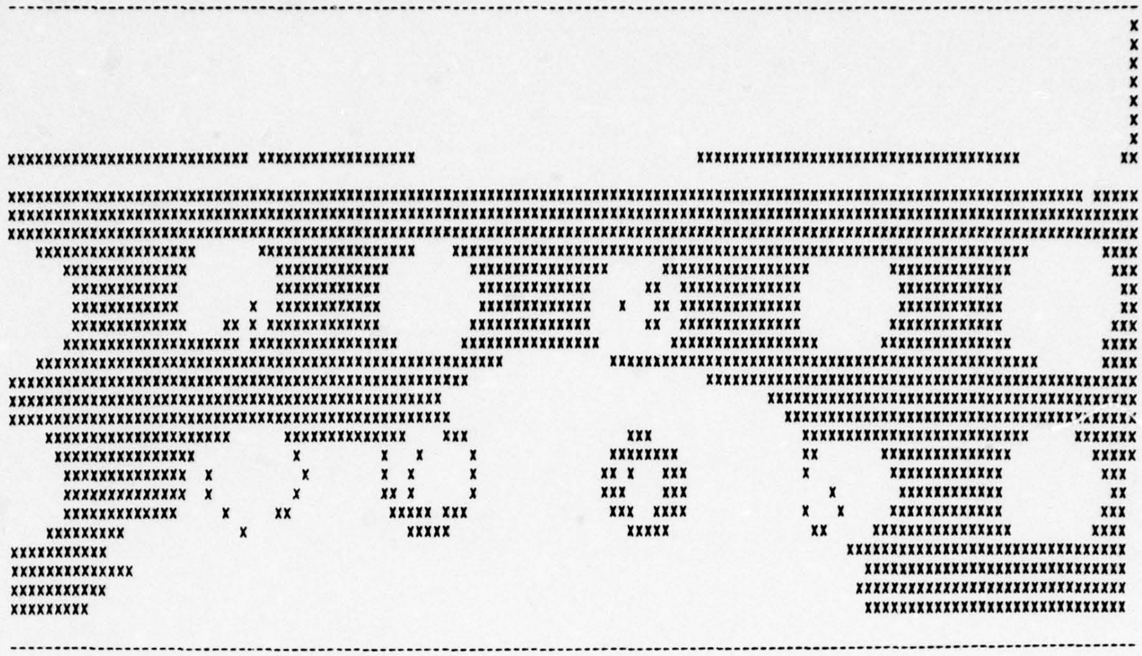


(b)

FIGURE 6. MAPS OF THE IMAGE FIELD SHOWING THE REGIONS CORRESPONDING TO PARTICULAR GREY-LEVEL BANDS.

6a: The dark detail from the rivets is included mainly in grey levels 165-327. Other features also contribute to this range.

6b: Grey levels 232-291 are contributed mainly by the dark band at the top of the selected area. This range of grey levels is included in Figure 6a.

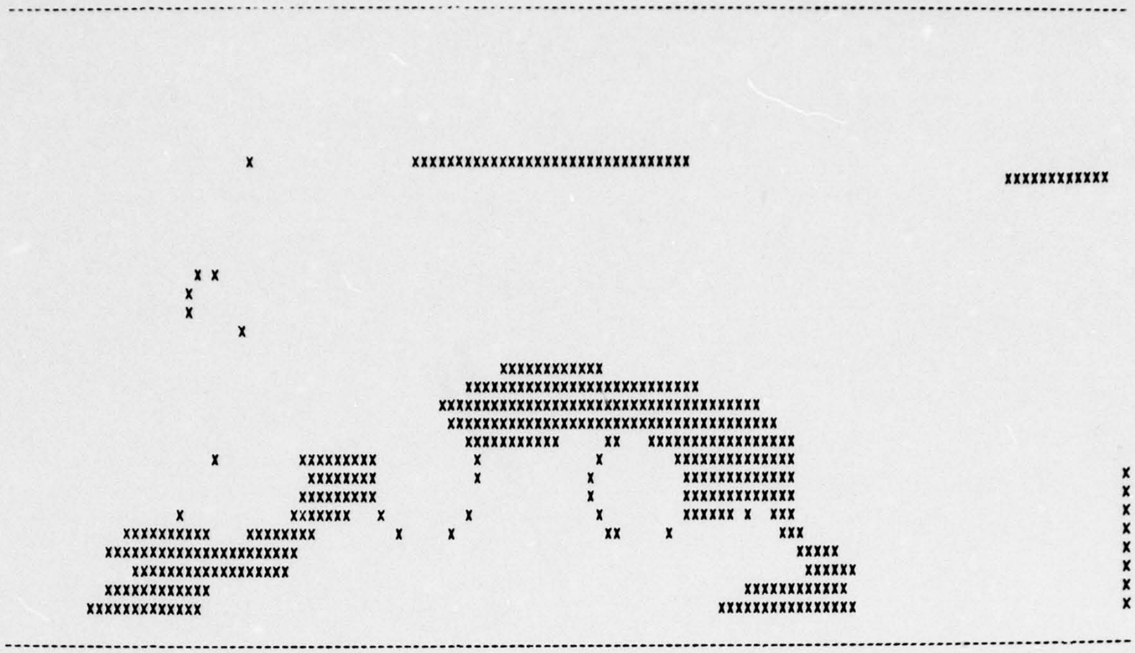


(c)

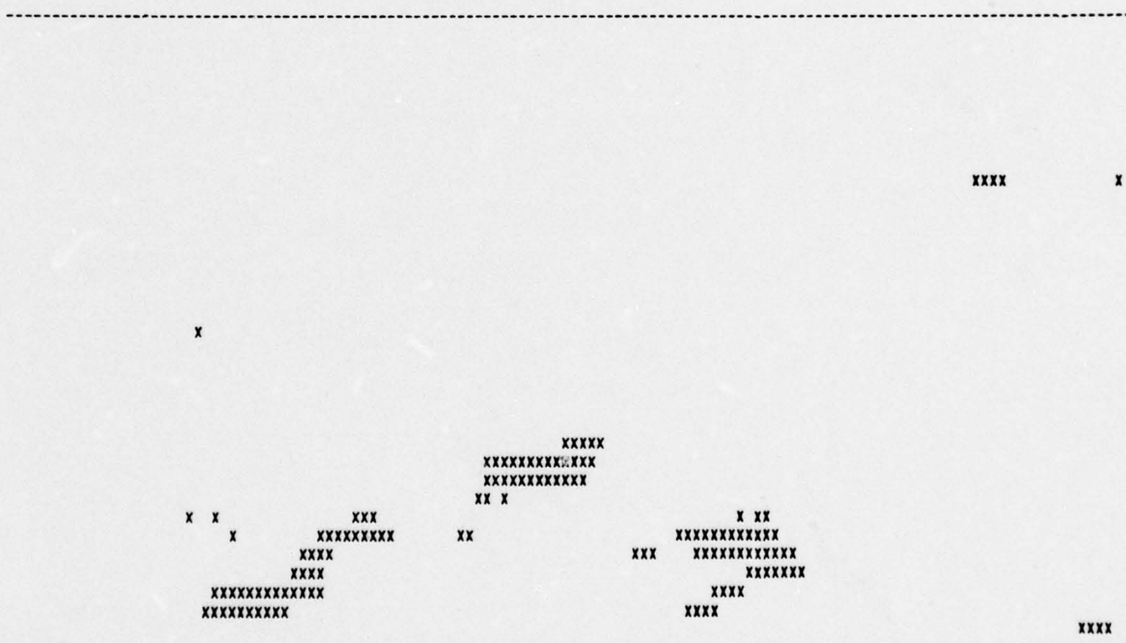
(d)

6c: Grey levels 294-352 are contributed by the region surrounding the rivets, excluding the area of known corrosion. This range of grey levels partly overlaps the range in Figure 6a.

6d: Grey levels 353-468 are contributed by the corrosion region.



(a)

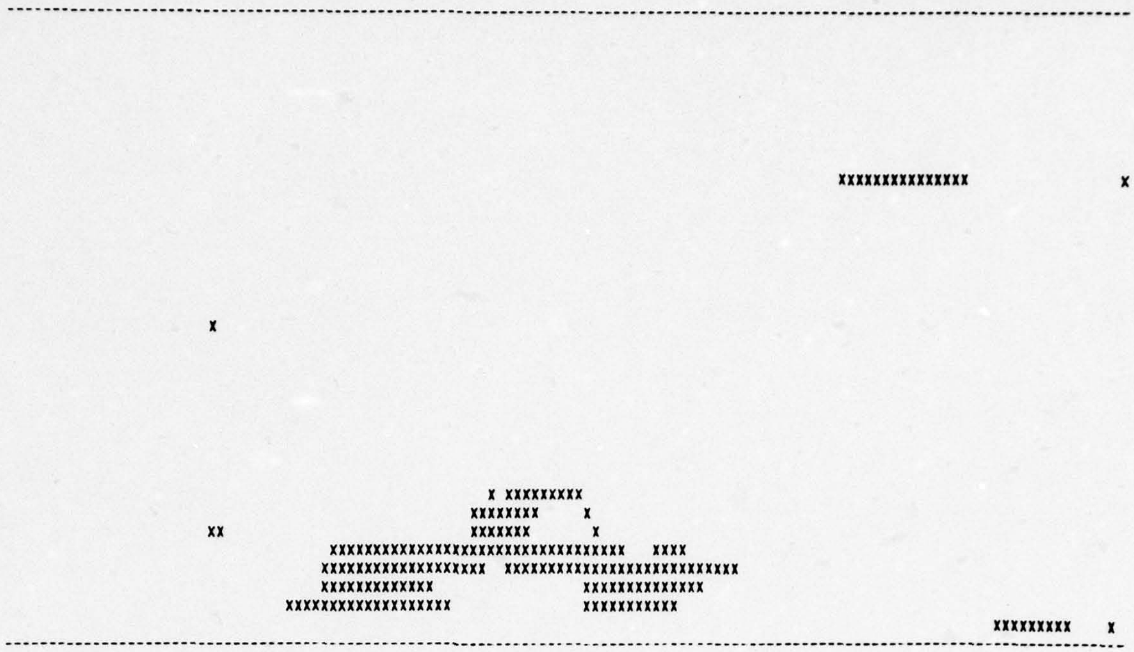


(b)

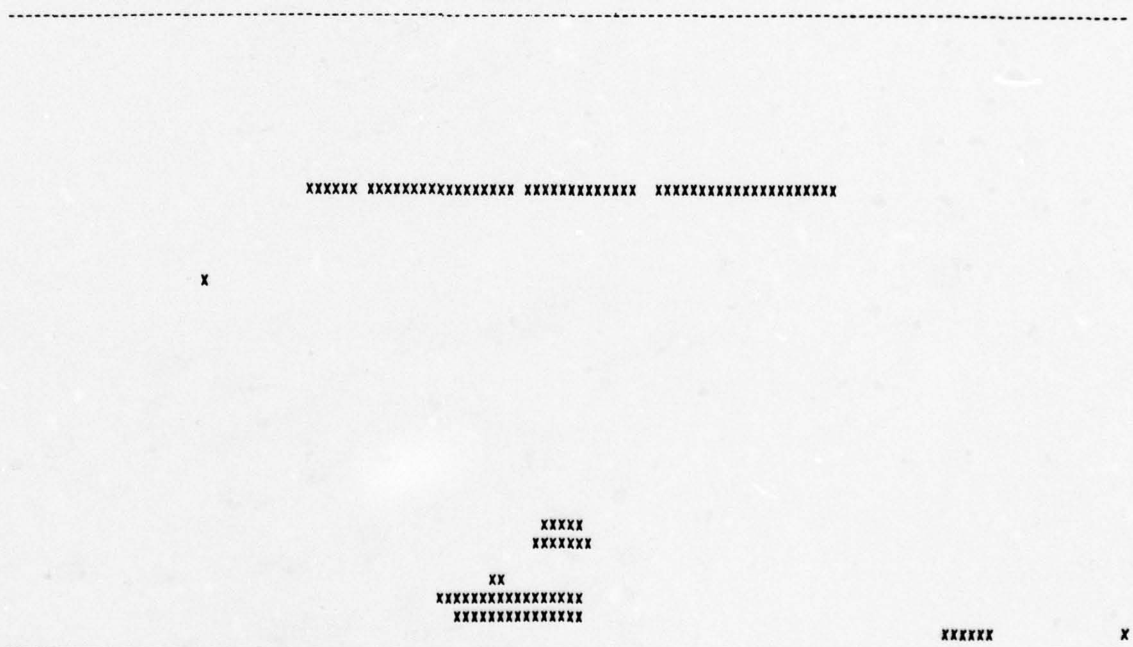
FIGURE 7. MAPS OF THE IMAGE FIELD SHOWING THE REGIONS CORRESPONDING TO MINOR PEAKS IN THE HISTOGRAM (FIGURE 5).

7a: Grey levels 353-387,

7b: Grey levels 388-410,



(c)



(d)

7c: Grey levels 411-445,
7d: Grey levels 446-468.

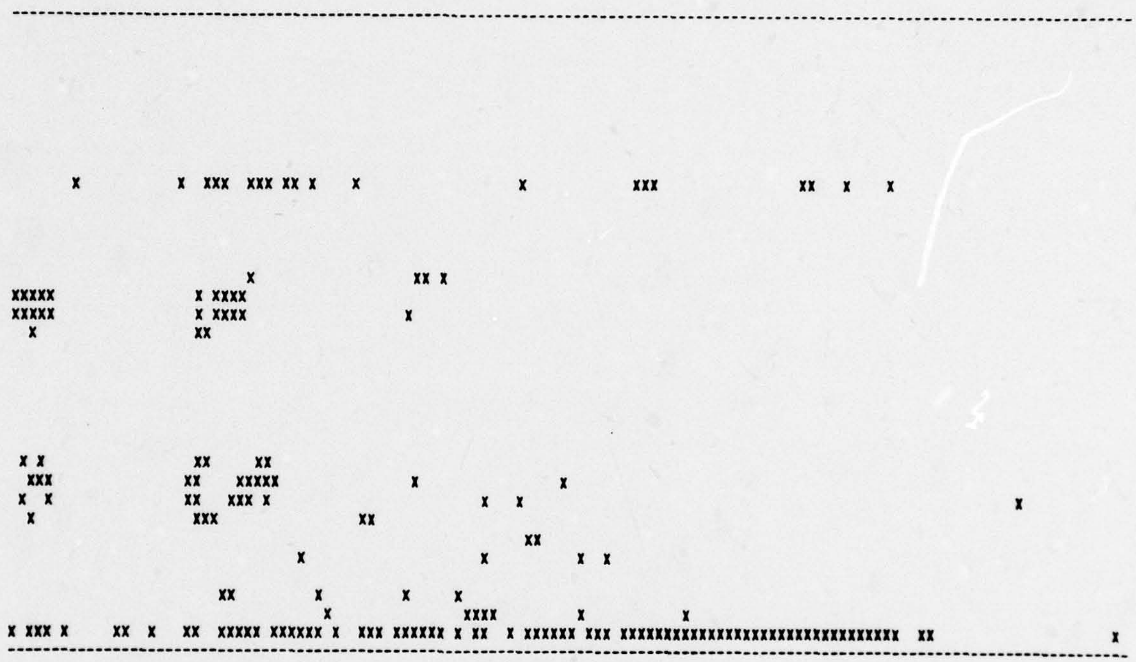


FIGURE 8. MAP OF IMAGE FIELD, INDICATING THE AREAS WHERE CONTRAST COMPRESSION WILL OCCUR AS A RESULT OF HISTOGRAM EQUALISATION.

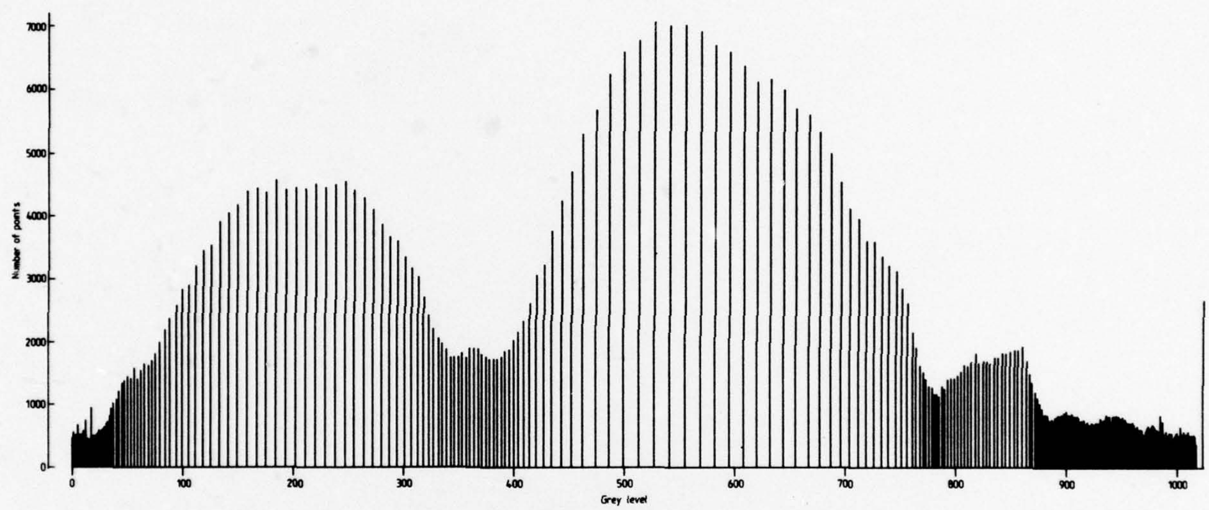


FIGURE 9. MODIFIED HISTOGRAM. THE MORE DENSELY POPULATED LEVELS ARE SEPARATED BY VACANT LEVELS, SO THAT THE MEAN OCCUPANCY IN ANY NEIGHBOURHOOD IS CONSTANT (500 POINTS PER GREY LEVEL).

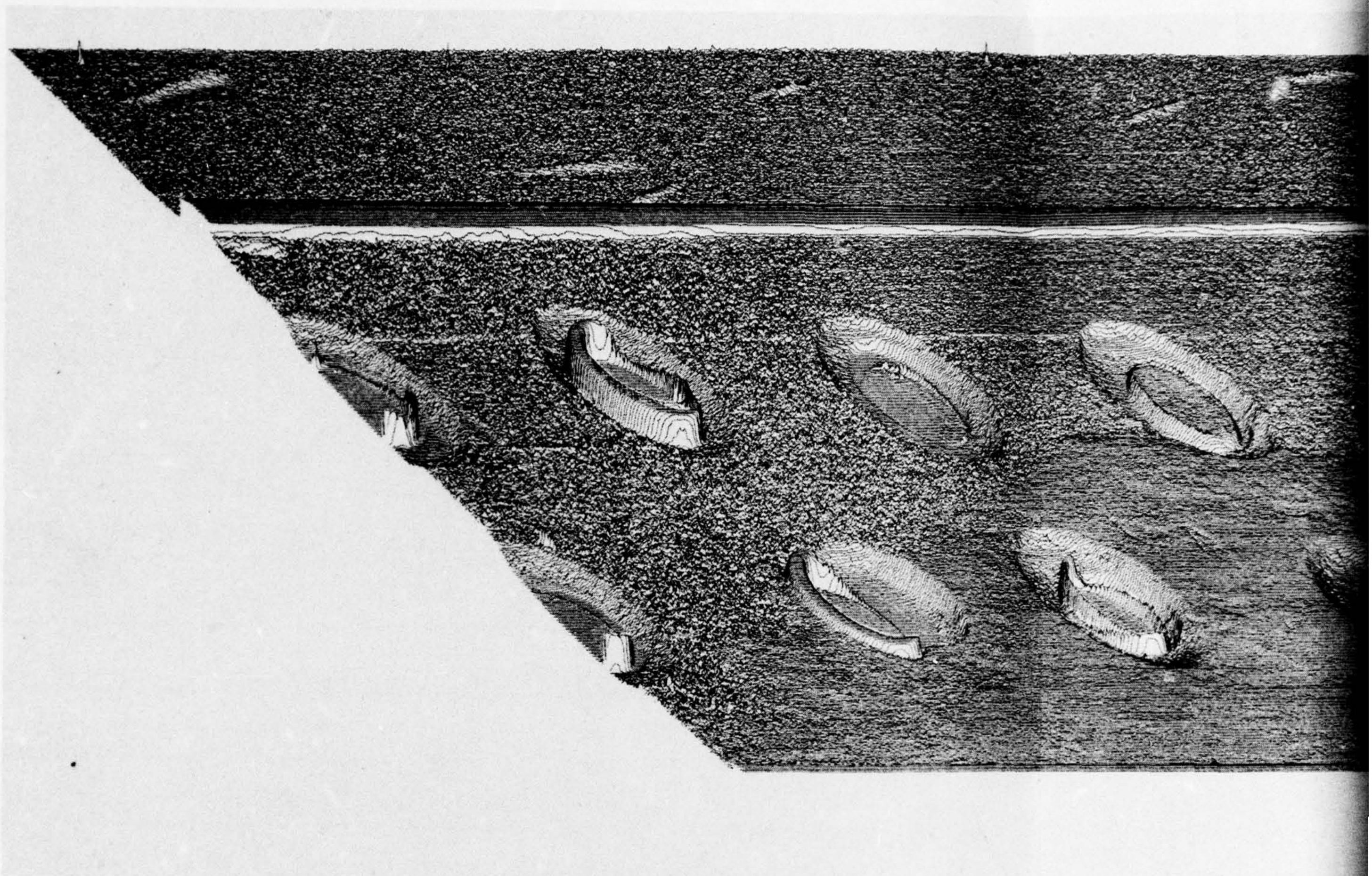
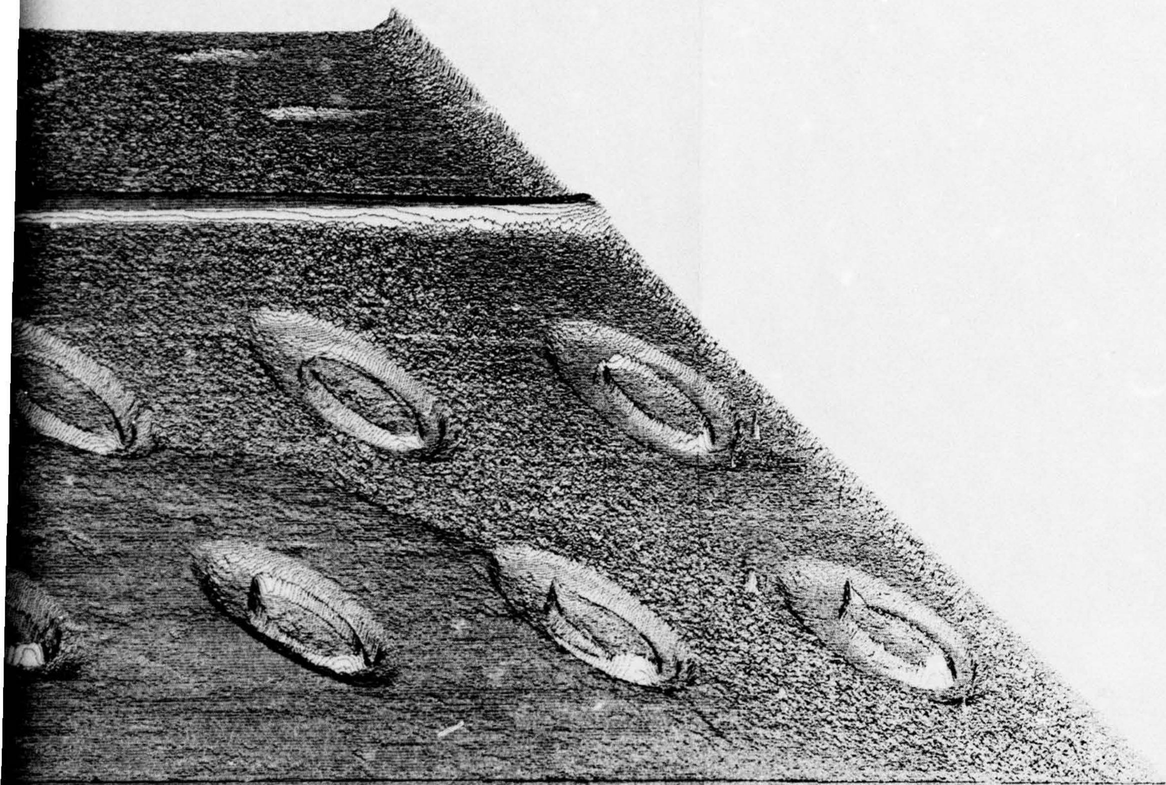


FIGURE 10. GRAPH-PLOTTER REPRESENTATION OF RADIOGRAP
HISTOGRAM EQUALISATION.



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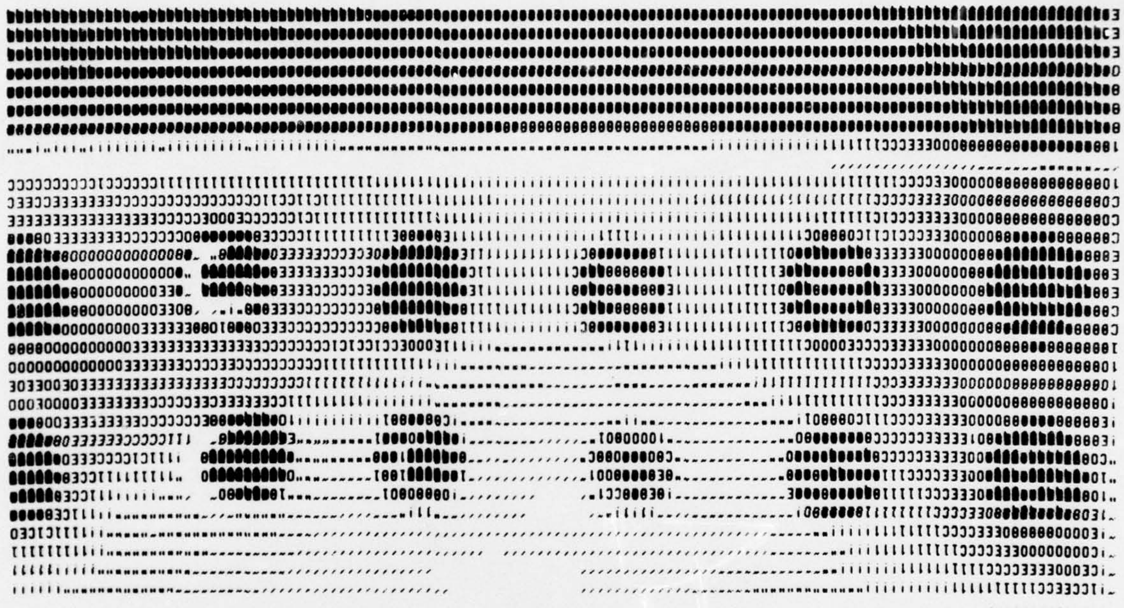

FIGURE 11. TELETYPE REPRESENTATION OF RADIOGRAPH AFTER HISTOGRAM EQUALISATION.

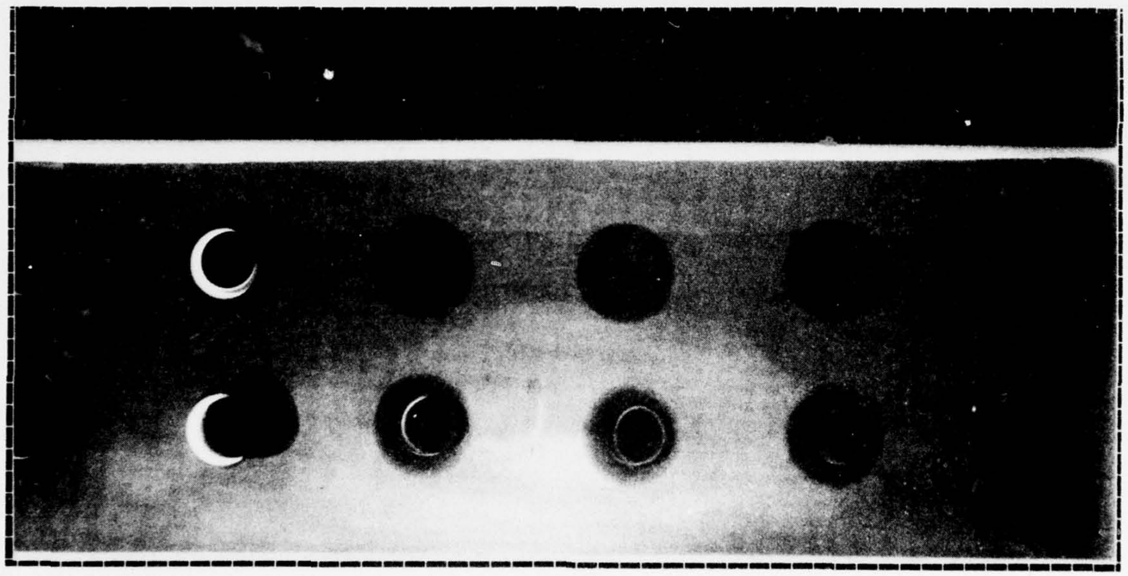

FIGURE 12. RECONSTRUCTED RADIOGRAPH AFTER HISTROGRAM EQUALISATION.

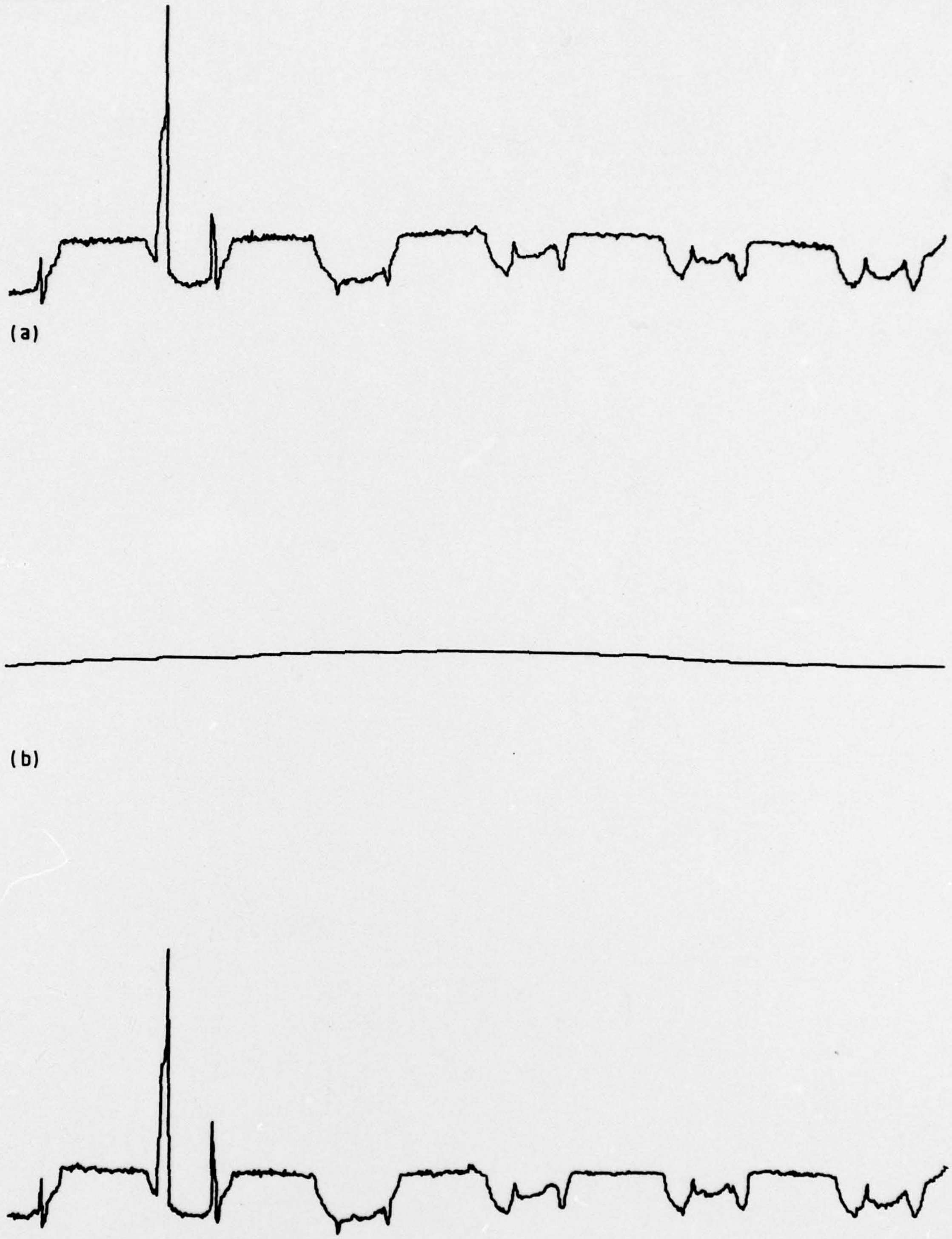

FIGURE 13. EFFECT OF BACKGROUND CORRECTION ON INDIVIDUAL TRACES.
13a: Original trace through the centre of the upper line of rivets in Figure 2.
13b: Estimate of the background for the trace in Figure 13a.
13c: Original trace after subtracting the correction term.

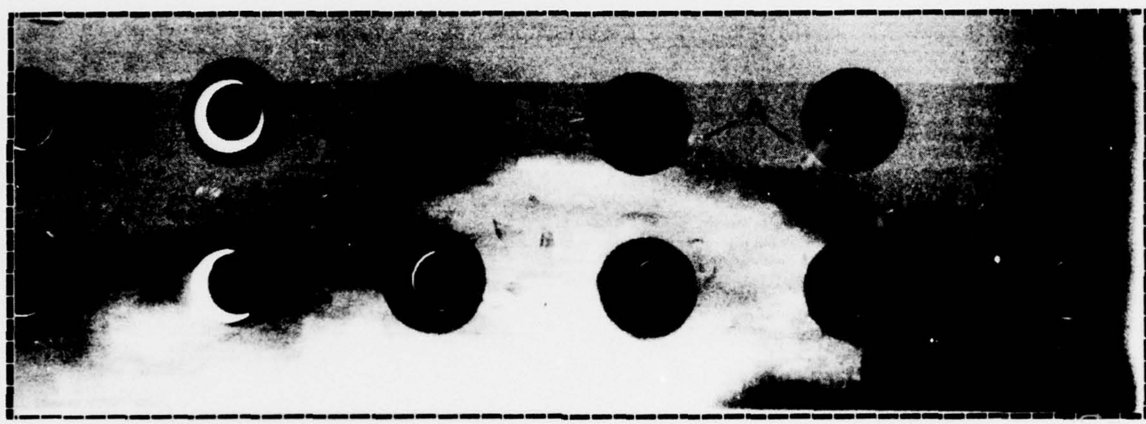

FIGURE 14. RECONSTRUCTED RADIOGRAPH, CORRECTED FOR NON-UNIFORM EXPOSURE, AND HISTOGRAM EQUALISED. (Part of the original test area is not included in this figure).

DOCUMENT CONTROL DATA SHEET

Security classification of this page: Unclassified

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16. ABSTRACT

The computer processing of digitised radiographs has been investigated with a view to improving x-radiography as a method for detecting corrosion. Linearisation of the image-density distribution in a radiograph has been used to enhance information which can be attributed to corrosion, making the detection of corrosion by radiography both easier and more reliable. However, conclusive evidence has yet to be obtained that image processing can result in the detection of corrosion which was not already faintly apparent on an unprocessed radiograph. A potential method has also been discovered for analysing the history of a corrosion site.

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Assistant Secretary, D.I.S.B.	8–23
Aeronautical Research Laboratories	
Chief Superintendent	24
Superintendent—Materials Division	25
Divisional file—Materials	26
Library	27
Author: M. E. Packer	28
S. McK. Cousland	29
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Library	30
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Army Scientific Adviser	36
Royal Military College	37
US Army Standardisation Group	38
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Aircraft Research and Development Unit	40
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D. Air Eng.—AF	42
HQ Support Command (SENGSO)	43

Department of Productivity

Australian Government Engine Works (Mr J. L. Kerin)	44

Government Aircraft Factories

Library	45

Department of National Resources

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Department of Transport

Secretary/Library	47
Airworthiness Group (Mr R. Ferrari)	48

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	Professor of Mechanical Engineering	80
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	Prof. Allen-Williams, Mechanical Engineering	102
R.M.I.T.	Library	103
	Mr H. Millicer, Aeronautical Engineering	104
	Mr Pugh, Mechanical Engineering	105

CANADA

CAARC Co-ordinator Structures	106
NRC, National Aeronautics Establishment, Library	107
NRC, Division of Mechanical Engineering (Dr D. McPhail, Director)	108
NRC, Division of Mechanical Engineering, Gas Dynamics Laboratory (Mr R. A. Tyler)	109

Universities

McGill	Library	110
Toronto	Institute for Aerospace Studies	111

FRANCE

AGARD	Library	112
Gaz de France	Library	113
Institute Francais de Petrole	Library	114
ONERA	Library	115
Service de Documentation	Technique de l'Aeronautique	116

GERMANY

ZLDI	117

INDIA

CAARC Co-ordinator Materials	118
CAARC Co-ordinator Structures	119
Civil Aviation Department (Director)	120
Defence Ministry, Aero Development Establishment, Library	121
Indian Institute of Technology, Library	122
National Aeronautical Laboratory (Director)	123

INTERNATIONAL COMMITTEE ON AERONAUTICAL FATIGUE

(Through Australian ICAF Representative)	124–146

ISRAEL

Technion—Israel Institute of Technology (Prof. J. Singer)	147

ITALY

Associazione Italiana di Aeronautica e Astronautica (Prof. A. Evla)	148

JAPAN

National Aerospace Laboratory, Library 149

Universities

Tohoku (Sendai)	Library	150
Tokyo	Institute of Space and Aeroscience	151

NETHERLANDS

Central Organization for Applied Science Research in the Netherlands TNO, Library 152
National Aerospace Laboratory (NLR), Library 153

NEW ZEALAND

Defence Scientific Establishment, Library 154
Defence Scientific Establishment (Mr H. Levinsohn) 155
Transport Ministry, Civil Aviation Division, Library 156

Universities

Canterbury	Library	157
	Prof. D. Stevenson, Mechanical Engineering	158
	Mr F. Fahy, Mechanical Engineering	159
	Mr J. Stott, Chemical Engineering	160

SWEDEN

Aeronautical Research Institute 161
Chalmers Institute of Technology, Library 162
Kungliga Tekniska Hogskolan 163
SAAB, Library 164
Research Institute of the Swedish National Defence 165

SWITZERLAND

Armament Technology and Procurement Group 166
Brown Boverie (Management Chairman) 167
Escher-Wyss Ltd (Manager) 168
Institute of Aerodynamics E.T.H. 169
Institute of Aerodynamics (Prof. J. Ackeret) 170
Sulzer Bros. Lts. (General Manager) 171

UNITED KINGDOM

Mr A. R. G. Brown, ADR/MAT (MEA) 172
Ministry of Power (Chief Scientist) 173
Aeronautical Research Council, N.P.L. (Secretary) 174
CAARC NPL (Secretary) 175
Royal Aircraft Establishment Library, Farnborough 176
Royal Aircraft Establishment Library, Bedford 177
Royal Armament Research and Development Establishment, Library 178
CATC Secretariat 179
Aircraft and Armament Experimental Establishment 180
Admiralty Fuel Experiment Station, Library 181
Military Vehicles Engineering and Experimental Establishment 182
Admiralty Materials Laboratories (Dr. R. G. Watson) 183
National Engineering Laboratories (Superintendent) 184
National Gas Turbine Establishment (Director) 185
National Industrial Fuel Efficiency Services (Director) 186
National Physical Laboratories, Library 187
British Library, Science Reference Library 188
Naval Construction Research Establishment (Superintendent) 189
CAARC Co-ordinator, Structures 190

Aircraft Research Association, Library	191
British Ship Research Association	192
C. A. Parsons Library	193
C. A. Parsons Gas Turbine Department Library	194
Central Electricity Generating Board	195
Electrical Power Storage Ltd (Director of Fuel Cell Research)	196
English Electric Co. Ltd Gas Turbine Department (Dr W. Rizk)	197
Energy Conversion Ltd (Research Director)	198
Institute of Fuel (Secretary)	199
Fulmer Research Institute Ltd, (Research Director)	200
Lucas Gas Turbine Equipment (Director)	201
Motor Industries Research Association (Director)	202
Ricardo II Co. (Manager)	203
Rolls-Royce (1971) Ltd, Aeronautics Division (Chief Librarian)	204
Ruston and Hornsby, Turbine Division, (Mr A. V. Jackman)	205
Shell Research Laboratory (Director of Fuel Cell Research)	206
Science Museum Library	207
Welding Institute, Library	208
Hawker Siddeley Aviation Ltd, Brough	209
Hawker Siddeley Aviation Ltd, Greengate	210
Hawker Siddeley Aviation Ltd, Kingston-upon-Thames	211
Hawker Siddeley Dynamics Ltd, Hatfield	212
British Aircraft Corporation (Holdings) Ltd, Commercial Aircraft Division	213
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British Aircraft Corporation (Holdings) Ltd, Commercial Aviation Division	215
British Hovercraft Corporation Ltd, (East Cowes)	216
Fairey Engineering Ltd, Hydraulic Division	217
Short Brothers and Harland	218
Westland Helicopters Ltd	219

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	Professor of Mechanical Engineering	234
	Dr Eisenklen	235
	Prof. B. G. Neal	236

UNITED STATES OF AMERICA

NASA Scientific and Technical Information Facility	237
Sandia Group (Research Organisation)	238
American Institute of Aeronautics and Astronautics	239
The John Crerar Library	240
The Chemical Abstracts Service	241
Allis Chalmers Inc. (Director)	242