PB87-137964

Pavement Management Using Video Imaging Techniques
Phase 1 Final Research Report

AMI Consultants, Reno, NV

Prepared for

National Science Foundation, Washington, DC

Jul 84

U.S. Department of Commerce
National Technical Information Service
NTIS

NSF/CEE-84076

PB87-137964

AMI CONSULTANTS

APPLIED MATERIALS INSTRUMENTATION CONSULTANTS

PAVEMENT MANAGEMENT USING VIDEO IMAGING TECHNIQUES

PHASE I FINAL RESEARCH REPORT

TO

THE NATIONAL SCIENCE FOUNDATION

SBIR / ROOM 1250

1800 G Street, N. W.

Washington, D. C. 20550

940 MATLEY LN., SUITE #5 • RENO, NEVADA 89502 • (702) 786-0348

50272-101

REPORT DOCUMENTATION PAGE	1. REPORT NO. NSF/CEE-84076	2.	3. Recipient's Accession No. PB87 137964/AS

4. Title and Subtitle
Pavement Management Using Video Imaging Techniques, Phase I Final Research Report

5. Report Date
July 1984

6.

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8. Performing Organization Rept. No.

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10. Project/Task/Work Unit No.

11. Contract(C) or Grant(G) No.
(C)
(G) CEE8360719

12. Sponsoring Organization Name and Address
Division of Industrial Science and Technological Innovation (ISTI)
Directorate for Scientific, Technological, and International Affairs (STIA)
National Science Foundation, Washington, DC 20550

13. Type of Report & Period Covered
SBIR Phase I

14.

15. Supplementary Notes

16. Abstract (Limit: 200 words)
This research is directed at improving the quality and quantity of pavement management system information being used by highway organizations. This feasibility study investigates: (1) the use of a "slit" sensor for observing pavement surfaces at highway vehicle speeds; (2) image processor algorithms for the detection of pavement distress; (3) pavement scoring procedures best suited to video imaging; and (4) pertinent non-video data acquisition requirements. Results have shown that, for highway speeds, a "slit type video sensor is not only desirable, but mandatory. Video image processing algorithms have been developed to detect pavement distress. Pavement scoring vectors and non-video data acquisition requirements have been identified.

17. Document Analysis a. Descriptors

Pavements	Highways	Detectors
Algorithms	Maintenance	Maintenance management
Wear	Defects	Cracks
Histograms		

b. Identifiers/Open-Ended Terms
Imaging

D15

c. COSATI Field/Group

18. Availability Statement	19. Security Class (This Report)	21. No. of Pages
NTIS		90
	20. Security Class (This Page)	22. Price

(See ANS–Z39.18) See Instructions on Reverse OPTIONAL FORM 272 (4-77) (Formerly NTIS-35) Department of Commerce

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Pavement Management
Using Video Imaging Techniques

Phase I Final Research Report

Grant No. CEE-8360719

to

The National Science Foundation

by

AMI Consultants
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Reno, Nevada 89502

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July 1984

This material is based upon work supported by The National Science Foundation under award number CEE-8360719. Any opinions, findings, and conclusions or recommendations expressed in this publication are those of the authors and do not necessarily reflect the views of The National Science Foundation.

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IDENTIFICATION AND SIGNIFICANCE OF THE PROBLEM

One of the single greatest investments of public agencies, if not the greatest, is its network of roads and streets. The maintenance of these highways has posed significant problems in the management and survey of pavement surfaces. Just observing pavement surfaces to determine potential maintenance is a tremendous labor intensive problem. The collection of huge amounts of "Visual Data" (and other data as well) is the focal point of this research effort.

Typically, road crews walk or ride slowly moving vehicles to determine and record, by hand-written notes, the various distresses present in pavement surfaces. This activity leads to the classification of cracks along the pavement direction, transverse to pavement direction, area cracking, and a host of other pavement conditions that require maintenance attention; rutting, pavement flow, etc. To complicate matters, there are many techniques for "scoring" the pavement surface.

A recent advancement by some Departments of Transportation is to employ photographic techniques to gather pavement surface data. Although this collection technique has advantages over "walking and scoring", someone still has to evaluate the raw photograph and provide a "score" based upon certain classification techniques. What is addressed in this research effort is to investigate the use of high speed video image processing techniques to evaluate scanned images of pavement surfaces in real-time.

BACKGROUND, TECHNICAL APPROACH, AND ANTICIPATED BENEFITS

A standard television image frame is produced in 33 milliseconds. Each frame is converted to an array of picture elements (pixels) by using a high speed analog to digital converter module. These pixels are processed individually for "gray" scale or color content. Typically, a television frame is divided into an array of 512 x 512 pixels. Other pixel formats are also used (256 x 256 - 1024 x 1024) and depend upon the nature of the measurement accuracies required for a particular application. Considerable attention is given to the optics portion of the system - wide angle, zoom, etc. The system must be able to detect not only the extent of surface cracking but also the width of the crack in question. An N x N array is shown in Figure 1 with an 8 bit gray scale resolution.

Cracks are typically observed by noticing the shadow associated with the pavement separation. Crack shadows are typically much darker than the surrounding pavement. To an image processor, the difference in gray scale is easily detected by simple "threshold" techniques. The problem here is that the shadow value depends upon the available lighting. This threshold must be calculated to determine a

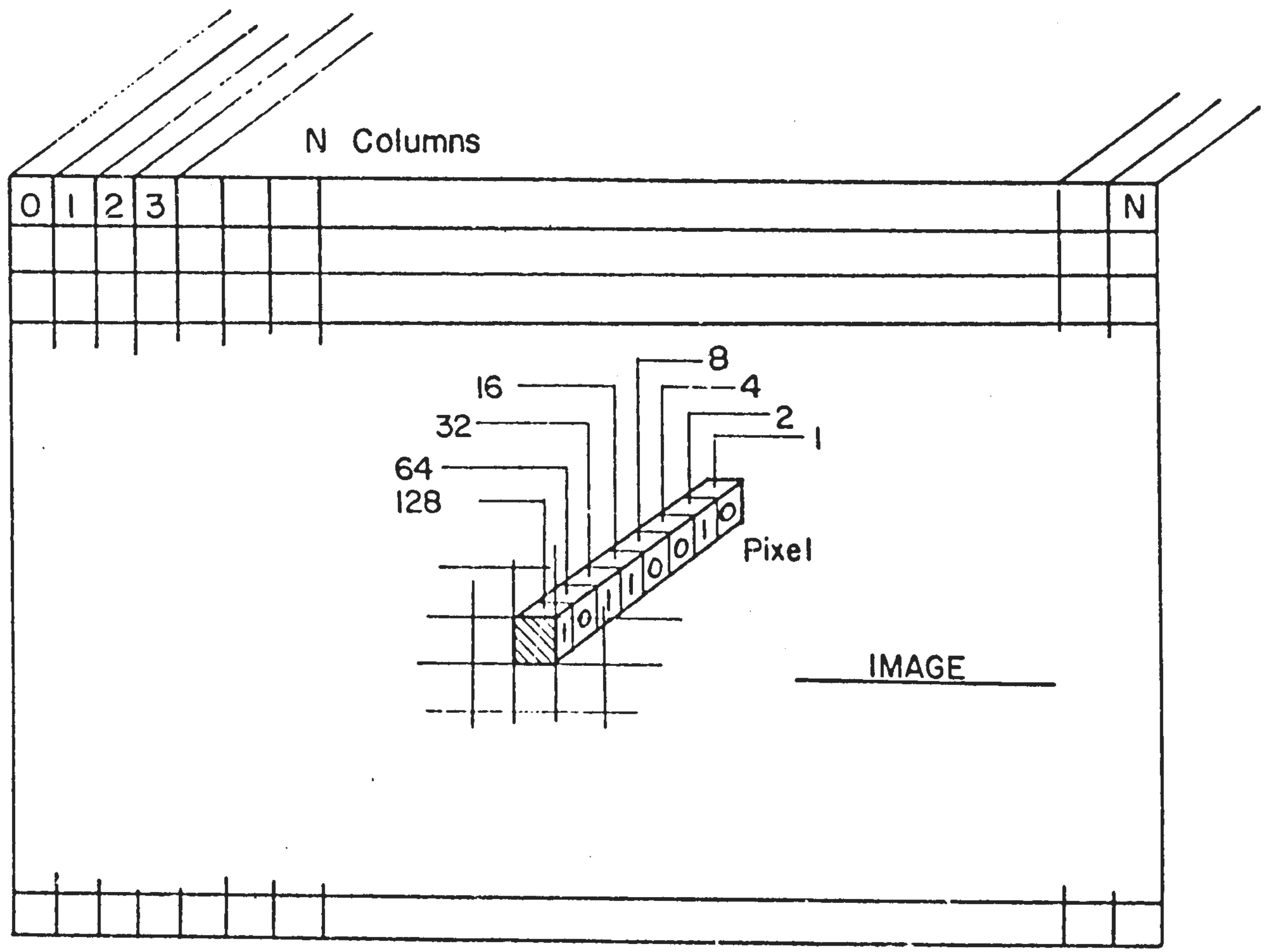


FIGURE 1 - N x N Pixel Array with 8 Bit Gray Scale Resolution

suitable value. As one would expect, pavement surface texture and aggregate color play an important role in this calculation. Additionally, images of pavement surfaces typically lack the contrast required for reliable processing. In order to do reasonable processing, contrast enhancement, threshold calculation, noise removal, and other pre-processing techniques must be employed.

As a first step in pre-processing, each pixel is "sorted" according to gray scale value. A simple count indicating the number of each gray value from black to white - typically 256 different gray scale values are plotted. This plot is called a <u>histogram</u> and provides much information about the original image. Objects such as cracks appear to "cluster" around a similar gray scale level as do larger objects of similar color. A typical histogram is shown in Figure 2.

The pavement texture appears to contain the bulk of the pixel information at medium gray scale and is typically found in the middle of the histogram. Dark objects will be indicated with activity close to the black end of the scale. The range of actual values are clearly indicated on a histogram plot.

Other objects of interest such as the white/yellow stripping are shown as a bump near the white end of Figure 2. In this example, the "determined" threshold for cracks is set equal

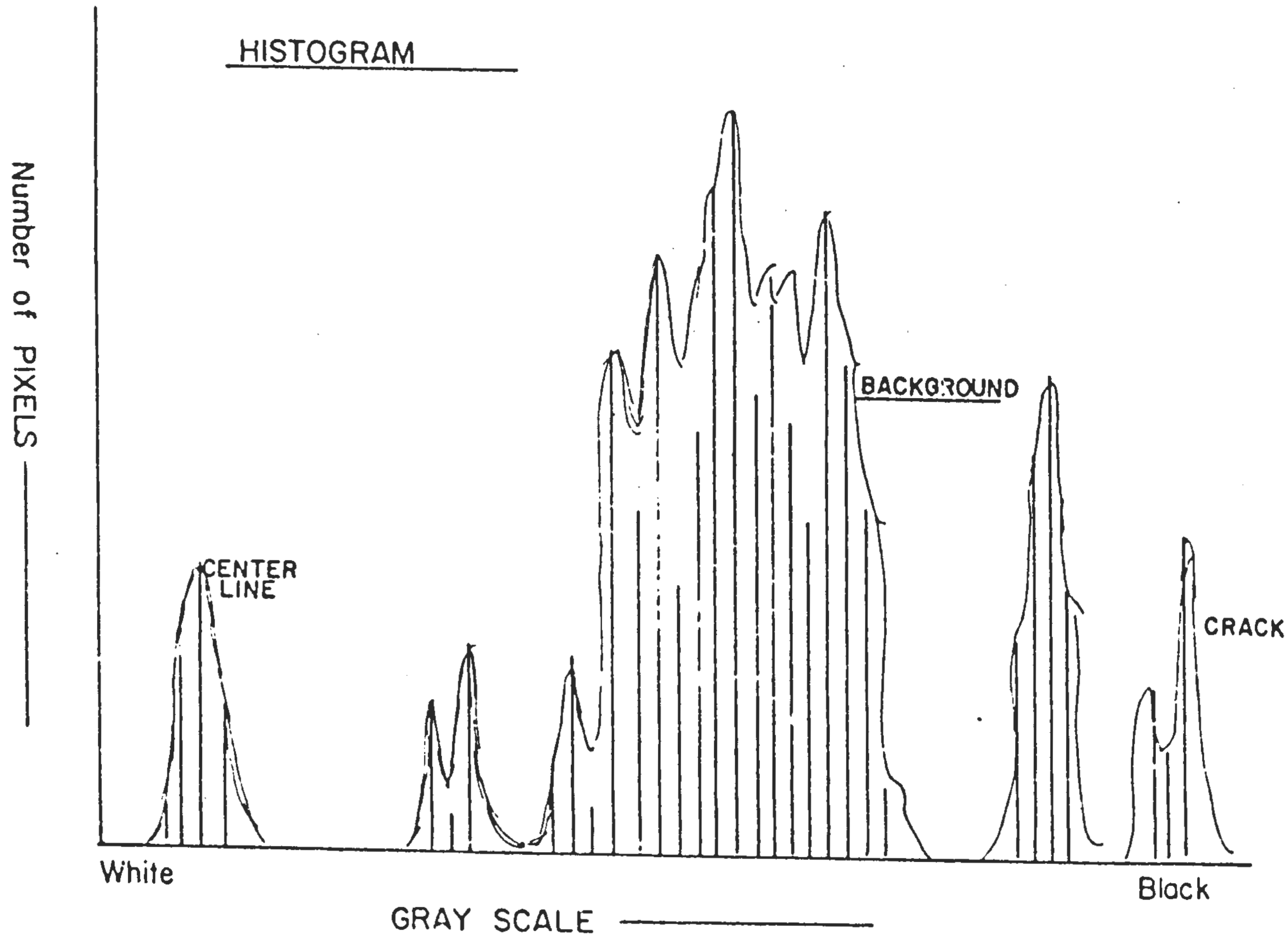


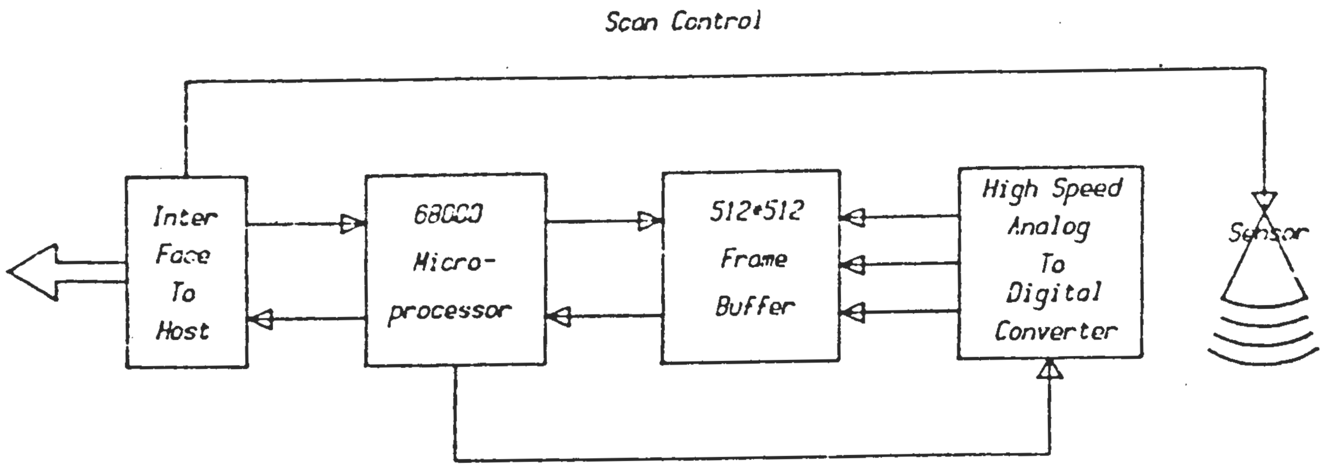
FIGURE 2 - Typical Pavement Gray Scale Histogram

to a value greater than the background gray levels. The thresholded image is composed of two values - black pixels and white pixels. By assignment, pixels with values greater than the background level are black and pixels of value less than or equal to the background level are assigned a white value. Ideally, only the cracks appear in the thresholded image. The actual situation is never ideal and more refined techniques are required.

A typical system is composed of a sensor, a "frame buffer" - image memory, a processor producing scored attributes and a suitable output display. The block diagram of a typical system is shown in Figure 3.

Several sensors are commonly used in image processing. Standard television raster scanned cameras are available using Charge Coupled Devices (CCD), Charged Capacitor Sensors (CCS), and a conventional image vidicon. These sensors are suitable for the processing of fixed images such as a photograph or even pavement while the camera is motionless. Some movement of the camera is tolerated but one frame is analogous to a timed interval of 1/30 sec. In order to provide an image processing system capable of taking data while moving - a highly desirable feature - special consideration is given to a "slit" type of sensor shown in Figure 4.

Optics are provided to focus data in a single line across



Modular Product Concept

FIGURE 3 - Image System Block Diagram

FIGURE 4
1 x 512 Pixel Slit Sensor

one lane of the pavement to be measured. The motion of the vehicle provides the second dimension of the image and is carefully synchronized with vehicle speed. As the vehicle is moving, the pixel data is loaded into the processor. At the end of a "frame", data is stopped from entering the processor for a short period of time while the image is being processed. During the output of the processed image, new data replaces old information that has been scored and classified. It is possible to "classify" and "score" the pavement while the vehicle is in motion therby measuring the pavement condition and eliminating the previous labor intensive operation. The obvious advantage is the fast acquisition of data for an efficient and cost effective data management system.

If this research effort is ultimately successful, the benefits to highway departments and subsequently to highway users can be substantial. Highway officials will have at their disposal much broader and more relevant information in the form of a data base to use as input to a Pavement Management System (PMS). Subsequently, more effective decisions regarding the expenditure of highway maintenance funds can be made. Highway users will ultimately benefit from more efficient use of those funds and by being provided with roadways of a higher quality.

It is estimated that a total research effort on the order of

$500,000 will be required to produce a working prototype model of a pavement evaluation device. Production costs will be additional. A production model may have a user cost on the order of $200,000. Considering the number of highway miles in existence and the billions of dollars invested in our nation's street and highway system, the cost associated with the development of a device of the type described in this research report is extremely small.

PHASE I RESEARCH OBJECTIVES

The obvious objective of this phase I study is to establish the feasibility of employing the video image techniques described to a pavement management system. More specifically we attempted to answer the following questions:

1. Is the use of a slit sensor feasible for observing pavement surfaces?
2. What image processor algorithms are required for the detection of pavement distress?
3. What pavement condition scoring procedures best lend themselves to image processing techniques?
4. What data logging procedures are required to acquire, store and retrieve measured and processed data for the establishment of a usable data base?

DESCRIPTION OF THS RESEARCH CONDUCTED

Described in the following sections of this report are the research efforts conducted on the four objectives presented. Although the objectives overlap to some extent and the investigation of the four objectives was conducted in parallel, the objectives are discussed as independent efforts.

The most critical concern in this research study was the investigation of image processing algorithms. If algorithms could not be developed to detect pavement distress, then our research efforts would most likely be futile. If however, it could be shown that initial steps in the development of such algorithms showed promise, then the technical risk associated with the development of the proposed devise would be drastically diminished. To that end, AMI Consultants obtained three video image processing circuit boards on a loan basis from Imaging Technology, Inc. A picture of these boards is shown as Figure 5. These three boards consist of an ALU (arithmetic logic unit), a frame buffer (memory), and a microprocessor board.

In order to develop imaging software for specific use in a pavement monitoring device, AMI Consultants has designed and assembled a microprocessor circuit board and written the software to communicate with the Imaging Technology, Inc. board. AMI Consultants' board is shown in the foreground of

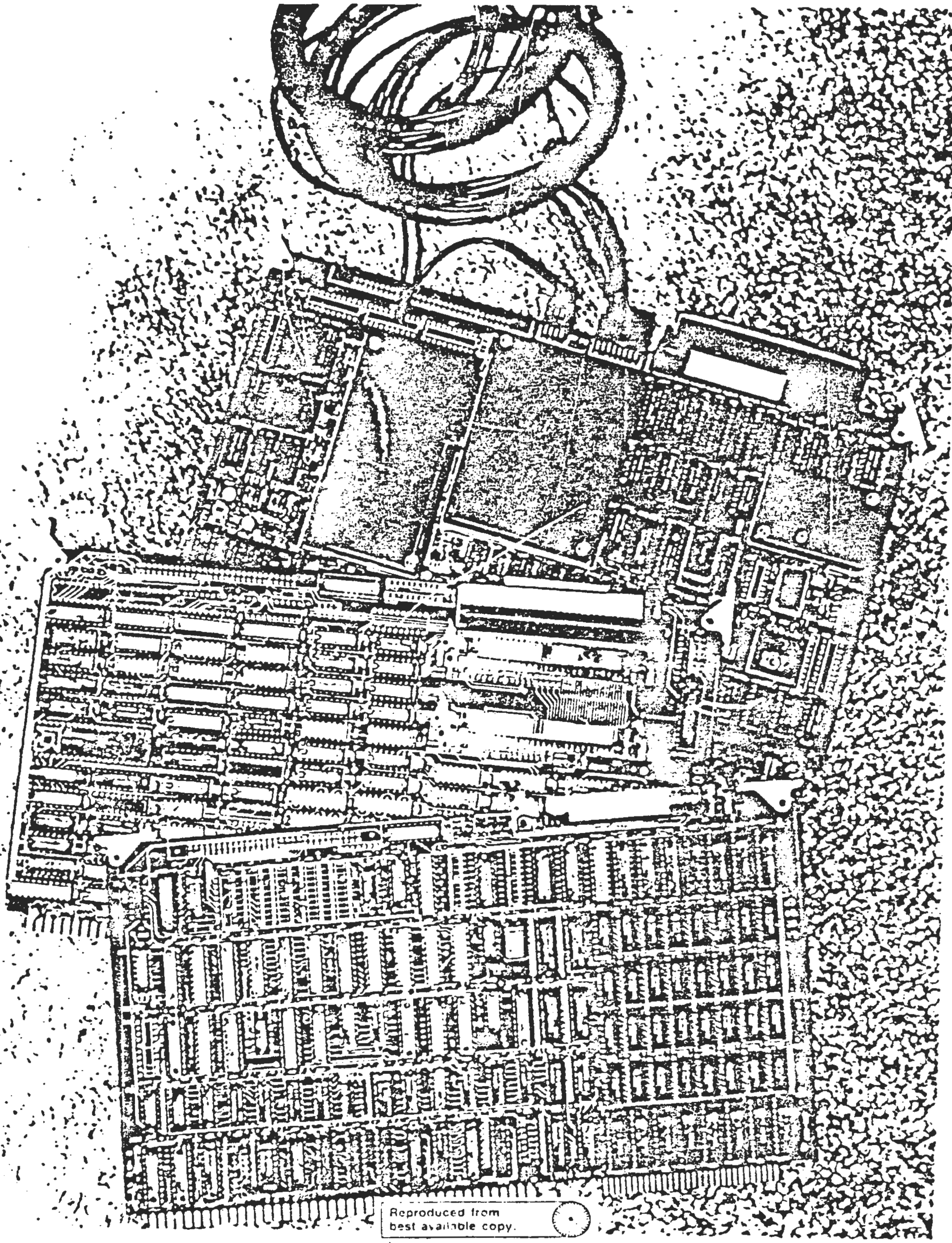


FIGURE 5 - Circuit Boards On Loan From Imaging Technology, Inc.

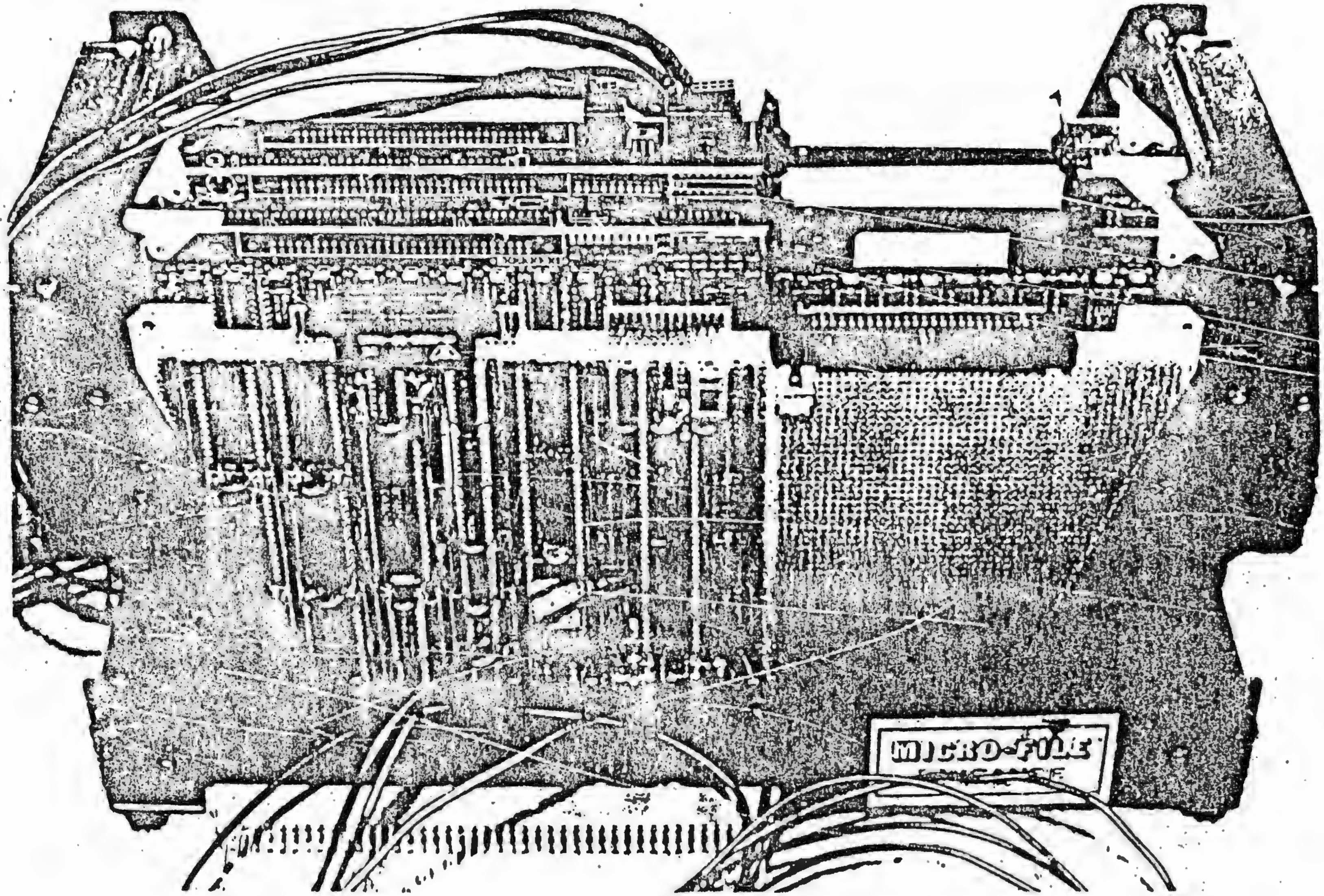


FIGURE 6 · AMI Consultants' Microprocessing Circuit Board

Figure 6 in a rack mount configuration with the three borrowed circuit boards.

LINE SCAN (SLIT) IMAGE SENSOR

For the pavement management vision system, the problem of relative motion (vehicle moving, pavement surface fixed) of the pavement surface image is a significant problem to the research effort. The normal raster scan (standard television rates) at 1/30 second per frame will cause "blurring" at less than 10 miles per hour for a camera mounted vertical to the pavement surface. Even cameras mounted at 45 degrees to the pavement surface will observe blurring at speeds much less than 55 mph, and yield images with severe geometric distortion. In order to obtain "reasonable" blurr-less images at highway speeds, a controlled line scan sensor must be employed.

The line scan camera is composed of the usual optics (lens, focus arrangement, and diaphram), a line scan sensor (called a "slit" sensor) in 1 x 256, 1 x 512, etc. formats, and control circuitry to specify sensor scan rates, cell integration time, and output data flow. A block diagram of a typical slit sensor is shown in Figure 7. Photo energy is focused on the narrow slit which is composed of 256 photosites (512, 1024, etc.). These photosites are divided into even and odd picture elements (pixels). During the

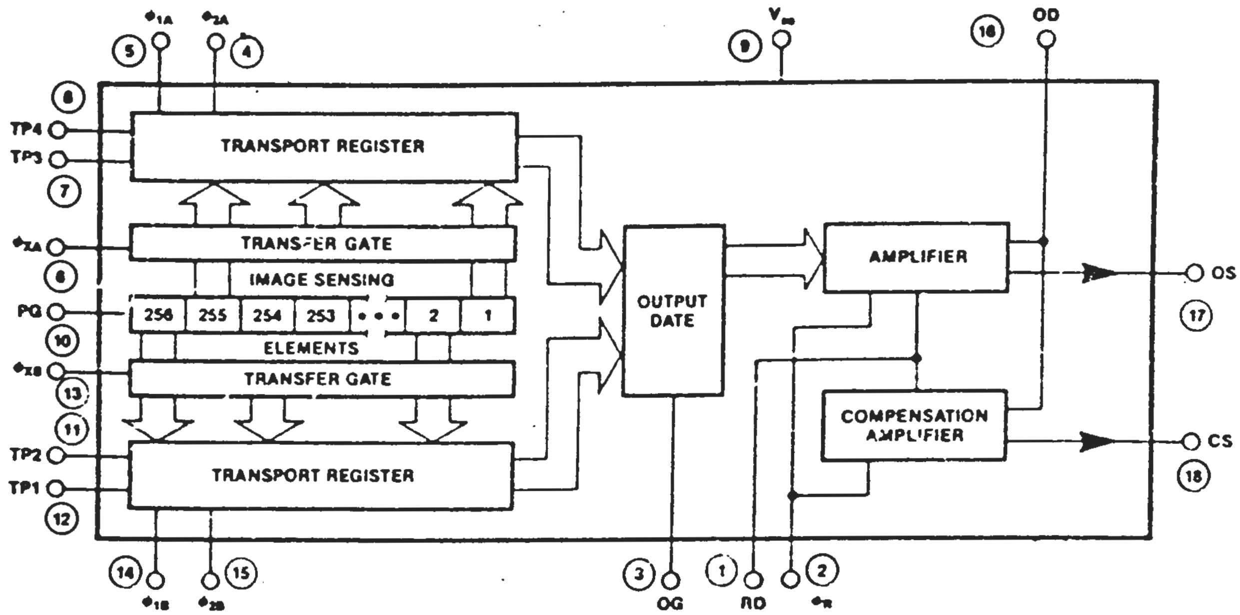


FIGURE 7 - Block Diagram of a Typical Slit Sensor

scanning process, the linear array is transferred to a shift register memory which is composed of even and odd photosite data. This transfer is done during a single clock pulse. The time between these transfer clock pulses is called the "integration time", so called because this time is directly proportional to amount of photo energy "collected" by each photosite. This time is very important to the success of blurr-less images.

AMI Consultants has investigated two well known manufactures of linear scan image sensors (Fairchild, and Thomson-CSF). The minimum integration time required, therefore determining the blurring characteristics, is a function of transfer clock frequency, photosite saturation levels, and the lighting provided. In addition to the integration restriction, the output data rate must be within achievable levels. For example, a line scan sensor with 2048 photosites may have an acceptable integration time but may fail the required sensor specifications because of a slow image generation characteristic--i.e. may not be able to generate the image fast enough for image processing as the vehicle moves along the pavement. It is clear that the sensor data rates must be closely matched to the image processor execution speed and the computer architecture.

The Fairchild CCD-111 device is a 1 x 256 n-channel isoplanar sensor with analog shift registers, output amplifier, and two (even, odd) charge transfer gates. This device specifies a 10 mhz typical output rate with an integration time of 32 microseconds. (At 32 microseconds, approximately 1000 line scans may be performed within a "standard raster" of 33 milliseconds. Since AMI Consultants proposes to use a 512 x 512 pixel format, i.e. only 512 lines, the sensor may be used with adequate margin. At 60 mph (88 feet per second), the pavement is moving under the vertically mounted sensor at 0.001 inches per microsecond. The transfer of photosite data to the odd/even shift register occurs in one clock time (0.1×10^6 seconds for a 10 mhz clock signal). This represents a ground movement of 0.0001 inch in the pavement direction. For 0.1 inch pixels, the movement is approximately 0.1%--well within the tolerable level and will not require any restoration in the processor. In fact, some movement is quite desirable and will provide the effect of "neighborhood" pixel averaging. This innovative approach saves many precious milliseconds of processor time.

Real-time processing will require a data processor that can keep up with sensor data rates and handle the algorithms that produce the processed image. Algorithms must be chosen carefully to run efficiently on special purpose processor architecture--A system that has been developed at AMI Consultants. AMI Consultants has also obtained a small evaluation system from Fairchild called an I-SCAN Design Development Board Set for further verification of the line scan sensor. A discussion of this system appears later in this report.

IMAGE PROCESSING ALGORITHMS

AMI Consultants has investigated several data acquisition approaches for remote sensing using video image processing. And, in particular those high speed systems that use the linear array sensor (slit sensor). The system algorithms have been broken down into five general categories:

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Algorithm Category	Description
1. Input	Sensor Scan Control, Vehicle Speed-Image Synchronization, Frame Buffer Storage Selection, Non-visual Data Acquisition.
2. Preprocessing	Image Noise Removal, Gradient and Edge Detection, Global and Local Thresholding, Perimeter and Edge Calculation, Direction Cracking Detection.
3. Processing	Object Identification, Instantaneous and Cumulative Pavement Scoring, Rut Depth Calculation, Signature Analysis--Moments, Transforms, Output Formatting.
4. Output	Image Display, Data Display, Recording Format.
5. Administrative	Interactive Operator Data Inputs, Self-Test and Diagnostic Comments, System Performance Monitor, Directory Formats, Calibration, Histogramming.

Many of the preprocessing algorithms are currently running on a laboratory prototype developed by AMI Consultants. The results of the Phase I study look very promising and are briefly discussed here. Except for the Administrative category, the algorithms appear in approximately the order that must be accomplished during vehicle movement on the pavement lane.

As the vehicle moves across the road surface, the "slit sensor" scans a very small portion of the image. The scanning repetition rate is controlled by the vehicle speed

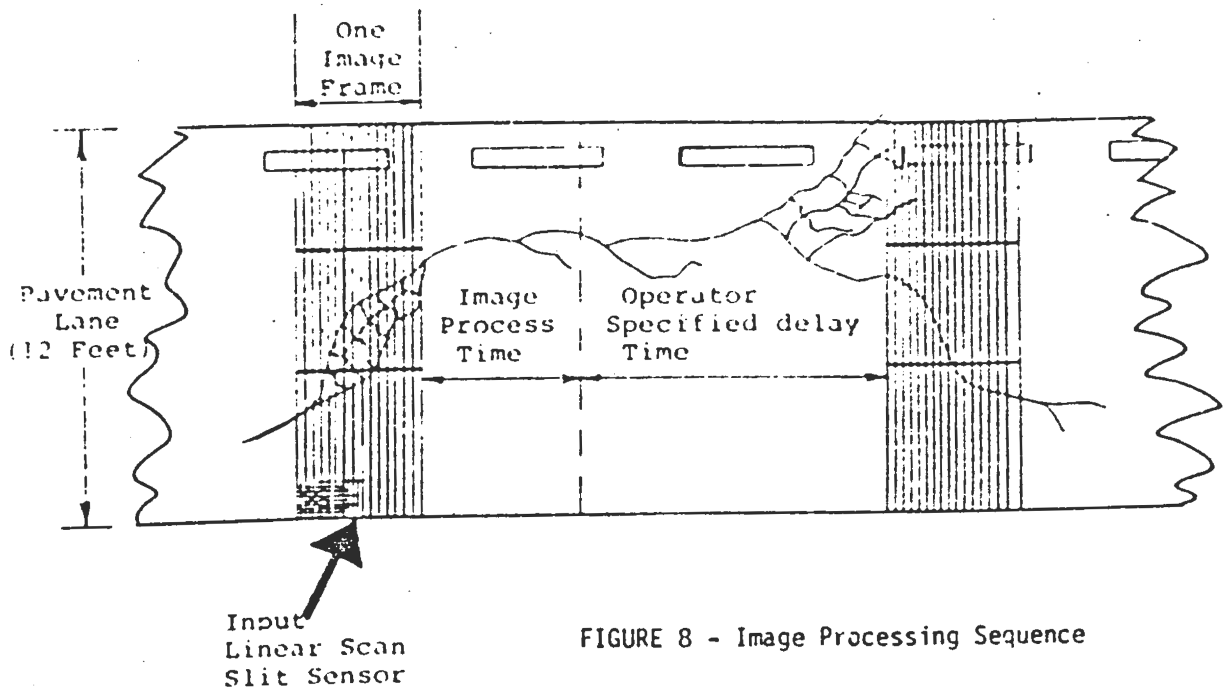

FIGURE 8 - Image Processing Sequence

and desired image format. When enough scans are completed (when the frame is complete) to fill the image, processing begins. The timing sequence, except for calibration and some other administrative functions, proceeds as, "input frame image, processing, input frame image, processing, input ....". An operator may choose to control the number of frame images per lane mile by introducing a "delay" at the end of a processed image and before the input of the next frame as shown in Figure 8.

An additional approach recommended by AMI Consultants is to take advantage of the "serial" nature of the scanned slit sensor and design a hardware "convolver" (a special 3 x 3 neighborhood multiplier circuit) that will directly be interfaced to the sensor for "preprocessing". As soon as the convolver "fills" with data approximately two scan lines), processed image lines are produced and may be ready for simple scoring. The suggested convolver arrangement is shown in Figure 9. The convolver receives serial data that is shifted byte by byte through the 3 x 3 neighborhood aperature, plus two 509 byte shift registers (assuming a 512 x 512 image format). After 1027 shifts (3+509+3+509+3), the convolver is "full" and neighborhood processing can begin. Neighborhood processing uses a "weighted" 3 x 3 Kernel in multiplying the 3 x 3 pixel image to produce a neighborhood:

1. Average
2. Gradient
3. Directly Cracking Correlation
4. Enhancement
5. Threshold

Noise Removal Algorithm :

The first order of preprocessing is to remove signal noise from the image. This could be caused by spurious vehicle noise, pavement surface background texture, and generally containes a "high frequency" signal content that should be removed prior to the application of the gradient algorithm.

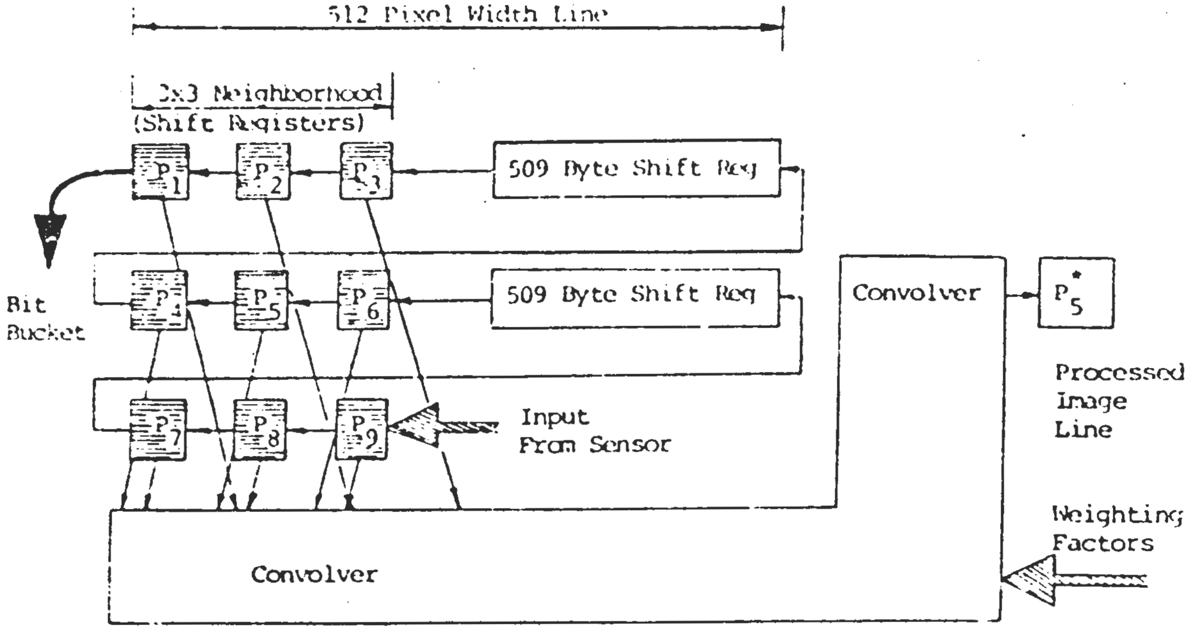

FIGURE 9 - Serial Convolver/Shifter

The general convolver equation is used:

$$P_5^* = \frac{P_1W_1 + P_2P_2 + \cdot \cdot + P_9P_9}{D} \qquad (1)$$

$$\begin{bmatrix} \cdot & \cdot & \cdot \\ \cdot & P_5^* & \cdot \\ \cdot & \cdot & \cdot \end{bmatrix} = \begin{bmatrix} P_1 & P_2 & P_3 \\ P_4 & P_5 & P_6 \\ P_7 & P_8 & P_9 \end{bmatrix} X \begin{bmatrix} W_1 & W_2 & W_3 \\ W_4 & W_5 & W_6 \\ W_7 & W_8 & W_9 \end{bmatrix} \qquad W_{i's} = 1, \; D = 9 \qquad (2)$$

Then,

$$\frac{P_1 + P_2 \cdot \cdot \; P_9}{9} = P_5^* \qquad (3)$$

P_5^* is the processed pixel and represents the "center of the 3 x 3 solution image. As the 3 x 3 window is effectively "passed" over the image, a series of P_5^*'s form the processed image. An increase in speed occurs if a second convolver follows the first. Then,

$$\frac{P_1^*W_1^* + P_2^*W_2^* + \ . \ . \ . + P_9^*W_9^*}{D^*} = P_5^{**} \qquad (4)$$

The second convolver is "filled" after 2054 byte shifts (1027 from the first convolver plus 1027 from the second convolver) and begins to produce a solution, P_5^{**} a short time after fill (between shift 2054 and 2055). Each convolver stage will usually have different sets of W_i's and therefore will provide for many kinds of neighborhood operations. Window "averaging" can be also accomplished by intentionally "blurring" the original slit sensor data. This is accomplished by controlling the sensor "integration time"--i.e. slowing down the cell transfer rate thereby increasing the integration time that will cause image blurring. AMI Consultants has determined that approximately 5%--8% blurring is desirable and can eliminate the need for averaging by convolution.

Gradient and Edge Detection Algorithm :

Pavement cracking, as seen in the "gray scale" image is characterized by a very narrow shadow caused by side lighting and shadow cast--shown in Figure 10.

The image camera "views" the crack as a "darker" shade of gray against a lighter gray background. The distance or difference in gray scale value is called the <u>Crack Margin</u> . For high speed, reliable, and efficient calculation, a large crack margin is desired. This feature also allows for considerable rejection of false cracking (oil spots, sealed cracks, etc.). A very nice algorithm to accomplish the increased crack margin is to use a "gradient" technique that is similar to differentiation. The slight difference in gray scale values are amplified. Larger differences in gray scale are also amplified and may cause gray scale saturation. The gradient operation may be implemented by again using the neighborhood operations on four pixels:

$$\begin{matrix} P_1 & P_2 & \cdot \\ P_4 & P_5 & \cdot \\ \cdot & \cdot & \cdot \end{matrix}$$

$$(P_1-P_5)+(P_2-P_4) = P_5^* \quad (5)$$

$$\frac{P_1+P_2+OP_3+\ldots-P_4-P_5-OP_6-\ldots-P_9 = P_5^*}{D} \quad (6)$$

$$W_1=1,\ W_2=1,\ W_3=0,\ W_4=4\ldots W_9 = 0,\ D=1$$

The gradient operation will produce low outputs (P_5^*'s) for approximately equal gray scale pixel values and high outputs for adjacent differing pixel gray values. Typically, the crack shadow is protrayed as an "object" noted in Figure 11.

The gradient will "outline" the crack with a perimeter

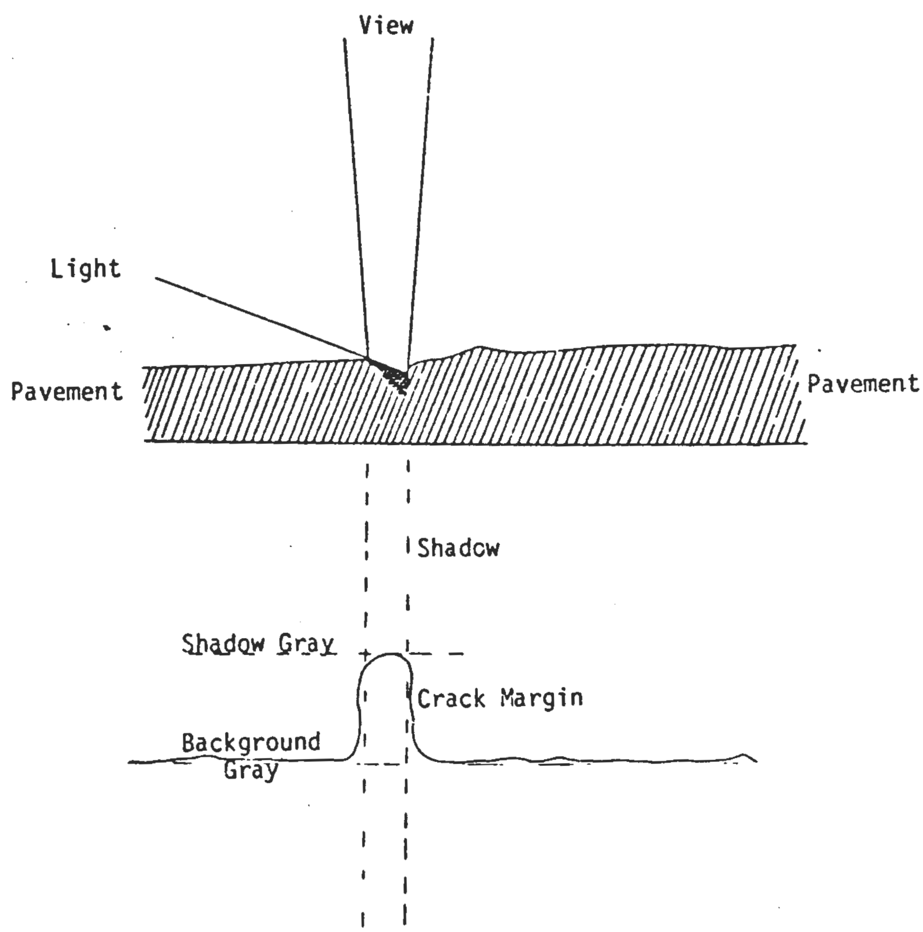

FIGURE 10 - Crack and Shadow Representation

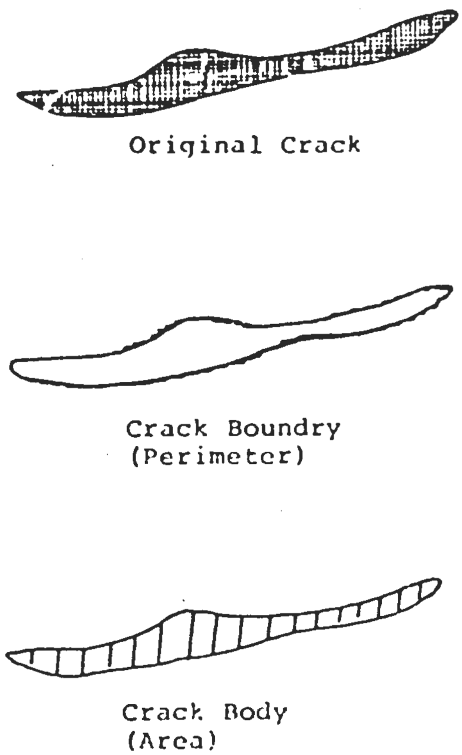

FIGURE 11

Crack Object
(Area/Perimeter)

identified against a low level background. Except for slight anomalies, the gradient background will be close to zero (white), while the edge will be "elevated" in gray scale value tending toward a black representation.

Local and Global Thresholding Algorithm :

Thresholding, naturally follows the gradient algorithm for edge detection. The result of this arithmetic step is to produce a binary image--background white, edge or area data will be black. The simplest form of thresholding is to just apply a "threshold" test value to all the pixels in the image to be processed in the following fashion:

$$\text{Assign} \quad \begin{array}{l} P_5^* = 1 \text{ If } P_i \geq \text{Threshold Value, } T \\ P_5^* = 0 \text{ If } P_i < T \end{array} \qquad (7)$$

The problem with this technique is two fold: First, the threshold value must be determined (not an easy task) which will be dependent upon ambient lighting (bright sunlight, cloudy, reflections, etc.). Secondly, the same threshold may not be advantageous to use in certain regions in the overall image--shadows and other low contrast, low detail, regions. The technique posed in Equation 7 is called "global" while a series of smaller areas within the image may also be thresholded, each area separatley, accordingly to Equation 7. This technique is called "local" thresholding. AMI Consultants has developed both global and local thresholding algorithms using a Motorola 6809 microprocessor. Additional thresholding, called bandpass thresholding by AMI Consultants, provided by:

$$\text{Assign} \quad \begin{array}{l} P_5^* = 1 \text{ If } P_i \leq T_2 \text{ AND } P_i \geq T_1 \\ P_5^* = 0 \text{ If } P_i > T_2 \text{ OR } P_i < T_1 \end{array} \qquad (8)$$

For example, if a pavement background is represented by some gray value, say T_1, and the shadow of the crack at another gray value, say T_2, then all pixels between T_2 and T_1 would represent the body of the crack. A "Bandpass" threshold algorithm would quickly identify the crack for classification. The establishment of values T_2 and T_1 were found to be very effective if "local" thresholding techniques were used. This technique is illustrated in Figure 12.

Two significant figures of merit that emerge from the thresholding and gradient algorithms are the determination of shadow crack area (body of the distressed pavement) and the perimeter (edge of the distressed area). A thresnolded gradient algorithm provides the perimeter and a bandpass thresholded algorithm provides the crack area.

Crack Validation Algorithm :

So far, the algorithms discussed will detect cracks in relatively new pavement. This capability is not realistic and suitable techniques must be used to reject patches, sealers, and other non-crack gray scale objects contrasted with the pavement background. At this point, a valid crack is assumed to be a long slender object (as seen by the image sensor). This feature is verified using the area to perimeter ratio as shown in Equation 9.

$$S = K\frac{A}{P^2} \qquad (K = 4\pi, \text{ (circle normalizing factor)}) \qquad (9)$$

If S = 1 Shape is circular
S = .8 Shape is square
S = .5 Shape is rectangular
S = .3 Shape is long, slender
S = .05 Shape most likely is "crack line"

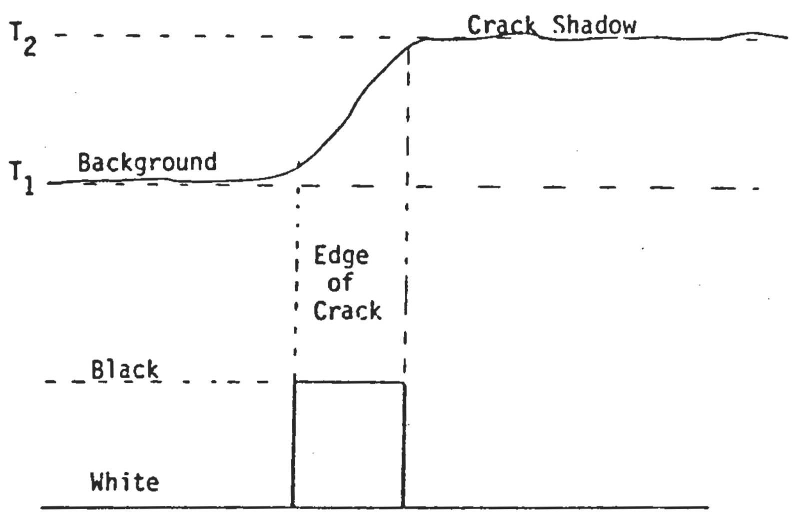

FIGURE 12 - Bandpass Threshold Selection

Assuming the processed "object" is a crack, then other attributes may be necessary for proper scoring from image detection. These are:

1. Crack Area--Proportional to total image area.
2. Crack Direction--Recognizing longitudinal and traverse cracking.
3. Crack Width, Length, Depth.

<u>Directional Cracking Algorithm</u> :

The crack detection algorithm is composed of several parts--averaging, gradient, thresholding, edge and area calculations. The "area" subroutine of the algorithm determines the "amount" of pavement distress--most likely a majority of cracking activity. The "area" image will contain thresholded "black" pixels that are simply counted. The entire 512 x 512 pixel image is then composed of 262,144 pixels. The number of black pixels in relation to 262,144 (times 100) is the percentage of "bad" pavement. The direction of the crack within the pavement lane now has a bearing on the scoring. It becomes very desirable to determine the <u>direction</u> of the cracking in at least two directions:

1. Longitudinal to the pavement lane.
2. Transverse to the pavement lane.

AMI Consultants has developed four direction sensitive detection neighborhood operators much like the "Kirsch" operators. As the neighborhood 3 x 3 window passes over the perimeter image, four counters keep track of those crack pixels that are oriented in each direction. These values are then provided for scoring of the pavement surface. These direction operators detect crack activity in the directions noted in Figure 13.

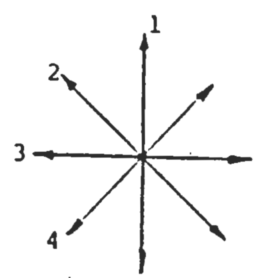

FIGURE 13

Crack Direction Sensitivity

Threshold Calculation and Image Calibration Algorithm:

The contrast difference between pavement background and a crack shadow will be largely dependant upon the reflected light and the texture of the pavement surface--variables that are largely independent. In order to obtain the necessary local and global threshold values, calibration must be performed. A "Histogram" algorithm is executed that establishes the number of pixels at each gray level. For a 262,144 pixel image, these pixels are "sorted" according to the gray levels from all white (zero gray scale value) to all black (255 gray scale value). The sorting algorithm works very fast and may be done at the same time as other neighborhood operations. A "well lighted" histogram for road pavement surface is shown in Figure 14. It is clear from this histogram that the global threshold should be chosen between points "X" and "Y". Similarly, local histograms (meaning a smaller area of the image) will allow selection of a "local" threshold. The bandpass threshold window is clearly $T_1 = X$, and $T_2 = Y$.

On a dark day, the reflected light is very much less and therefore the histogram appears heavily "bunched" at the dark end of the gray scale. Points X and Y now become closer together and harder to determine. A histogram "equalization" algorithm is applied to enhance the image contrast and therefore "spreads" the histogram gray scale toward the white end. The histogram equalization process is lengthy and is not done for every image (done for every 10 to 100 images). Furthermore, the histogram calculation may survey a total of three adjacent image cameras--i.e. only one calculation for a three camera system need be processed.

Scoring Vector :

The image processor algorithms are computing "figures of merit" that will be used by a host computer to determine the pavement condition score. A "Scoring Vector" is defined as a collection of "figures of merit". AMI Consultants is

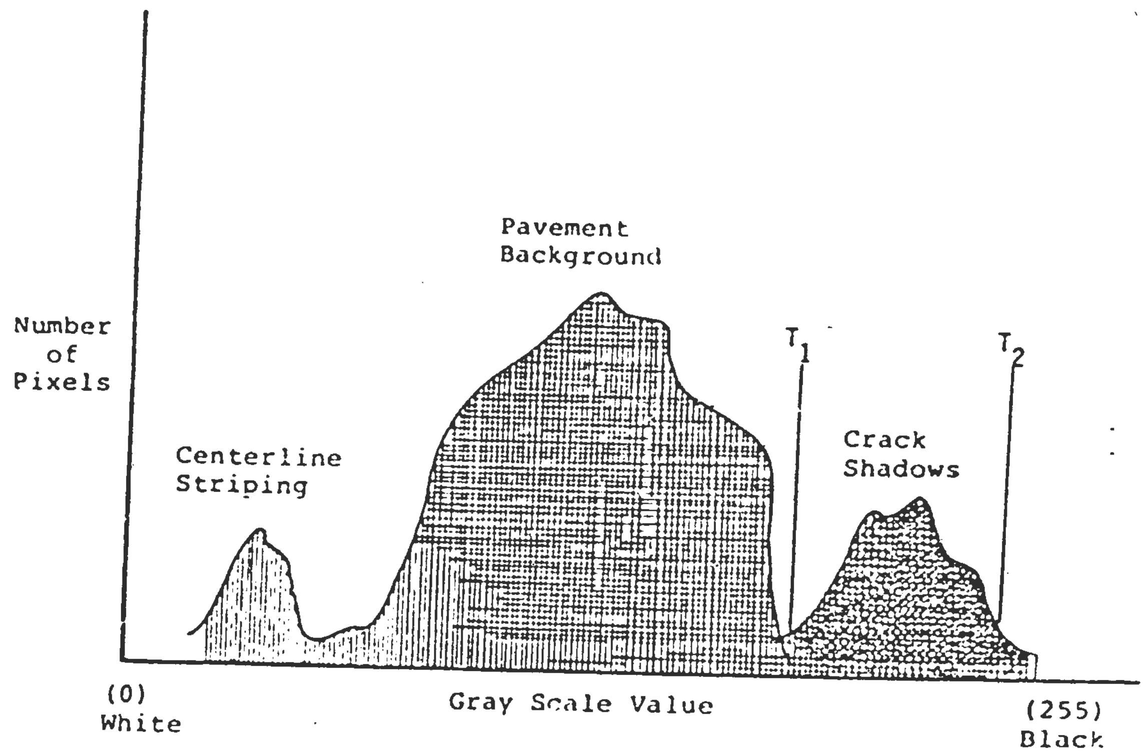

FIGURE 14 - Gray Scale Histogram

continuing the research for suitable pavement scoring, but has established the following format for each camera system.

1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18

Scoring Vector

These registers contain <u>all</u> of the necessary operand values needed for scoring. AMI Consultants proposes that at least two scores be made immediately available to the operator. These are called "quick look" scores and will aid the operator in determining the condition of the pavement surface as the vehicle is moving and recording data. The first score is an instantaneous distressed area count--the second score is an accumulation (integration) of the instantaneous score that is reset every mile or as determined by the operator.

The "Weighting" factors would be a representation of a state's scoring criteria. Florida, for example is known to use sea shells in the asphalt concrete mix. The textured background would then appear much different than the reddish aggregate found in the State of Oregon. The initial thresholded values would be generated from the weighting factors. Other effects would, of course, be included in the weight vector and would change all non-image sensor input weighting towards the final scoring value.

Presented in Appendix A are examples of computer software developed by AMI Consultants. Although not all of the software used and/or developed during this Phase I effort is presented, the software shown does give an example of the nature of the software required for the proper operation of a computer based video imaging system. It should be noted that Appendix A is set aside
as containing proprietary information.

Self Test :

The image processing pavement system is a moderately complicated device. It is very high speed and requires calibration while in operation (which is done by computer). In addition to these features, a system self test provides all the data required to perform system checks, and will identify modules requiring attention. Each sensor is exercised, calibration images are processed, memory modules are checked for proper operation. Output levels are "windowed" to insure proper recording. This test algorithm will be developed to insure a high "friendliness" factor toward a non-technical operator and will emphasize clear , simple instructions to execute the directory driven system.

PAVING SCORING

In conjunction with our research effort, we have had discussions with some state highway officials regarding pavement scoring systems. A summary of the comments by these officials indicate:

1. Each state agency has evolved its own scoring method based upon an empirical approach unique to its particular conditions of traffic, environment, availability of highway materials, etc.

2. A need exists for the development of a standardized system of scoring.

3. No particular preference was given for a scoring system which starts with a score of 100 for a perfect pavement and decreases in value with increasing pavement distress, and a scoring system which starts with zero for a perfect pavement and increases in value with increasing pavement distress.

It would appear from these discussions that almost any reasonable approach to a scoring scheme would be acceptable for use in the system being researched. In that it would be much easier to start with a score of zero for a perfect pavement and add points for distress, as observed by the scoring vectors previously discussed, our research team has made the decision to proceed with our study on this basis.

Presented as Figure 15 is an example of a computer generated pavement scoring system under development by AMI Consultants. This system has its roots in the system developed by the State of Nevada Department of Transportation and was adopted by AMI Consultants because it uses the "zero and increasing" approach to scoring. Additionally, the State of Nevada has agreed to cooperate with AMI Consultants on future development efforts.

NON-VIDEO DATA ACQUISITION

As part of the Phase I objectives, question four addresses all necessary non-video parameters required as part of the overall data acquisition system. The total system is composed of a multi-processor video image data acquisition system and an 8 channel multiplexer, programmable gain amplifier, sample/hold amplifier, 12-bit analog to digital converter (ADC) and control logic clock. The non-video data acquisition system will provide analog inputs from contacting transducers mounted on the vehicle, and will allow extra channels for future expansion. The contacting transducers will provide vehicle distance traveled, velocity, and vehicle displacement between the rear axle and the body. This data then will be correlated with the video image processed data to provide a direct measurement to the

NEVADA
DEPARTMENT OF TRANSPORTATION

****

******** QA INPUT DATA ********

OPERATERS NAME IS JOHN J DOE

DATE IS---------- 4/12/1984

DISTRICT IS------ 3

COUNTY IS-------- WASHOE

ROUTE NUMBER IS-- US 395

BEGINNING M.P. IS 22.15

TRAVEL DIRECTION- NORTH

****

MILE POST IS 23.15

******** MEASURED DATA ********

SLOPE VARIANCE, in = 13.0
EXT OF ALLIGATOR, ft^2 = 71
EXT OF LINEAR CRACK, ft = 187
WIDTH OF LINEAR CRACK, in = .86
RUT DEPTH, in = .88
EXT OF PATCHING, ft^2 = 83
EXT OF BLEEDING = NONE
EXT OF RAVELING = SLIGHT

********* SCORED DATA *********

SLOPE VARIANCE = 226
ALLIGATOR CRACKING = 106
LINEAR CRACKING = 362
RUT DEPTH = 412
PATCHING = 42
BLEEDING = 0
RAVELING = 100

*** TOTAL TEST SECTION SCORE ***

TOTAL SCORE = 1206

****

MILE POST IS 24.15

******** MEASURED DATA ********

SLOPE VARIANCE, in = 3.9
EXT OF ALLIGATOR, ft^2 = 190
EXT OF LINEAR CRACK, ft = 13
WIDTH OF LINEAR CRACK, in = .22
RUT DEPTH, in = .21
EXT OF PATCHING, ft^2 = 13
EXT OF BLEEDING = MODERATE
EXT OF RAVELING = NONE

********* SCORED DATA *********

SLOPE VARIANCE = 48
ALLIGATOR CRACKING = 285
LINEAR CRACKING = 90
RUT DEPTH = 0
PATCHING = 7
BLEEDING = 100
RAVELING = 0

*** TOTAL TEST SECTION SCORE ***

TOTAL SCORE = 523

****

MILE POST IS 25.15

******** MEASURED DATA ********

SLOPE VARIANCE, in = 1.5
EXT OF ALLIGATOR, ft^2 = 54
EXT OF LINEAR CRACK, ft = 167
WIDTH OF LINEAR CRACK, in = .49
RUT DEPTH, in = .14
EXT OF PATCHING, ft^2 = 205
EXT OF BLEEDING = NONE
EXT OF RAVELING = NONE

********* SCORED DATA *********

SLOPE VARIANCE = 18
ALLIGATOR CRACKING = 80
LINEAR CRACKING = 214
RUT DEPTH = 0
PATCHING = 102
BLEEDING = 0
RAVELING = 0

*** TOTAL TEST SECTION SCORE ***

TOTAL SCORE = 313

FIGURE 15 - Example of Computer Generated Pavement Scoring Technique

visual measurement correlation thus adding confidence to the image processed data in addition to contributing information to the data base.

The two types of contacting transducers will be used initially. The first type will be a pulse counting encoder to measure distance. It is capable of resolving 0.006% of a mile. The second transducer type is a displacement measuring system. It consists of two ultrasonic transducers with integrated signal conditioners. Their only requirement for operation is a bi-polar D.C. voltage power supply. The two displacement transducers will be mounted near the wheels at each end of the rear axle and the sum of the outputs will be acquired and processed to provide displacement data that is in time phase with video processed data. The system resolution for these transducers is 0.002 inches over a 10 inch range. The vehicle velocity will be determined by the pulse counting encoder transducer and the on-board system clock. This velocity measurement will be used to control the non-video and video data acquisition system rates.

It is recognized that a system operating in the field must have quality assured data, and that the system operator may not have all of the necessary skills required to calibrate sophisticated electronics sub-systems or diagnose electronic system problems. We propose to establish an automatic calibration procedure that serves as a systematic test of all sub-system operations without the use of software diagnostic routines or costly manual maintenance procedures. With calibration conducted prior to a test run, the user is assured that the system is fully operational as well as completely calibrated.

If any calibration point cannot be succesfully calibrated, an error flag is issued. Any error detected during calibration of the post amplifier is a gross error since it affects all data acquisition channels. In this case, the calibration process is aborted and the operator is notified that immediate attention is required at a specific location. During preamplifier calibration, any channel drawing excessive current from the calibration bus is automatically disconnected for the remainder of the calibration procedure and flagged as a faulty channel. If an error is detected during zero and upscale preamplifier calibration or during the bi-polar linearity check, the faulty channel is identified as well as the gain or filter step at which the error was detected. In this case, the user can decide, after consultation, whether or not to proceed with the test depending upon the effect the error would have on the test run objectives.

RESEARCH DATA

The DATA set presented in Appendix B and discussed in this section of the report was taken using the laboratory equipment shown in Figure 16. This equipment is composed of:

1. A Video Camera--Standard Raster Scan (1/30 sec per frame).
2. A Frame Buffer--Quantex Company, 256 x 256 x 8.
3. A motorola Microprocessor (6809)--Developed by AMI Consultants.
4. A Video Monitor--Sony Black and White.
5. CRT Terminal--To communicate with the microprocessor.
6. A lighted easel to hold the photograph of a pavement surface.

The software algorithms were developed during the Phase I investigation to evaluate timing, sensor response, processing capability, and other factors relating to specifying a prototype to be used in a vehicle in road testing. A minimum set of algorithms has been established to provide for crack detection. Execution speed was not a factor in the laboratory data analysis and typically took up to 5 seconds to produce a thresholded image.

Each photograph was taken late in the day thereby exhibiting a significant shadow. The distance represented by each photograph is approximately 2 x 3 feet. This was done to establish the actual viewing area with respect to detail and crack measurements. This laboratory system was only a 256 x 256 x 8 system and the proposed system will need to be a 512

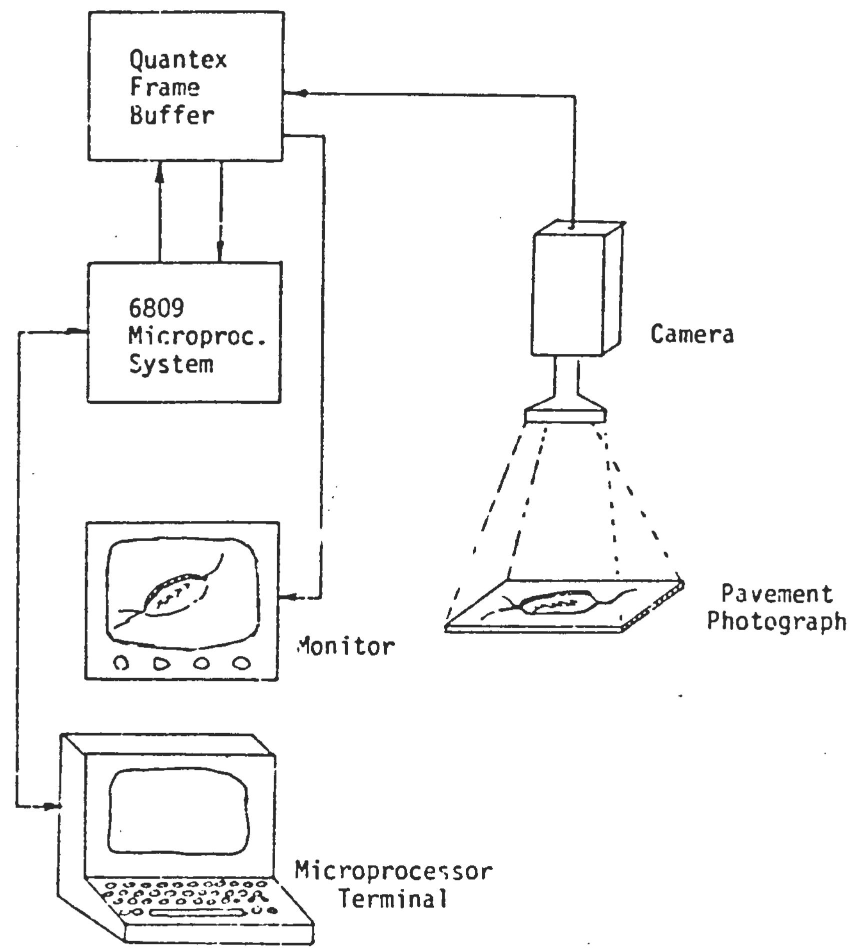

FIGURE 16 - Video Imaging System Prototype

x 512 x 8 image viewing area. Each of the 512 x 512 images will respond to a four foot square thereby producing image qualities similar to those shown in this report. All image processing is done on the actual linear photograph. The data presented here is a reproduction by a "copy machine" and actually introduces certain artifacts.

Data Photo	Description
1.	Good Pavement
2.	Oblique Cracking
3.	Transverse Cracking
4.	Crack With Moisture
5.	Longitudinal Cracking
6.	"Pot Hole"
7.	Large "Fork" Crack
8.	Pot Hole and Cracking
9.	Large Pot Hole

For each data photograph taken, the following analysis is performed:

1. Histogram--Indicating the pavement sample composition.
2. Simple Threshold--Indicating the body/crack area of the crack shadow.
3. Simple Gradient--Indicating the crack body edge.

As each photograph is being examined, make a mental note of the white, gray, and black areas. This information is carefully examined during the generation of the histogram. Very light areas are represented to the left and very dark areas (cracks, and other objects) are located to the right. The cracks in this laboratory study are shown at the extreme right and are easily detectable to determine the thresholds, T and T (Figure 14). This information is then used to produce a simple gradient photograph. It can easily be noted that the edge and crack body has been segmented. The next step is ratio the area pixels to the whole image to determine the amount of distressed pavement. Weighting factors are incorporated to determine the pavement score. The purpose of this data is to grasp the potential capability of such image processing toward a high-speed prototype unit to be developed in Phase II.

TECHNICAL FEASIBILITY CONCLUSIONS

Based upon the results of the research efforts previously described in this Phase I study, it is the conclusion of AMI Consultants that a video image based pavement system is feasible. Although additional development effort is necessary, all of the individual potential problem areas researched to date have been shown to be solvable. The major effort remaining, in summary, is the integration of the research pieces into a total system so that TOTAL SYSTEM PERFORMANCE can be properly evaluated. As a result of this feasibility study, it appears that the greatest technical risk remaining lies in the quality of operation of each of the system components interacting as a total system. Specifically, the following questions were addressed:

1. The use of a "slit" type video sensor is not only desirable, but absolutely necessary for obtaining pavement data at highway vehicle speeds.
2. Image processing algorithms have been and will continue to be developed to recognize various types and degree of severity of pavement distress.
3. Pavement scoring vectors have been addressed in the image processing algorithm development. User meaningful pavement performance scores can easily be generated to reflect any particular highway agency's unique situation. Scoring which ranges from zero for a perfect pavement and assends in value with increased pavement distress, better lends itself to a computer generated composite rating score.
4. Vehicle speed and distance traveled are two manditory non-video data values to be acquired. Vehicle speed is required as input for video image scan rate control; while vehicle distance must be monitored to establish the locations of video images (pavement condition locations), and to allow for some operator control of the image scanning rate interval. Additional non-video data acquisition will include monitoring displacement transducers mounted to measure the relative movement

between the vehicle axle and frame. This data will be used to correlate road roughness to pavement condition as determined by the video portion of the test system.

POTENTIAL APPLICATIONS OF THE RESEARCH

The target application of this research effort is the automation of pavement conditon surveys. Specific benefits associated with a system of this type have been previously discussed. In summary, these benefits are:

1. Higher quality pavement condition data.
2. Data gathered in a more timely manner.
3. Less personnel required in data gathering.
4. Lower long-term costs than methods presently in use.
5. Establishment of a data base for input to pavement management system programs.

Two approaches are envisioned for the commercial application of the research findings. These are:

1. System production and sales.
2. Pavement condition survey services.

It is anticipated that large highway agencies will want to procure the proposed system for in-house use in evaluation of their highway system. Agencies above a particular size will be able to justify the initial capital outlay required to purchase the proposed system in that they will be in a position to use one or more systems on a continuous and full-time basis. It is believed that an international market also exists for the proposed device.

Smaller agencies, however, most likely will not be able to justify a large capital outlay because of the size of the highway system over which they have jurisdiction. In cases such as this, the need for pavement condition survey services would be more appropriate. A service company can be contracted with to provide pavement data on an hourly or cost per lane mile basis. It is estimated that more agencies would fall into this latter category.

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APPENDIX A

COMPUTER SOFTWARE PRINTOUT

Appendix A is proprietary information which AMI Consultants requests not be released to persons outside the Government, except for purposes of evaluation.

```
*                        BIFOS   INTRODUCTION
*
*
*
* INTRODUCTION
*
*  A BASIC HIGH SPEED IMAGE PROCESSING OPERATING SYSTEM (BIFOS) HAS
*    BEEN DEVELLOPED IN IMAGE PROCESSING LAB OF U.N.R. BIFOS IS WRITEN
*    BY ASSEMBLY LANGUAGE OF M6809 MICROPROCESSOR.THE ADVANTAGE OF THE
*    SYSTEM IS HIGH SPEED,EASY TO LEANR,EASY TO USE.PARTICULARLY IT IS
*    USEFUL FOR EDUCATION IN UNIVERSITY,ALSO FOR SOME BASIC APPLICATION.
*
* FIGURE 1 IS THE DIAGRAM OF IMAGE PROCESSING WHICH WE USE.
* FIGURE 2 IS M6809 MEMORY MAPPING.
*
*  ------------     ------------     ------------     ------------
*   KEY BOARD          ACIA           MPU M6809           RAM
*  ------------     ------------     ------------     ------------
*
*
*  ------------     ------------     ------------     ------------
*   SENSOR                                               USER RAM
*  ------------                         PIA 1         ------------
*                                    ------------
*                     QUANTAX                          ------------
*                                                        OP.SY
*                                    ------------      ------------
*
*                                                      ------------
*  ------------                         PIA 2
*                                    ------------         BIFOS
*   MONITER                                            ------------
*  ------------     ------------
*
*     FIGURE 1 IMAGE PROCESSING SYSTEM DIAGRAM
*
*                  ------------------------ FFFF
*                      M6809 OP.SY
*                  ------------------------ F800
*                  ------------------------ C7FF
*                      BIFOS
*                  ------------------------ C000
*                  ------------------------ A3FF
*                      BIFOS USE RAM
*                  ------------------------ A3C0
*                  ------------------------ A3BF
*                      USER RAM
*                  ------------------------ A100
*                      RAM STACK
*                  ------------------------ A000
*                  ------------------------
*                      ACIA                 8008
*                  ------------------------
*                  ------------------------ 4007
*                      QUANTAX
*                  ------------------------ 4000
*                  ------------------------ 03FF
*                      RAM ARRAY
*                  ------------------------ 0000
*
*           FIGURE 2  M6809      MEMORY     MAPPING
*
```

```
* BIPOS ORGANIZATION
*
*  THERE ARE 16 SUBROUTINE ORGANIZED INTO TWO ROM (INTEL2716).
*  FOLLOWING IS A LIST:
*
*                                  ROM  1
*
* ---------------------------------------------------------------------------------
* SUBROUTINE     ABSOLUTE    MEMORY OF                      OTPUT
* FUNCTION       ADDRESS     INPUT
* ---------------------------------------------------------------------------------
* INITIATE       $C000
* PIA
* ---------------------------------------------------------------------------------
* READ PIXEL     $C020
* FROM QUANTAX
* ---------------------------------------------------------------------------------
* WRITE PIXEL    $C040
* FROM QUANTAX
* ---------------------------------------------------------------------------------
* 16 BIT         $C060     DIVISOR M(A3F5,A3F60     QUOIENT M(A3F5,A3F6)
* DIVISION                 DIVIDEND M(A3F1,A3F2)   REMAINDER M(A3F7,A3F8)
* ---------------------------------------------------------------------------------
* READ ARRAY     $C090     STAR ROW     M(A3D0)
* FROM QUANTAX             STAR COLUMN M(A3D1)     ARRAY DATA ADDRESS
*                          STOP ROW     M(A3D2)     IN Y  REGISTER
*                          STOP COLUMN M(A3D3)
* ---------------------------------------------------------------------------------
* GRADIENT       $C0C0     THRESHOLD VALUE          ARE YOU SATISFIED?
*   WITH                     IN M(A3D4)
* THRESHOLD                                         INPUT THRESHOLD:
* ---------------------------------------------------------------------------------
* ENHANCE        $C180     START PIXEL M(A3E1)
* WHOLE IMAFE              STOP  PIXEL M(A3E2)
* ---------------------------------------------------------------------------------
* LOGICAL        $C1D0
* PRODUCT
* ---------------------------------------------------------------------------------
* THRESHOLD      $C290     START ROW    M(A3FF)     START X :
* WHOLE OR                 START COLUMN M(A3FE      START Y :
* PART OF                  STOP  ROW     M(A3FD)    STOP  X :
* IMAGE                    STOP  COLUMN M(A3FC)     STOP  Y :
*                          THRESHOLD 1   M(A3FB)    THRESHOLD 1 :
*                          THRESHOLD 2   M(A3FA)    THRESHOLD 2 :
* ---------------------------------------------------------------------------------
* FIDER PIXEL $C320                               POSITION ON CRT & PIXEL
* VALUE  AND                                      VALUE POINTED BY CURSOR
* POSITION
* ---------------------------------------------------------------------------------
* TUTOR          $C3E0                            MESAGE
* ---------------------------------------------------------------------------------
*
*
*                                  ROM  2
*
* ---------------------------------------------------------------------------------
* INITAITE       $C000
* PIA
* ---------------------------------------------------------------------------------
* READ PIXEL     $C020
```

```
* FROM QUANTAX
* ------------------------------------------------------------------------------------
* WRITE PIXEL   $C040
* FROM QUANTAX
* ------------------------------------------------------------------------------------
* HISTIGRA OF   $C060
* WHOLE IMAGE
* ------------------------------------------------------------------------------------
* WEIGHT        $C206    KERNER IN                 INPUT KERNER:
* AVERAGE                M(A3C0-A3C7)              W1: W2: W3: W4: W6: W7:
*                                                  W8: W9:
* ------------------------------------------------------------------------------------
* CONTRACT      $C345    SIZE M(A3C8)              SIZE:
* WHOLE IMAGE            IF SIZE=02
*                        SET M(A3CF)=00
*                        IF SIZE=03
*                        SET M(A3CF)=FF
* ------------------------------------------------------------------------------------
* BIT SLICE     $C383    BIT MASK M(A3F0)          BIT MASK :
* ------------------------------------------------------------------------------------
* TUTOR         $C3E0                              MESAGE
* ------------------------------------------------------------------------------------
*
* NOTE: $A3FF--$A3C0 IN RAM HAS BEEN MODIFIED !
*
* HOW TO USE BIPOS
*
*  THERE ARE TWO WAY TO USE BIPOS.THE EASY WAY IS TI FOLLOW TUTOR.
* THE SYSTEM TUTOR TELL YOU WHAT AND WHEN TO DO.
* THE FIGURE 3 IS THE DIAGRAM OF TUTOR'S WORK.
*
*
                   ----------------
                    TUTOR   ENTRY
                   ----------------
*
*
                          ------------------------
*
*
*
*                  ------------------        ------------
*                  TYPE CORRESPON-
*                  DING LETTER TO
*                  GET DESIRED                TYPE I TO
*                  SUBROUTINE                 GET A LIST
                   ------------------        ------------
*
*
                   ------------------
*                  DISPLY QUISTIONS
*                  SUBROUTINE ASKS
*
*
                   ------------------
*
*
*
*                  ------------------
*                  TYPE INPUT TO
```

```
*                                   ANSWER QUISTIONS
*                                   ----------------
*
*
*
*                                  --------------------
*                                   SUBROUTINE IS
*                                   RUNNING
*                                  --------------------
*
*
*
*                                  --------------------
*                                   "FINISH" INDICATE
*                                    THE END OF
*                                    SUBROUTINE
*                                  --------------------
*
*
* NOW WE DISCREBE HOW TO USE TUTOR AND WHAT QUISTIONS YOU SHOLD ANSWER
* FOR EACH SUBROUTINE.
*
*
*     REMEMBER  :  TYPE G C3E0   TO ENTER TUTOR.
*
*
* AFTER TYPED G C3E0 , THE CRT DISPLY :
*
*     IMAGE PROCESSING MODEL , TYPE I TO GET A LIST
*

*  AFTER TYPED I FOR ROM 1 , THE CRT DISPLY :
*
*     SUBROUTINES   LIST
*
*     PIAINT    C000         READP       C020
*     WRITEP    C040         DIVI16      C060
*     RARRAY    C090
*     G=GRADIENT        C0C0    E=ENHANCE        C180
*     L=LOGICAL AND     C1D0    T=THRESHOLD      C290
*     F=FINDER          C320
*     I=SUBROUTINE      LIST    Q=FRONBUG        F845
* AFTER TYPED I FOR ROM 2 , THE CRT DISPLY :
*
*     SUBROUTINES   LIST
*
*     PIAINT    C000         READP       C020
*     WRITEP    C040
*     H=HISTOGRAM       C060    A=AVERAGE        C266
*     C=CONTRACT        C345    B=BIT SLICE      C3B3
*     I=SUBROUTINE      LIST    Q=FRONBUG        F845
*
* NOW YOU CAN TYPE CORRESPONDING LETTER TO ENTER DESIRED SUBROUTINE.
*
* NOTE: IF YOU REMEMBER WHICH LETTER REPRESETS WHICH SUBROUTINE,IT
*       IS NO NEED TO TYPE I EVERY TIME. YOU CAN ENTER SUBROUTINE
*       IMMIDENTLY BY TYPING CORRESPONDING LETTER AFTER G C3E0.
*
* FIGURE 4 TELLS YOU WHAT QUISTIONS YOU HAVE AND HOW TO ANSWER THEM
* FOR EACH SUBROUTINE.
```

```
*
*
*                                              ROM  1
*
* TYPE   QUISTIONS ON CRT          EXAMPLE OF ANSWER        RESULT
* ----------------------------------------------------------------------
*  I          NO                                             LIST
* ----------------------------------------------------------------------
*  G     ARE YOU SATISFIED?                Y                FINISH
*        (DISPLY AFTER PROCESS)
*        INPUT THRESHOLD:                  10               RUN
* ----------------------------------------------------------------------
*  L     PIXEL VALUE 1:                    10
*        PIXEL VALUE 2:                    2A               RUN
* ----------------------------------------------------------------------
*  L          NO
* ----------------------------------------------------------------------
*  T     WHOLE PICTURE ?                   Y
*        THRESHOLD 1:                      30
*        THRESHOLD 2:                      1A               RUN
*                                       ANY KEY
*        START X:                          40
*        START Y:                          40
*        STOP  X:                          7F
*        STOP  Y:                          7F
*        THRESHOLD 1:                      70
*        THRESHOLD 2:                      50               RUN
* ----------------------------------------------------------------------
* F           NO                           U          CORSOR GOES UP
*                                   U WITH REPEAT     CORSOR GOES UP
*                                                     UNTIL RELEASE
*                                          D          CONSOR GOES DOWN
*                                   D WITH REPEAT     CORSOR GOES DOWN
*                                                     UNTIL RELEASE
*                                          L          MOVE TO LEFT
*                                   L WITH REPEAT
*                                          R          MOVE TO RIGHT
*                                   R WITH REPEAT
*                                                     CRT DISPLY PIXEL
*                                                     VALUE & POSITION
* ----------------------------------------------------------------------
* Q           NO                                      BACK TO FRONBUG
* ----------------------------------------------------------------------
*
*
*                                     ROM  2
*
* ----------------------------------------------------------------------
* I,Q                                .O THE SAME THING AS ROM 1
* ----------------------------------------------------------------------
* H           NO                                      RUN
* ----------------------------------------------------------------------
* A      INPUT CERNER
*        W1: W2: W3: W4         02 02 02 02
*        W6: W7: W8: W9         02 02 02 02           RUN
* ----------------------------------------------------------------------
* C      SIZE:                  03
* ----------------------------------------------------------------------
* B      BIT MASK:              10                    RUN
* ----------------------------------------------------------------------
```

```
PAGE  001  R        .SA:0

00010 00001                              *
00020 00002                              *     ROBERTS GRADIENT
00025 00003                              *    AFTER GRADIENT YOU HAVE SIGLE THRESHOLD.
00027 00004                              *    THRESHOLD VALUE IS IN M(A3D4).
00030 00005A C0C0                                  ORG     $C0C0
00040 00006                                        OPT     ABS
00050 00007A C0C0 BD    C000       A               JSR     $C000
00060 00008A C0C3 7F    A3D0       A               CLR     $A3D0
00070 00009A C0C6 86    01         A               LDA     #$01
00080 00010A C0C8 B7    A3D2       A               STA     $A3D2
00090 00011A C0CB 7F    A3D1       A L0            CLR     $A3D1
00100 00012A C0CE 86    01         A               LDA     #$01
00110 00013A C0D0 B7    A3D3       A               STA     $A3D3
00120 00014A C0D3 BD    C090       A L1            JSR     $C090
00130 00015A C0D6 E6    A4         A               LDB     ,Y
00140 00016A C0D8 E0    23         A               SUBB    3,Y
00150 00017A C0DA C5    80         A               BITB    #$80
00160 00018A C0DC 27    01    C0DF                 BEQ     L2
00170 00019A C0DE 50                               NEGB
00180 00020A C0DF 34    04         A L2            PSHS    B
00190 00021A C0E1 E6    22         A               LDB     2,Y
00200 00022A C0E3 E0    21         A               SUBB    1,Y
00210 00023A C0E5 C5    80         A               BITB    #$80
00220 00024A C0E7 27    01    C0EA                 BEQ     L3
00230 00025A C0E9 50                               NEGB
00240 00026A C0EA EB    E4         A L3            ADDB    ,S
00250 00027A C0EC 32    61         A               LEAS    1,S
00260 00028A C0EE B6    A3D0       A               LDA     $A3D0
00270 00029A C0F1 B7    4002       A               STA     $4002
00273 00030A C0F4 B6    A3D1       A               LDA     $A3D1
00277 00031A C0F7 B7    4000       A               STA     $4000
00283 00032A C0FA BD    C040       A L5            JSR     $C040
00290 00033A C0FD 7C    A3D1       A               INC     $A3D1
00300 00034A C100 7C    A3D3       A               INC     $A3D3
00310 00035A C103 26    CE    C0D3                 BNE     L1
00320 00036A C105 7C    A3D0       A               INC     $A3D0
00330 00037A C108 7C    A3D2       A               INC     $A3D2
00340 00038A C10B 26    BE    C0CB                 BNE     L0
00350 00039A C10D 8E    C14A       A L4            LDX     #MS0
00360 00040A C110 BD    F961       A               JSR     $F961
00370 00041A C113 BD    F948       A               JSR     $F948
00380 00042A C116 81    59         A               CMPA    #'Y
00390 00043A C118 27    24    C13E                 BEQ     DONE
00400 00044A C11A 8E    C161       A               LDX     #MS6
00410 00045A C11D BD    F961       A               JSR     $F961
00415 00046A C120 BD    F912       A               JSR     $F912
00420 00047A C123 B7    A3D4       A               STA     $A3D4
00423 00048A C126 7F    4000       A               CLR     $4000
00425 00049A C129 7F    4002       A               CLR     $4002
00430 00050A C12C BD    C020       A L7            JSR     $C020
00440 00051A C12F F1    A3D4       A               CMPB    $A3D4
00450 00052A C132 23    0B    C13F                 BLS     L8
00460 00053A C134 BD    C040       A L10           JSR     $C040
00470 00054A C137 7C    4000       A               INC     $4000
00480 00055A C13A 27    07    C143                 BEQ     L9
00490 00056A C13C 20    EE    C12C                 BRA     L7
00495 00057A C13E 39                 DONE          RTS
00500 00058A C13F C6    00         A L8            LDB     #$00
```

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PAGE  001  T          .SA:0

00010 00001                              * THE PROGRA TO THRESHOLD A PART OF IMAGE.
00020 00002                              * THE START POINT IS AT M(A3FF),M(A3FE)
00030 00003                              * THE STOP POINT IS AT M(A3FD),M(A3FC)
00040 00004                              * THE THRESHOLD VALUE IS AT M(A3FB),M(A3FA).
00045 00005                              * IF M(A3FA)=00 THEN IT IS SINGLE THRESHOLD FR..
00048 00006                              * WHEN USED  M(A3FB) GREAT THEN M(A3FA).
00049 00007                              * ***************************************
00050 00008A C290                                  ORG     $C290
00055 00009                                        OPT     ABS
00060 00010A C290 BD   C000      A                 JSR     $C000
00070 00011A C293 B6   A3FF      A                 LDA     $A3FF
00080 00012A C296 B7   4002      A                 STA     $4002
00090 00013A C299 B6   A3FE      A                 LDA     $A3FE
00100 00014A C29C B7   4000      A                 STA     $4000
00140 00015A C29F BD   C020      A QTOB            JSR     $C020
00150 00016A C2A2 F1   A3FB      A                 CMPB    $A3FB
00160 00017A C2A5 2F   27   C2CE                   BLE     THR2
00170 00018A C2A7 C6   FF        A                 LDB     #$FF
00180 00019A C2A9 BD   C040      A BTOQ            JSR     $C040
00190 00020A C2AC 7C   4000      A                 INC     $4000
00200 00021A C2AF B6   4000      A                 LDA     $4000
00210 00022A C2B2 B1   A3FC      A                 CMPA    $A3FC
00220 00023A C2B5 27   03   C2BA                   BEQ     NEWA
00230 00024A C2B7 7E   C29F      A                 JMP     QTOB
00240 00025A C2BA B6   A3FF      A NEWA            LDA     $A3FF
00250 00026A C2BD B7   4000      A                 STA     $4000
00260 00027A C2C0 7C   4002      A                 INC     $4002
00270 00028A C2C3 B6   4002      A                 LDA     $4002
00280 00029A C2C6 B1   A3FD      A                 CMPA    $A3FD
00290 00030A C2C9 27   12   C2DD                   BEQ     OPRT
00303 00031A C2CB 7E   C29F      A                 JMP     QTOB
00310 00032A C2CE F1   A3FA      A THR2            CMPB    $A3FA
00320 00033A C2D1 2F   05   C2D8                   BLE     BKGD
00330 00034A C2D3 C6   00        A                 LDB     #$00
00340 00035A C2D5 7E   C2A9      A                 JMP     BTOQ
00350 00036A C2D8 C6   FF        A BKGD            LDB     #$FF
00360 00037A C2DA 7E   C2A9      A                 JMP     BTOQ
00370 00038A C2DD 39               OPRT            RTS
00390 00039                                        END
TOTAL ERRORS: 00000 - LAST ERROR LINE: 00000
TOTAL WARNINGS: 00000 - LAST WARNING LINE: 00000
```

```
PAGE  001  RARRAY  .SA:0

00010 00001                                        *:::::::::::::::::::::::::::::::::::::::::::::::::
00020 00002                                        * READARRAY
00030 00003                                        * START LINE IN A3D0,END IN $A3D2
00040 00004                                        * START COLUMN IN A3D1,END IN $A3D3
00060 00005                                        * ARRAY DATA START ADDR IN Y REG
00070 00006                                        *:::::::::::::::::::::::::::::::::::::::::::::::::
00080 00007A C090                                         ORG    $C090
00090 00008                                                OPT    ABS
00100 00009A C090 34   26        A                         PSHS   A,B,Y
00110 00010A C092 B6   A3D0      A                         LDA    $A3D0
00120 00011A C095 4A                                       DECA
00130 00012A C096 B7   4002      A                         STA    $4002
00140 00013A C099 B6   A3D1      A L0                      LDA    $A3D1
00150 00014A C09C 4A                                       DECA
00160 00015A C09D B7   4000      A                         STA    $4000
00170 00016A C0A0 7C   4002      A                         INC    $4002
00180 00017A C0A3 7C   4000      A L1                      INC    $4000
00190 00018A C0A6 BD   C020      A                         JSR    $C020
00200 00019A C0A9 E7   A0        A                         STB    ,Y+
00210 00020A C0AB B6   4000      A                         LDA    $4000
00220 00021A C0AE B1   A3D3      A                         CMPA   $A3D3
00230 00022A C0B1 26   F0   C0A3                           BNE    L1
00240 00023A C0B3 B6   4002      A                         LDA    $4002
00250 00024A C0B6 B1   A3D2      A                         CMPA   $A3D2
00260 00025A C0B9 26   DE   C099                           BNE    L0
00270 00026A C0BB 35   26        A                         PULS   A,B,Y
00280 00027A C0BD 39                                       RTS
**** ERROR   219 - PREV. ERROR LINE: 00000
TOTAL ERRORS: 00001 - LAST ERROR LINE: 00027
TOTAL WARNINGS: 00000 - LAST WARNING LINE: 00000
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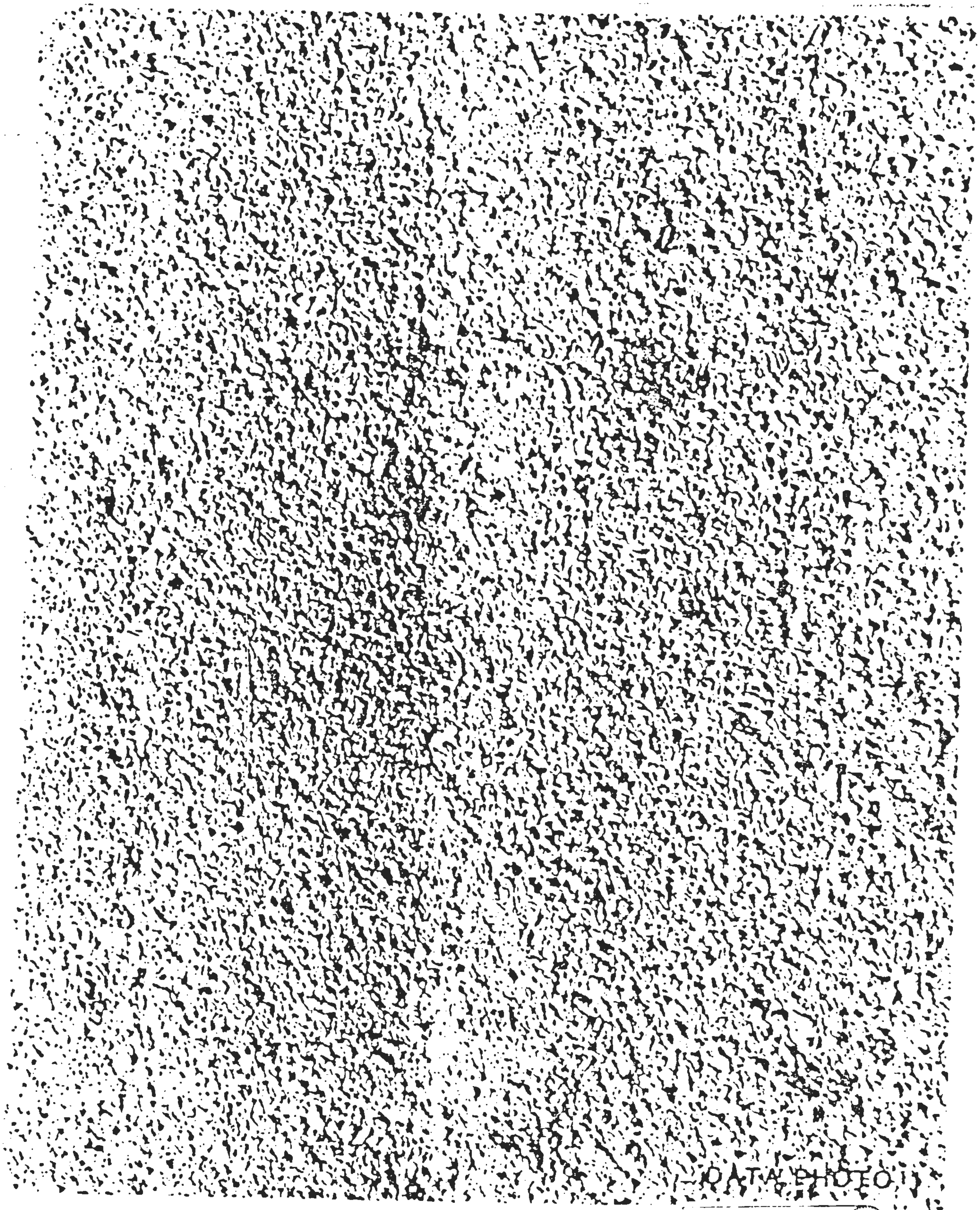
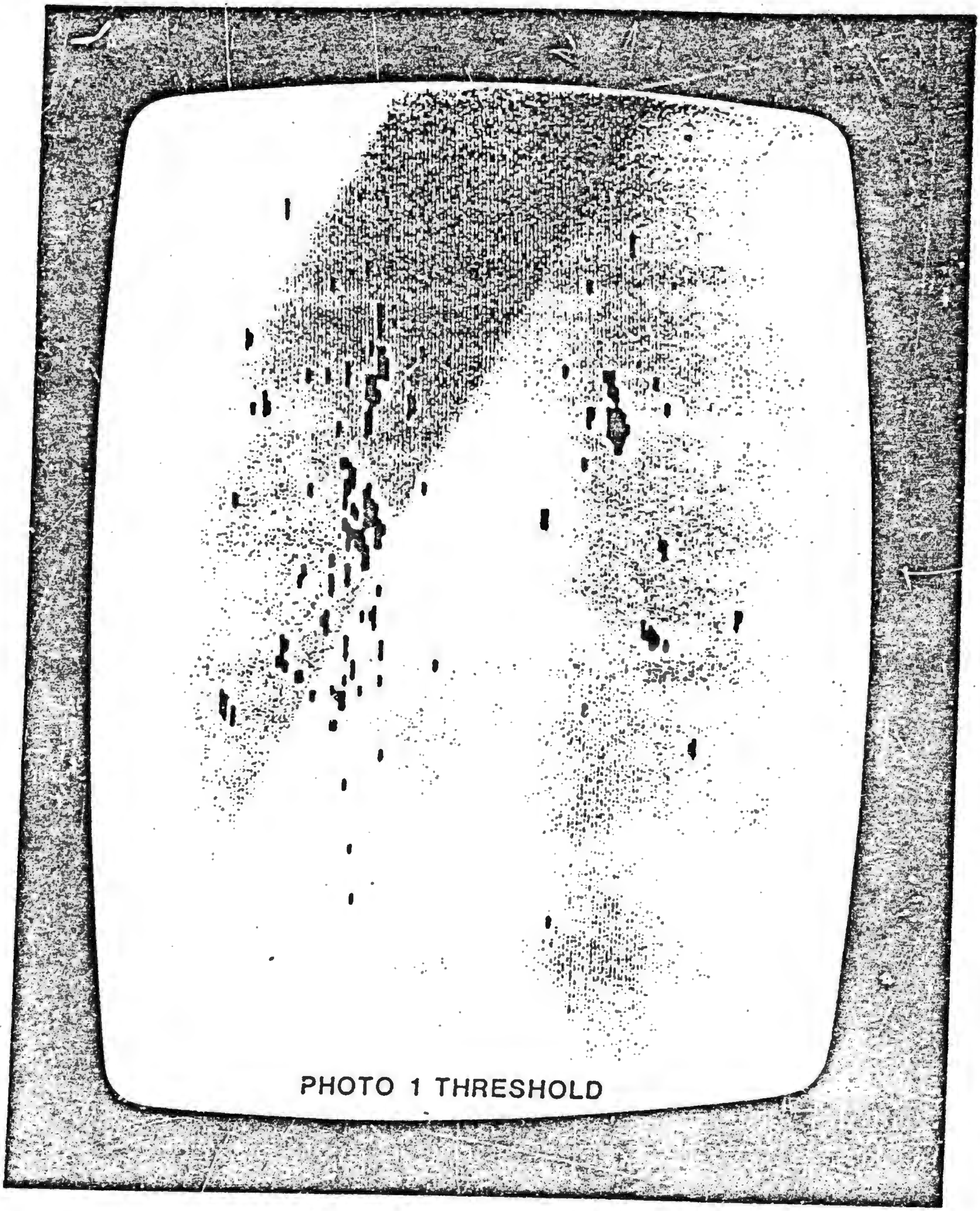
APPENDIX B

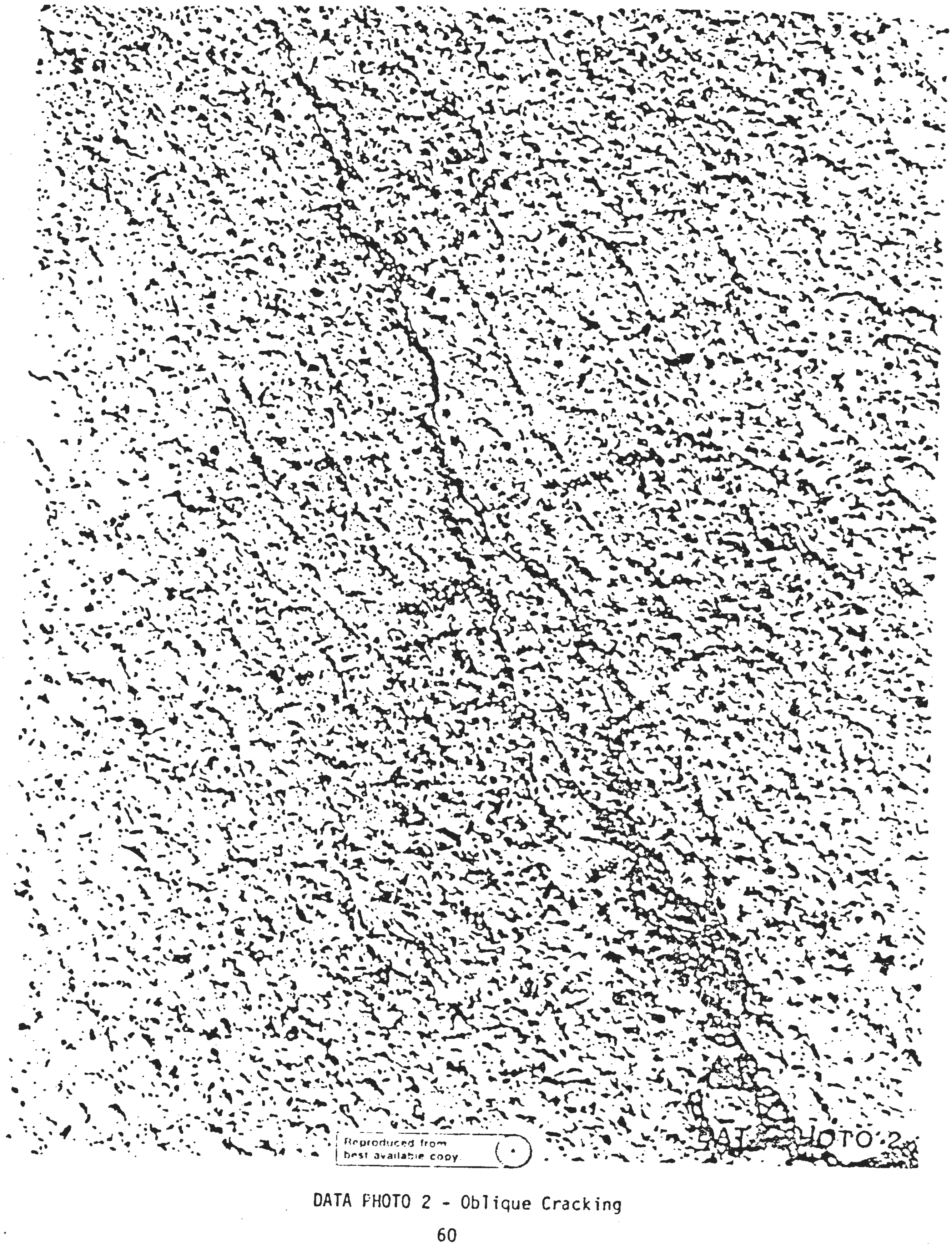
RESEARCH DATA PHOTOGRAPHS



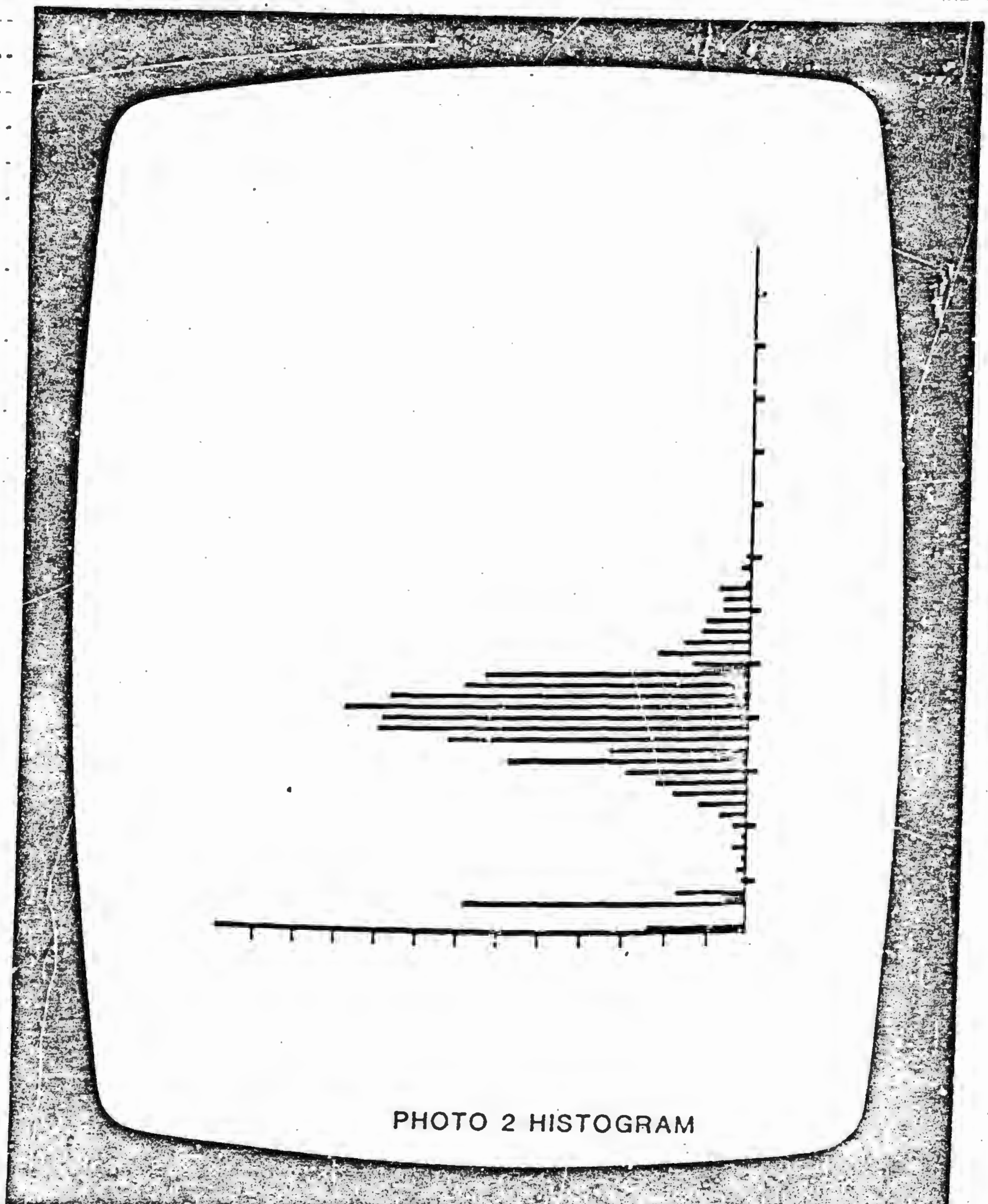
DATA PHOTO 1 - Good Pavement



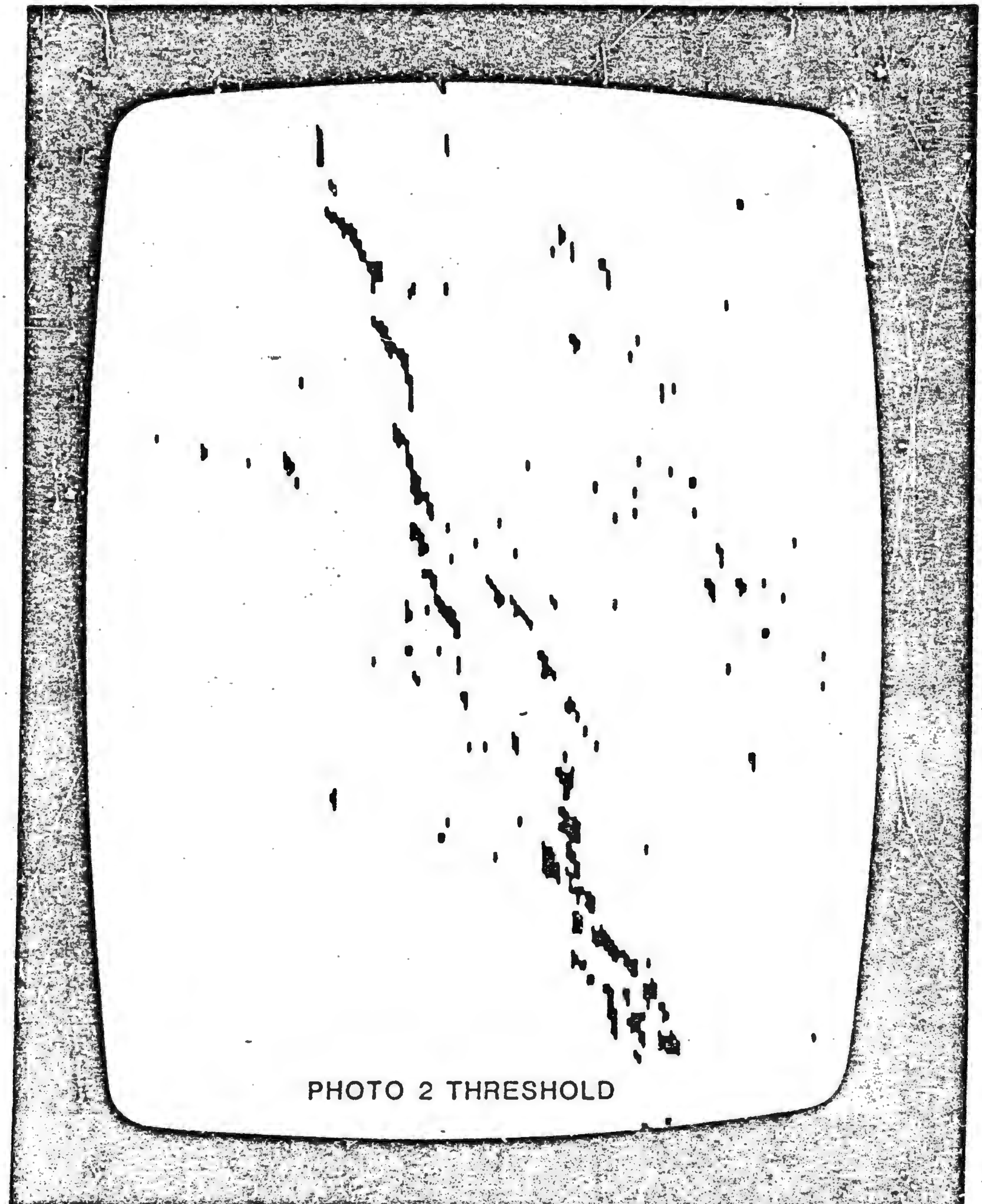
DATA PHOTO 1 - Threshold



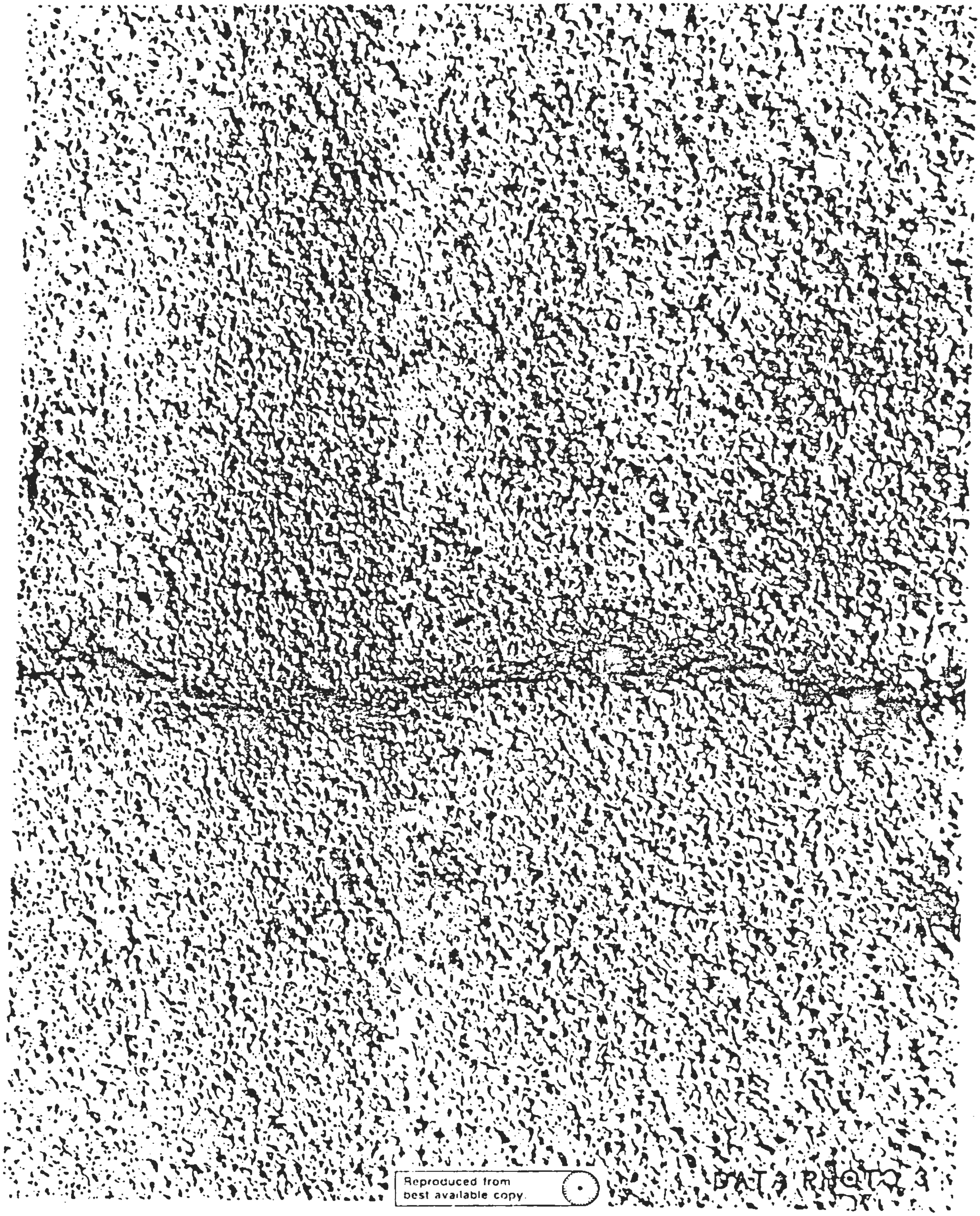
DATA PHOTO 2 - Oblique Cracking



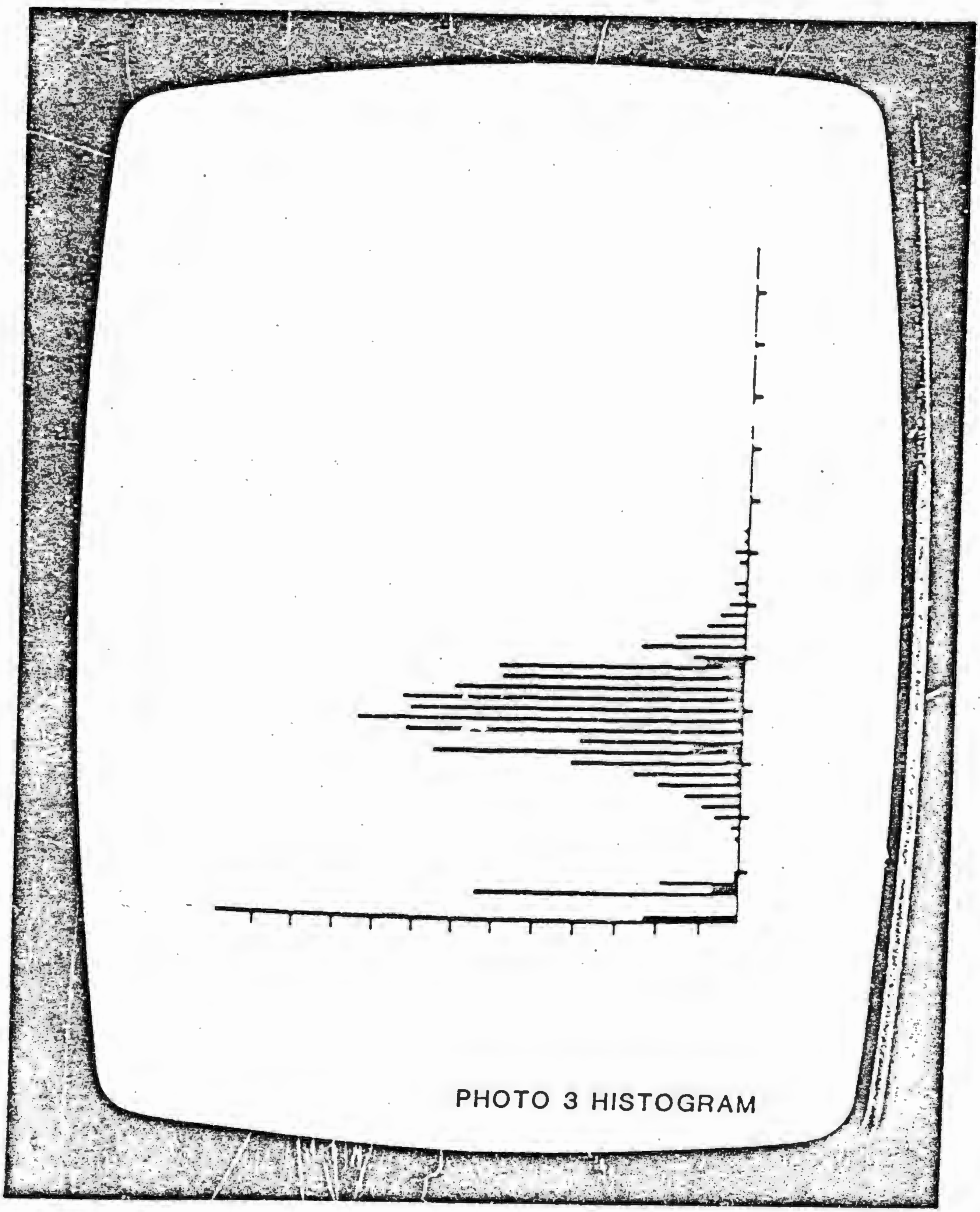
DATA PHOTO 2 - Histogram



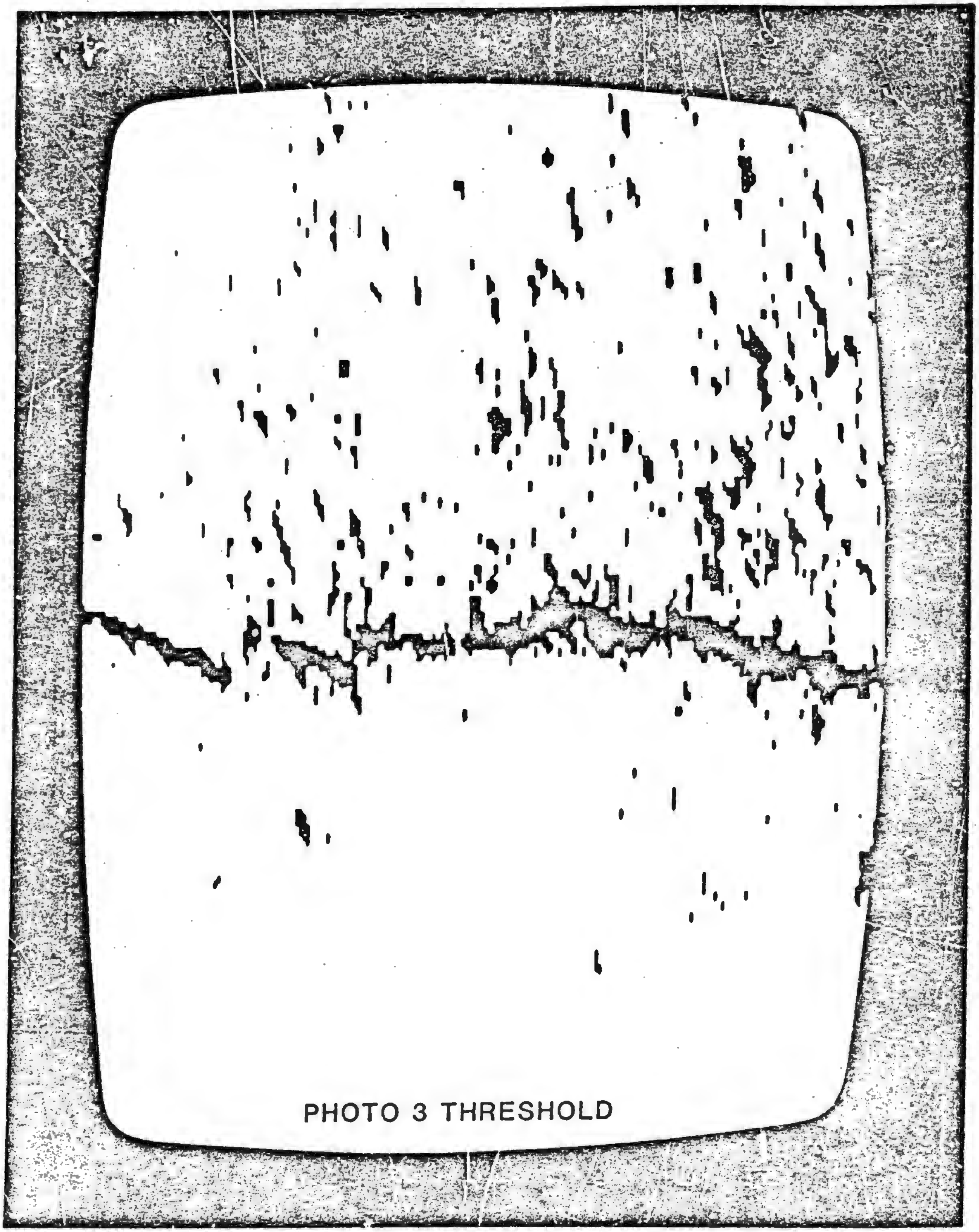
DATA PHOTO 2 - Threshold



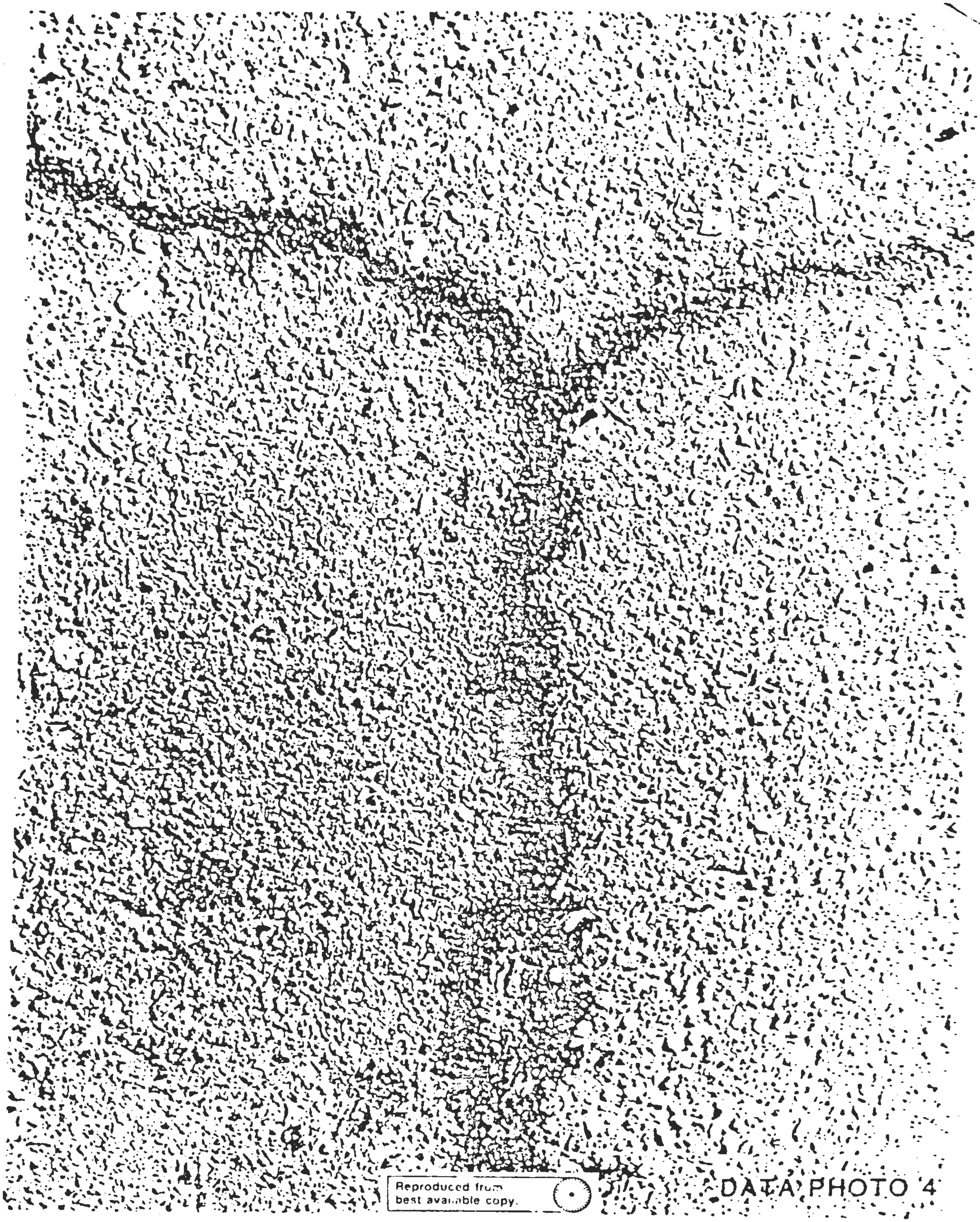
DATA PHOTO 3 - Transverse Cracking



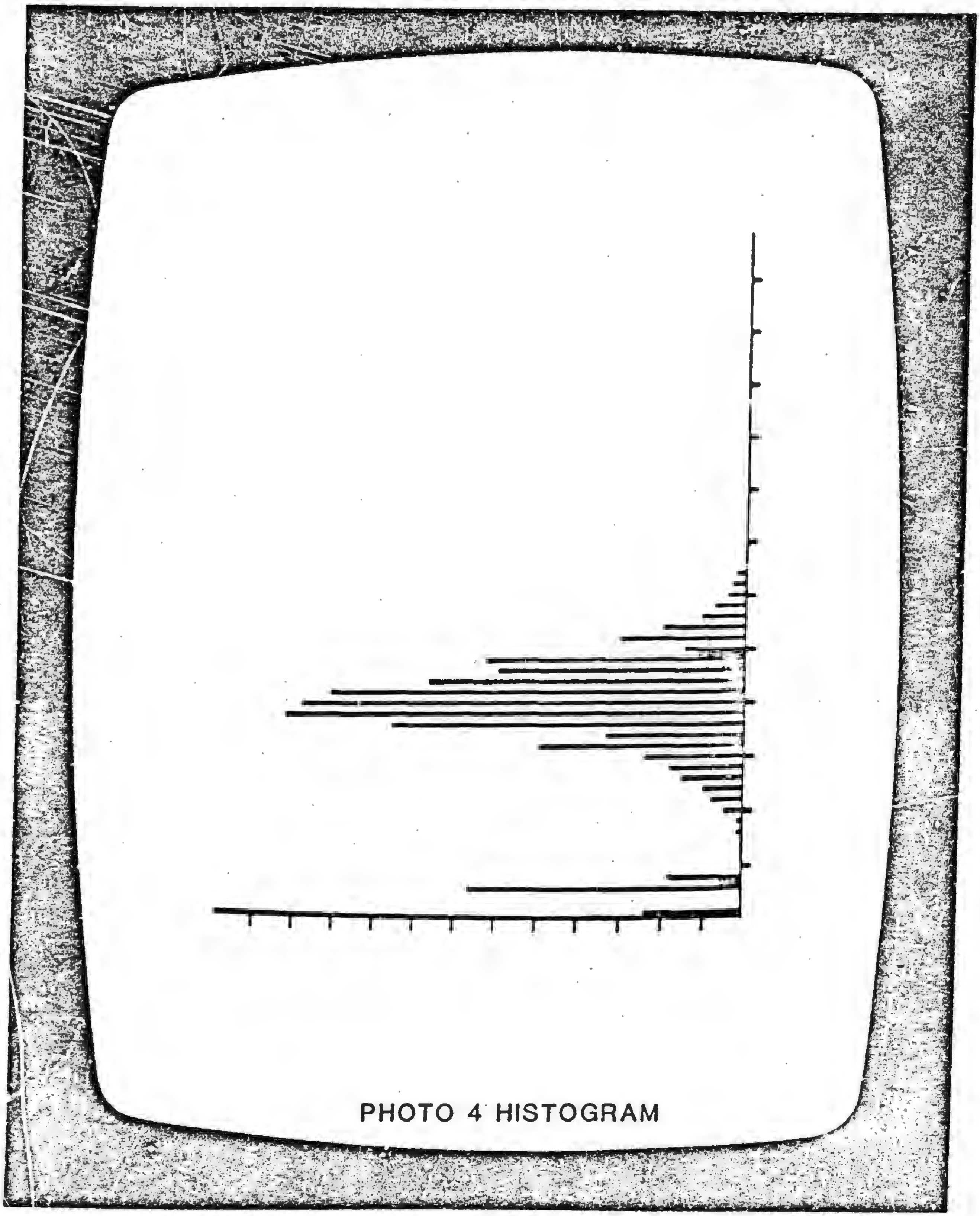
DATA PHOTO 3 - Histogram



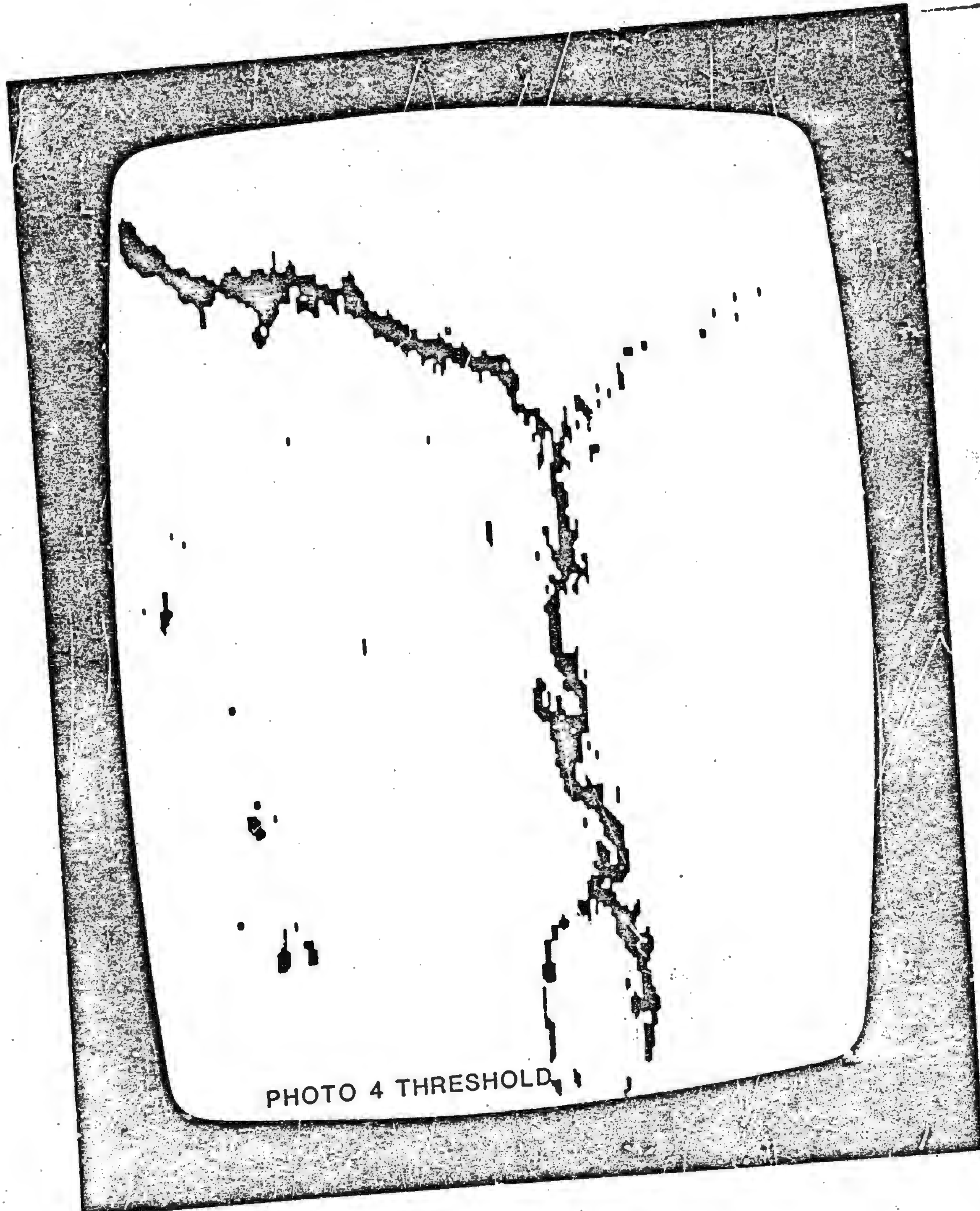
DATA PHOTO 3 - Threshold



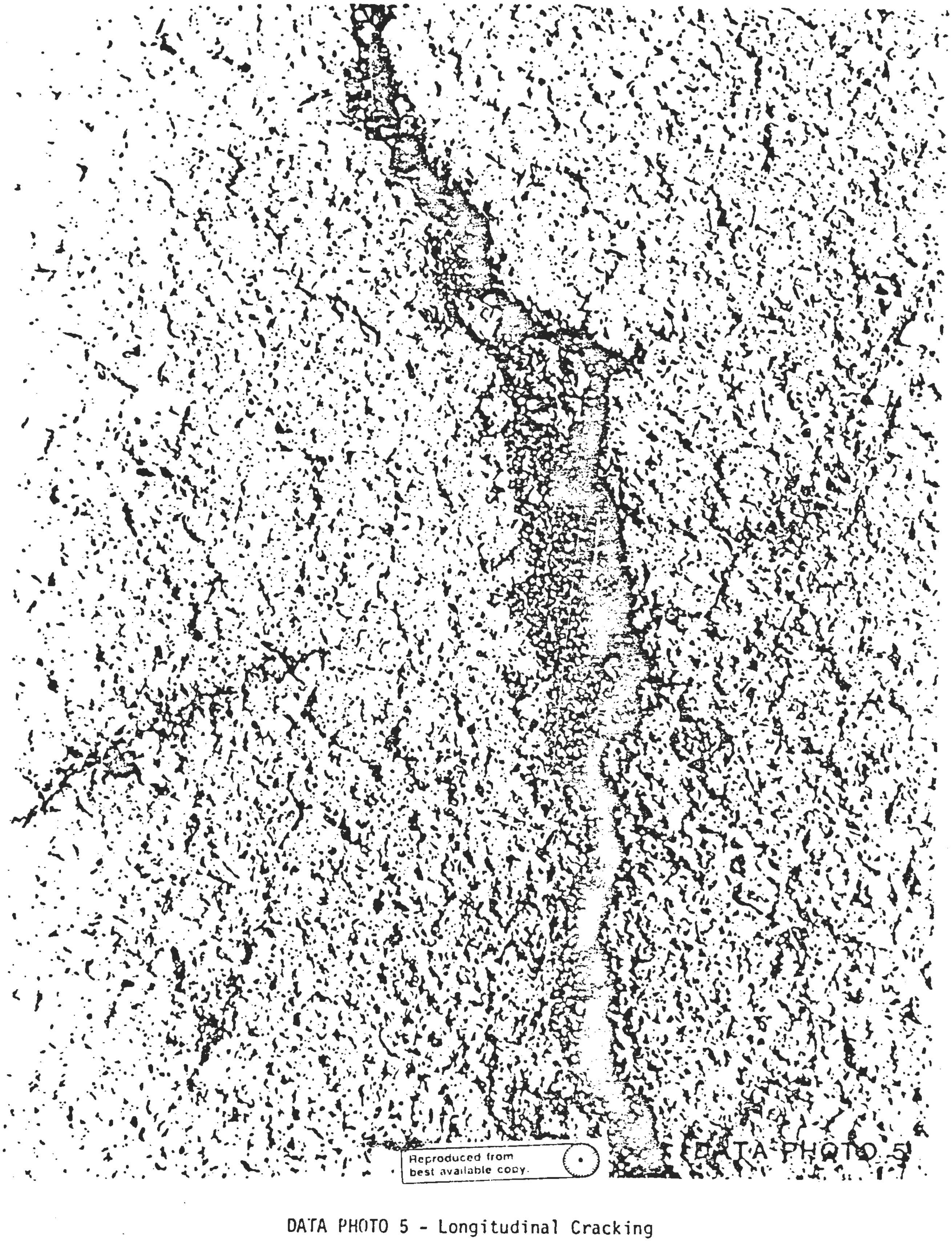
DATA PHOTO 4 - Crack with Moisture



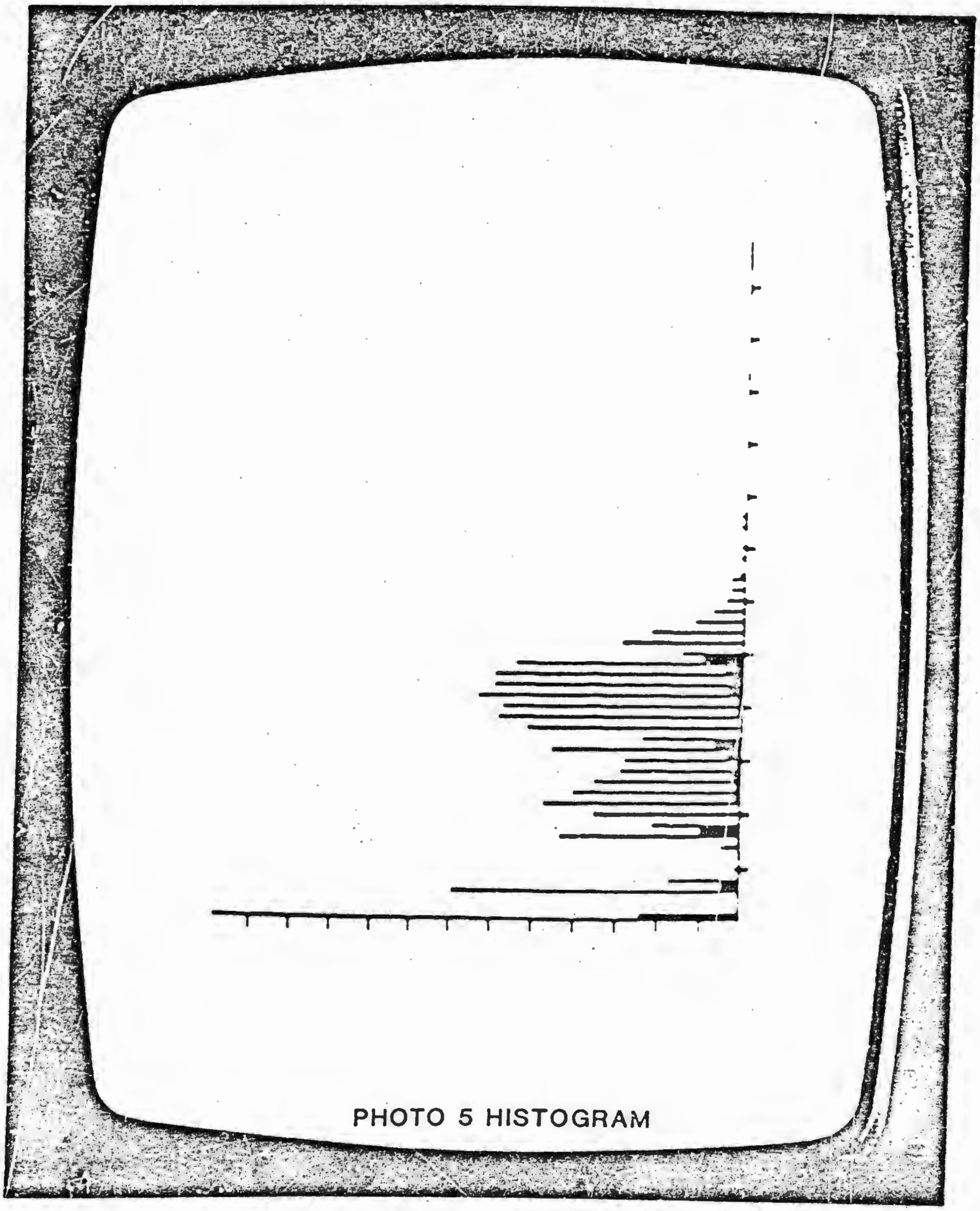
DATA PHOTO 4 - Histogram



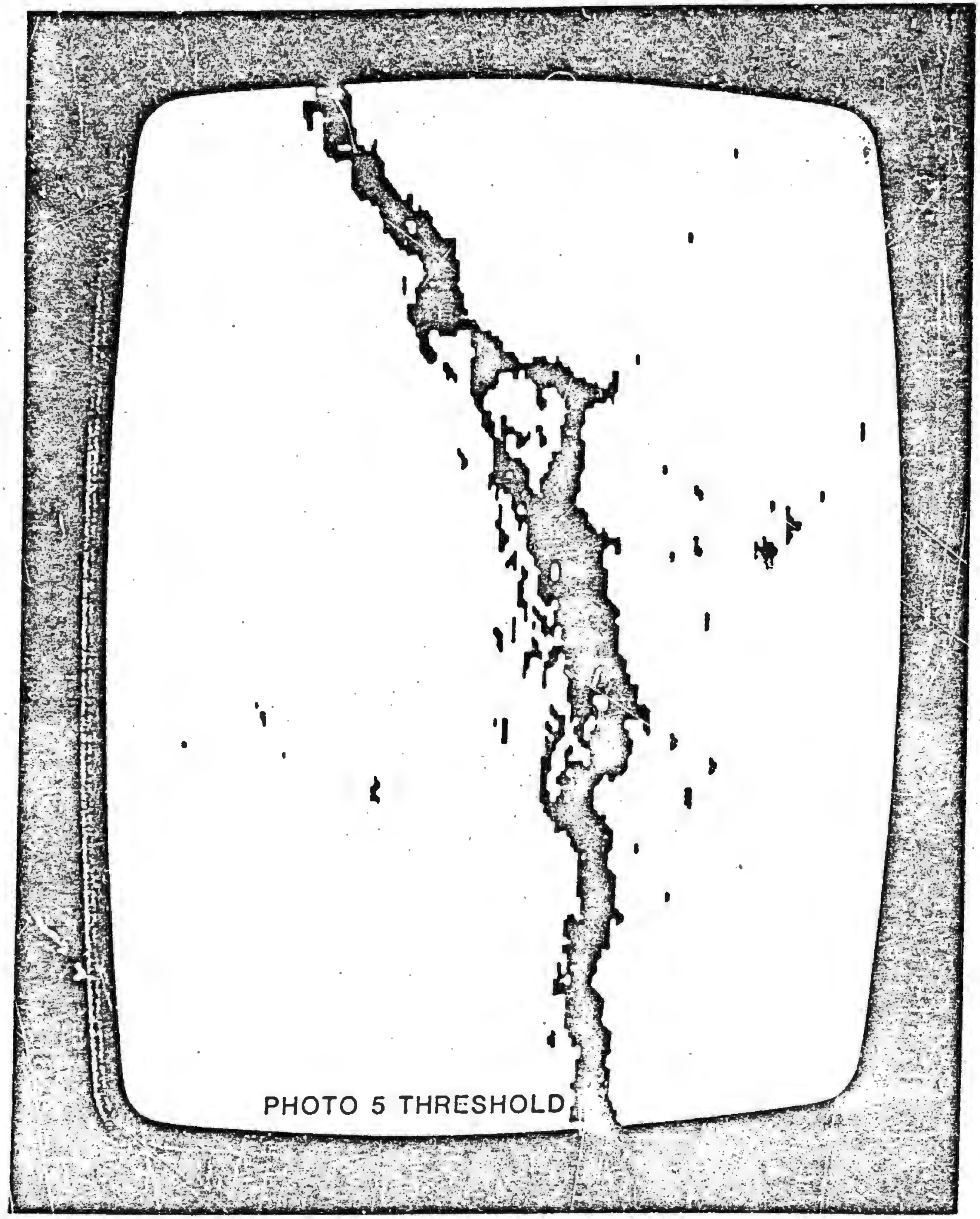
DATA PHOTO 4 - Threshold



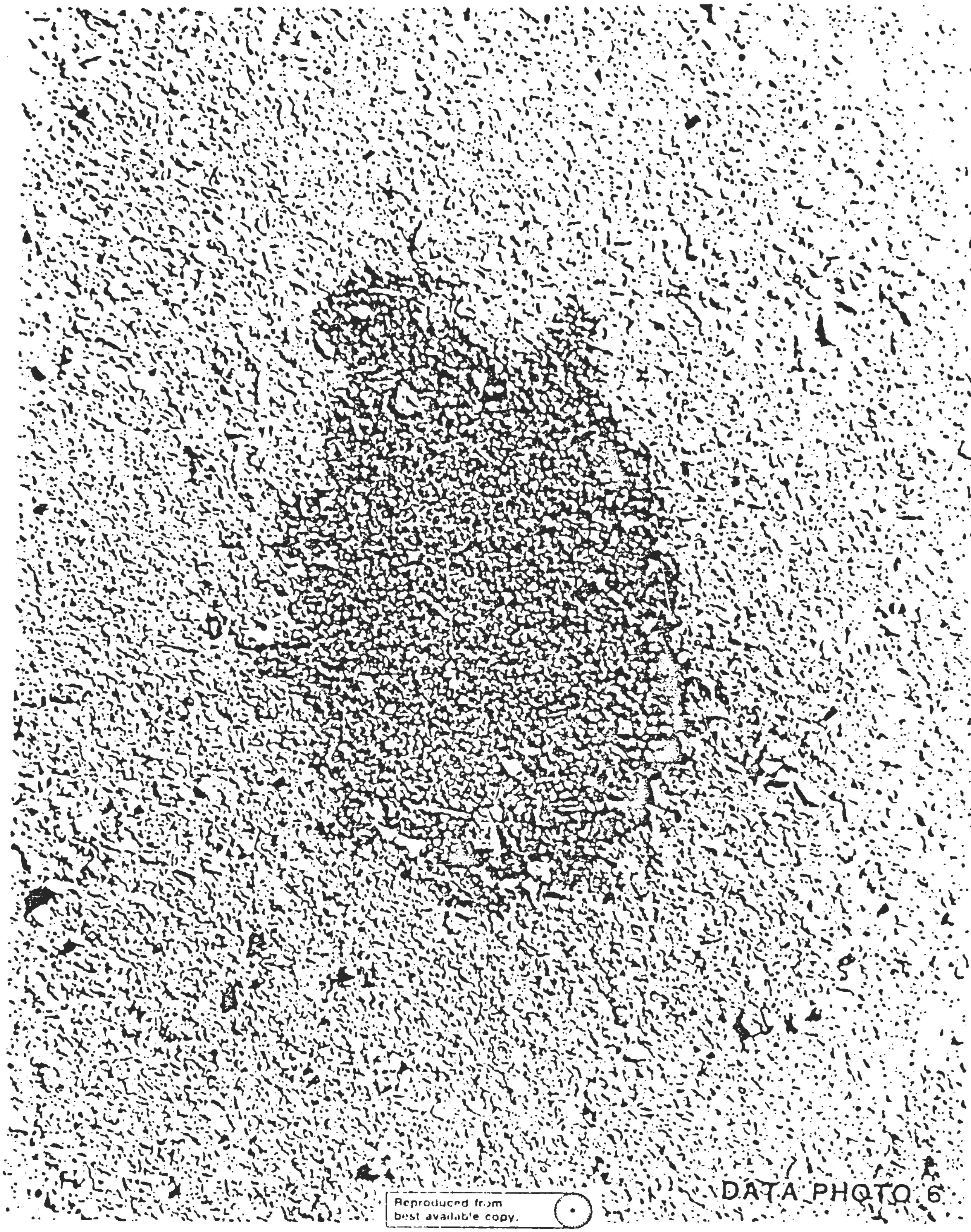
DATA PHOTO 5 - Longitudinal Cracking



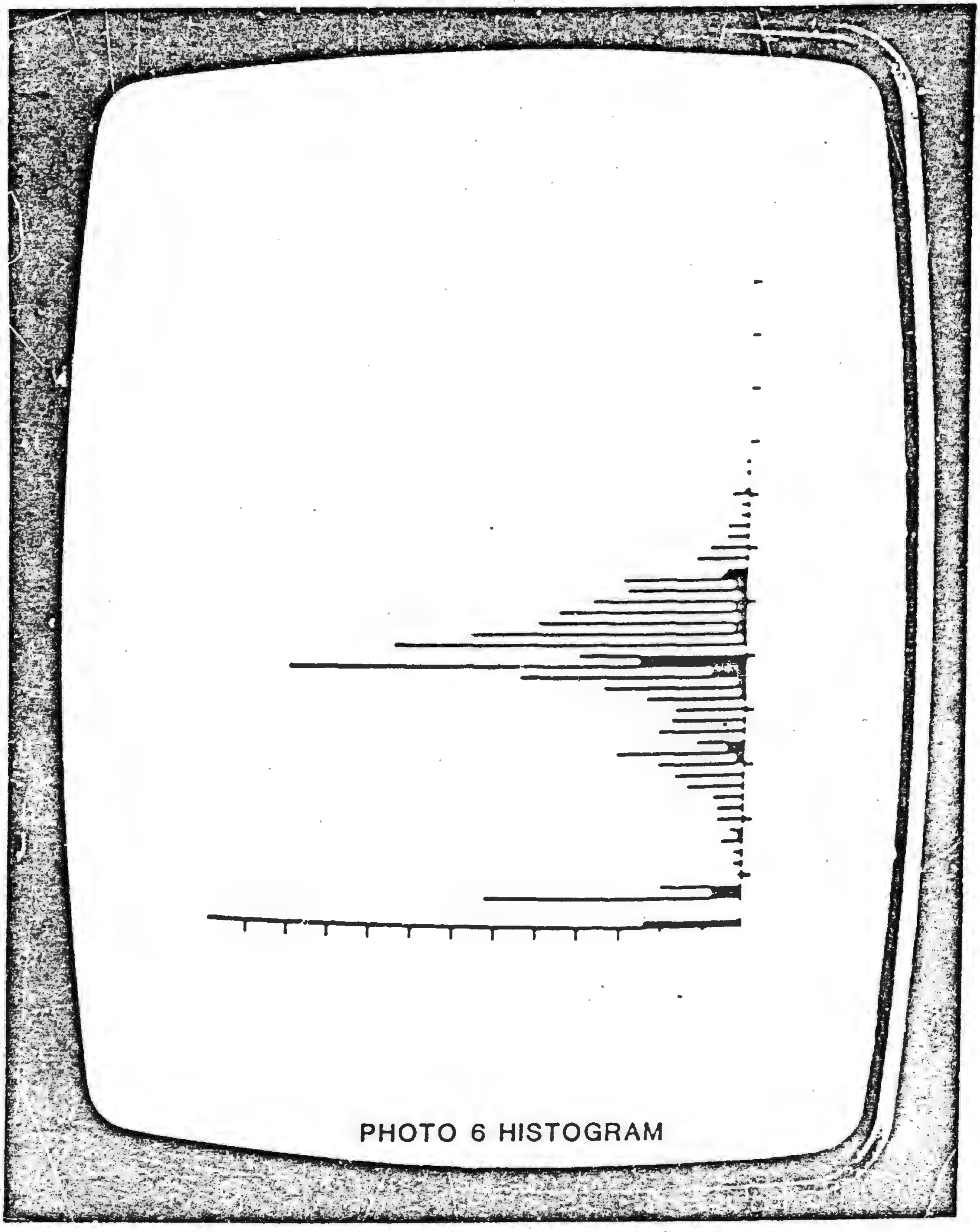
DATA PHOTO 5 - Histogram



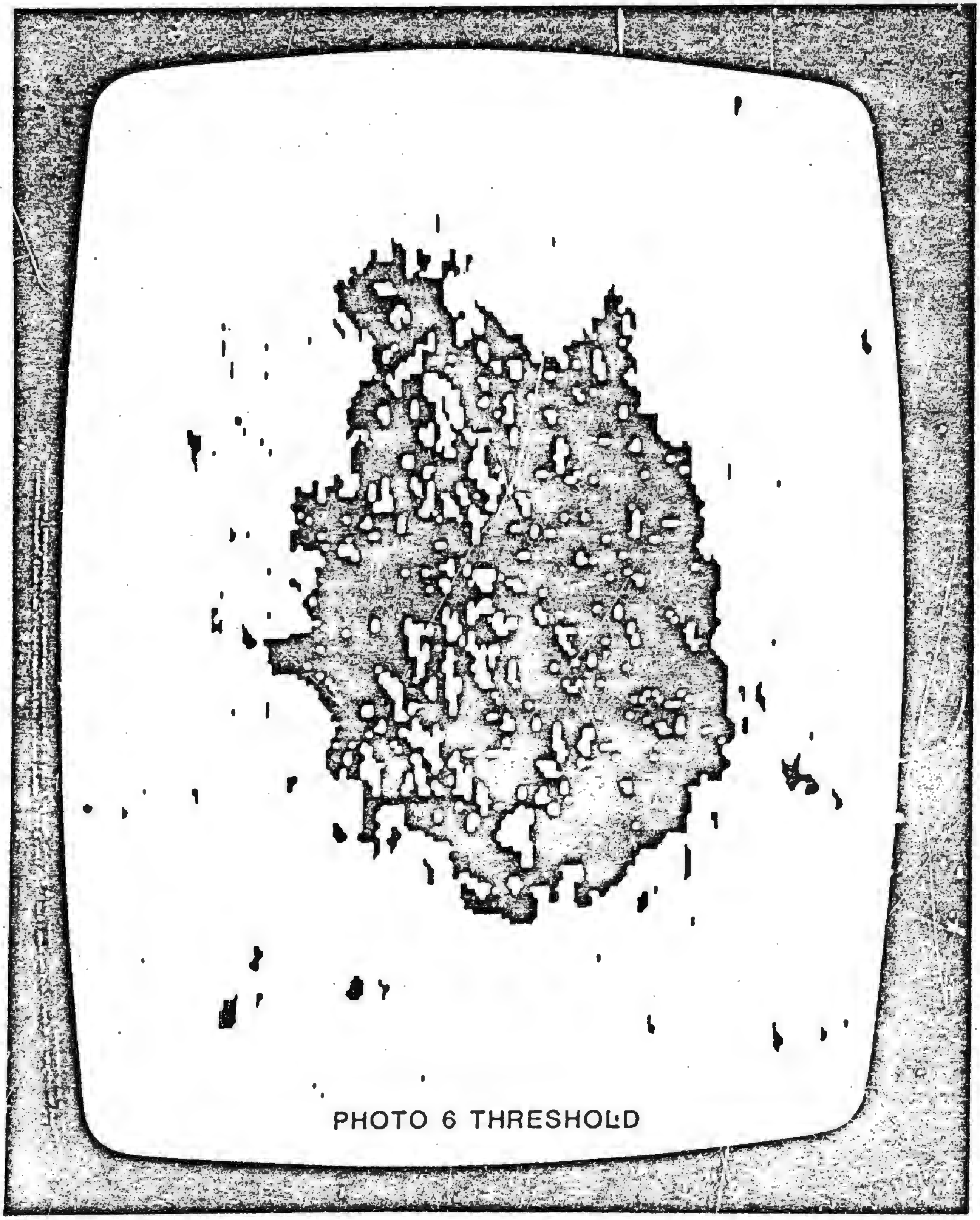
DATA PHOTO 5 - Threshold



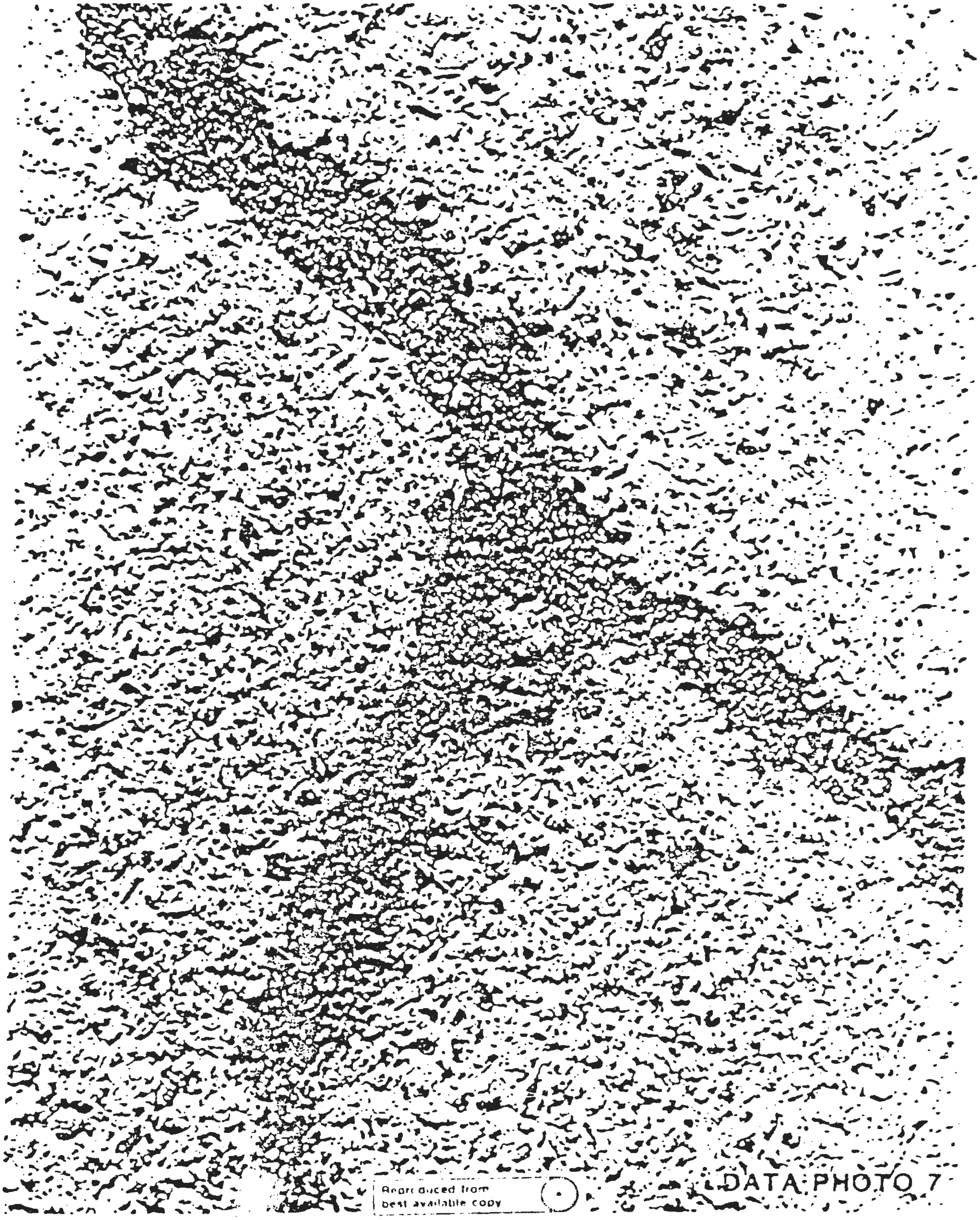
DATA PHOTO 6 - "Pot Hole"



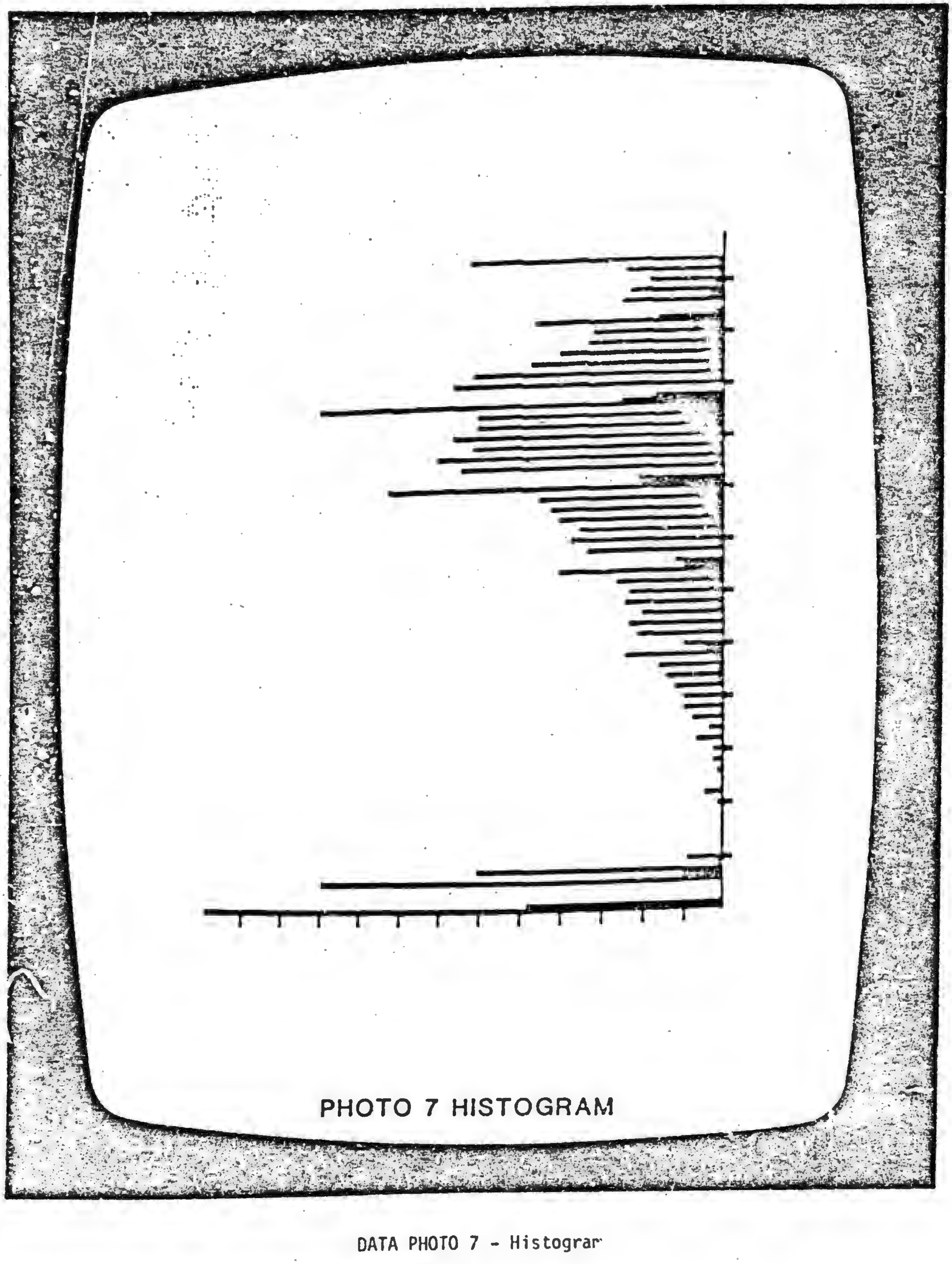
DATA PHOTO 6 - Histogram



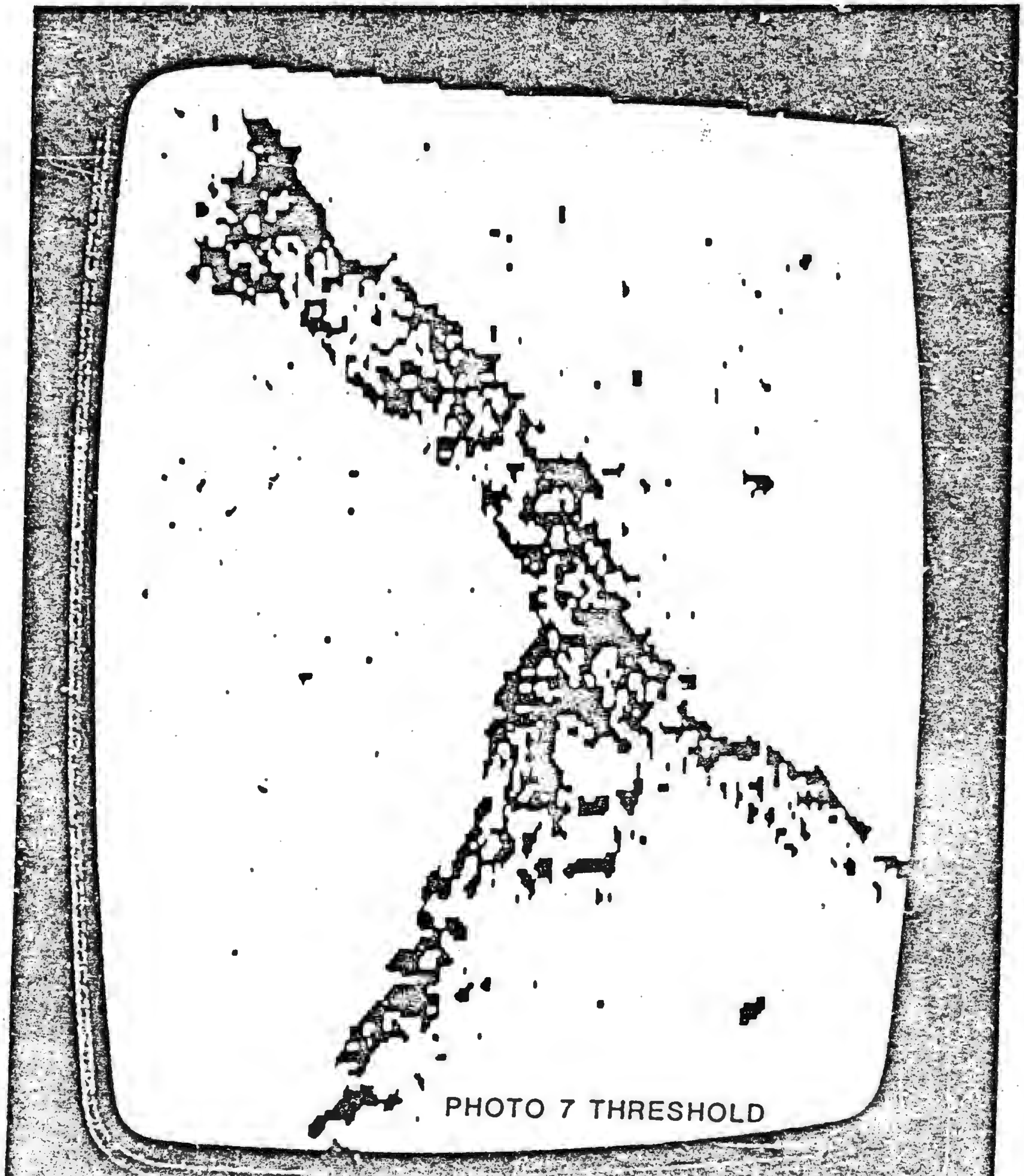
DATA PHOTO 6 - Threshold



DATA PHOTO 7 - Large "Fork" Crack

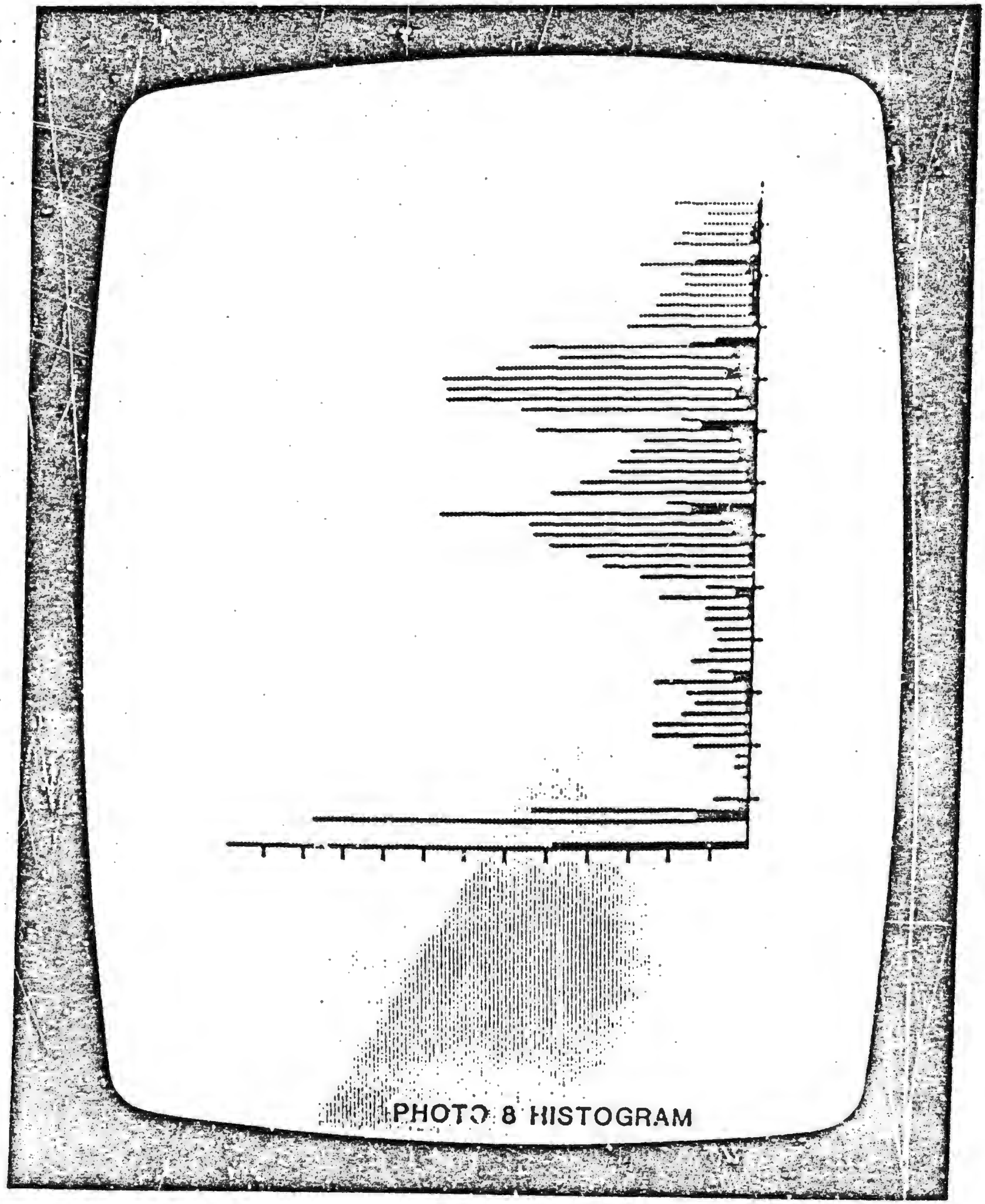


DATA PHOTO 7 - Histogram



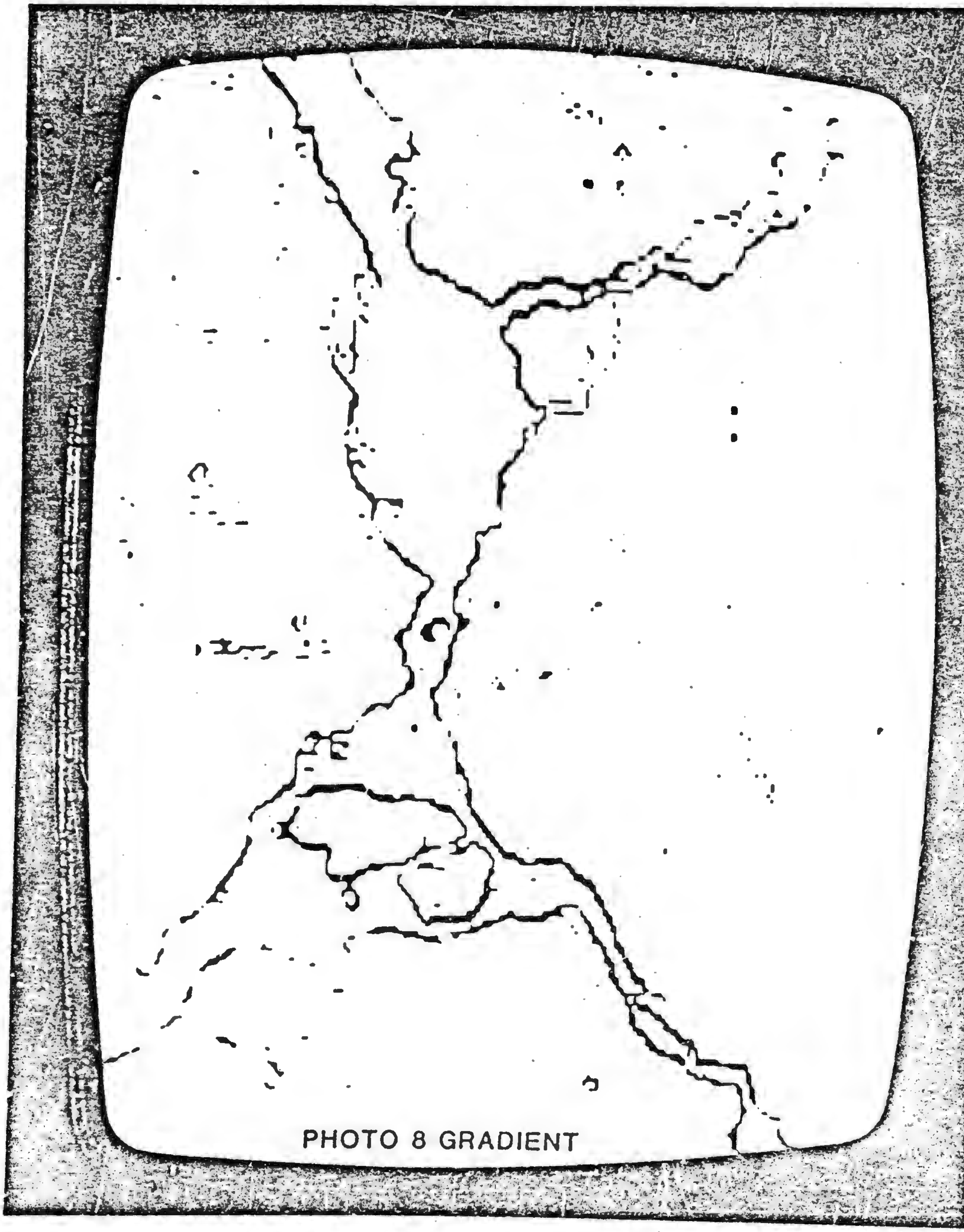
DATA PHOTO 7 - Threshold

DATA PHOTO 8 - Pot Hole and Cracking

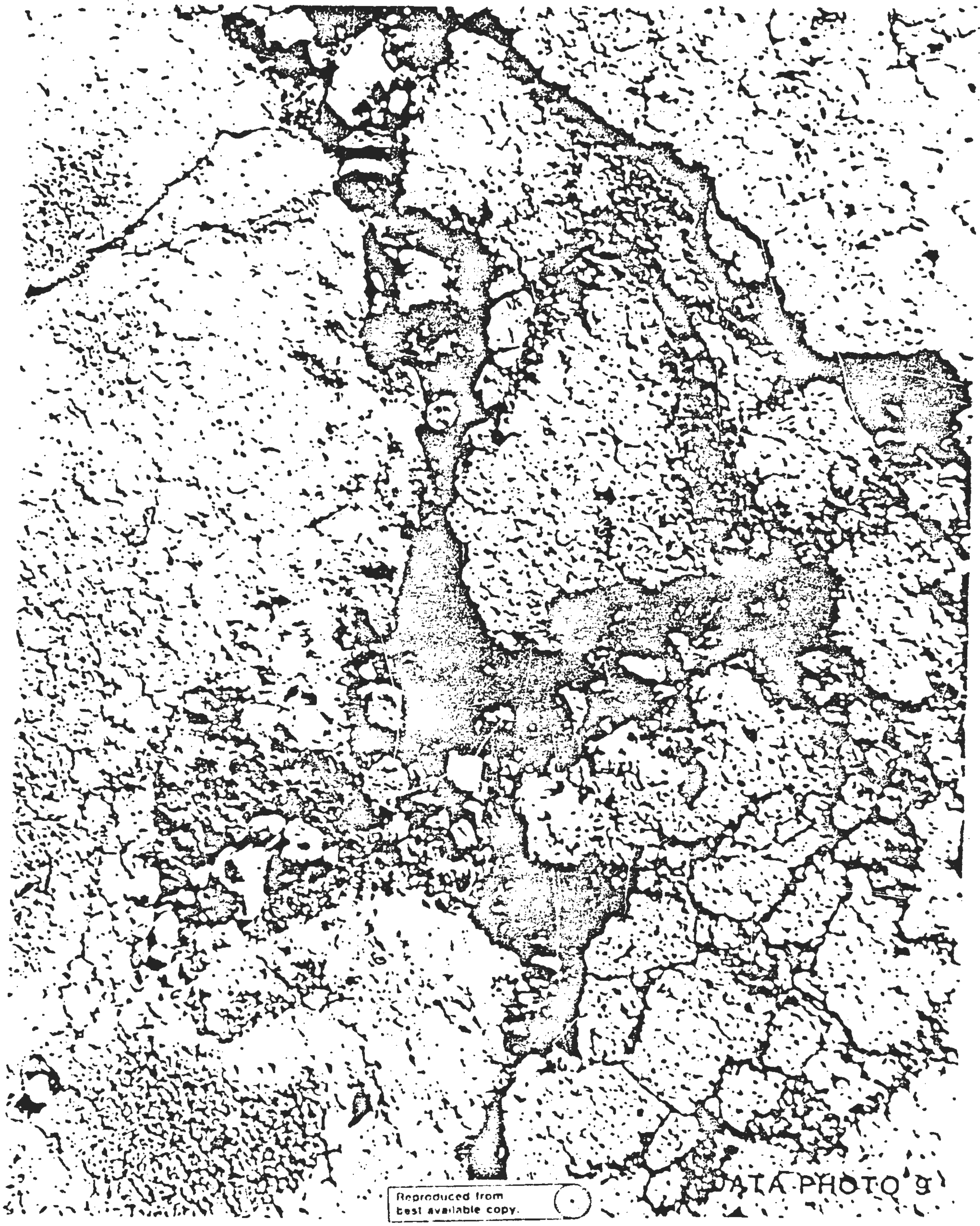


DATA PHOTO 8 - Histogram

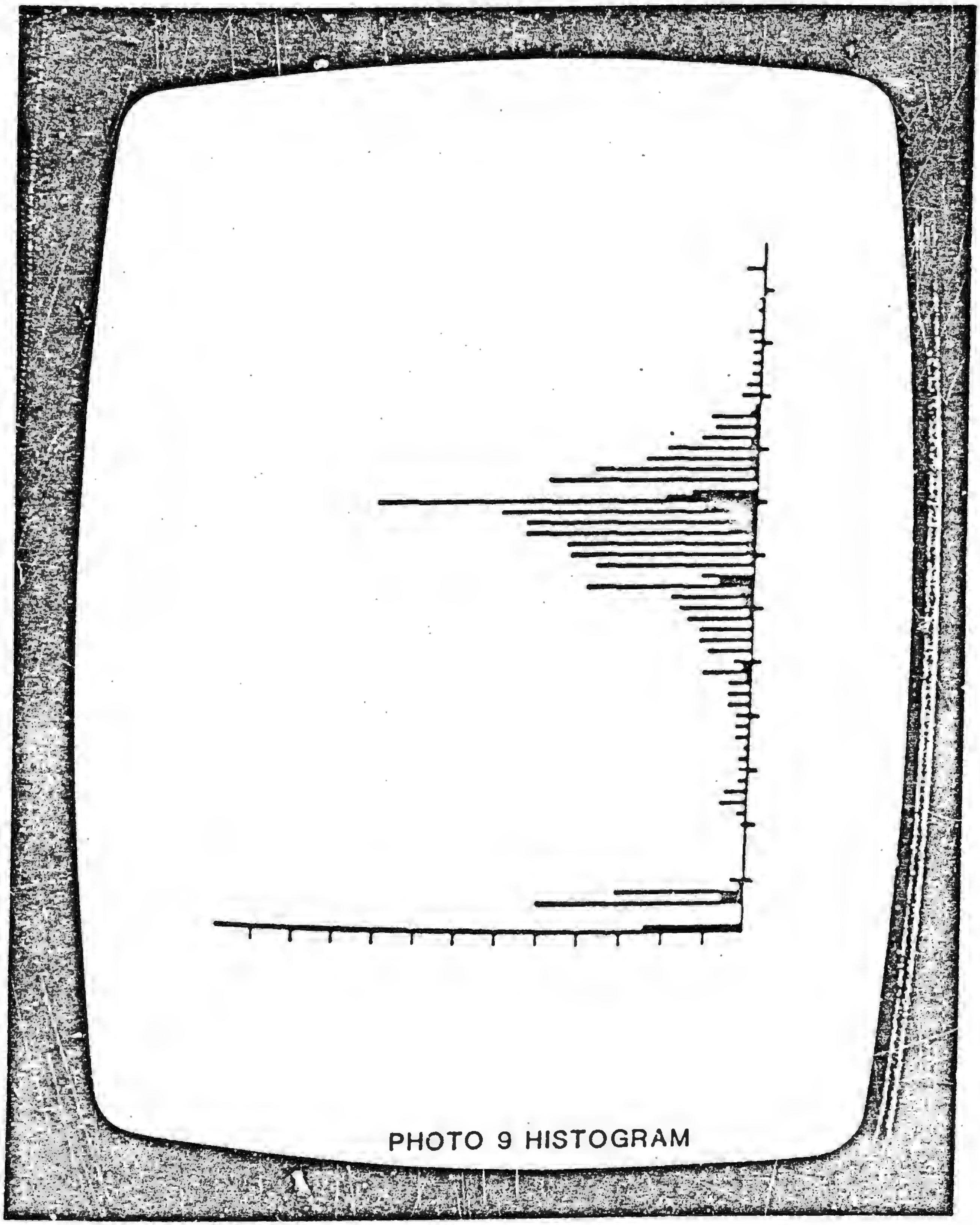
DATA PHOTO 8 - Threshold



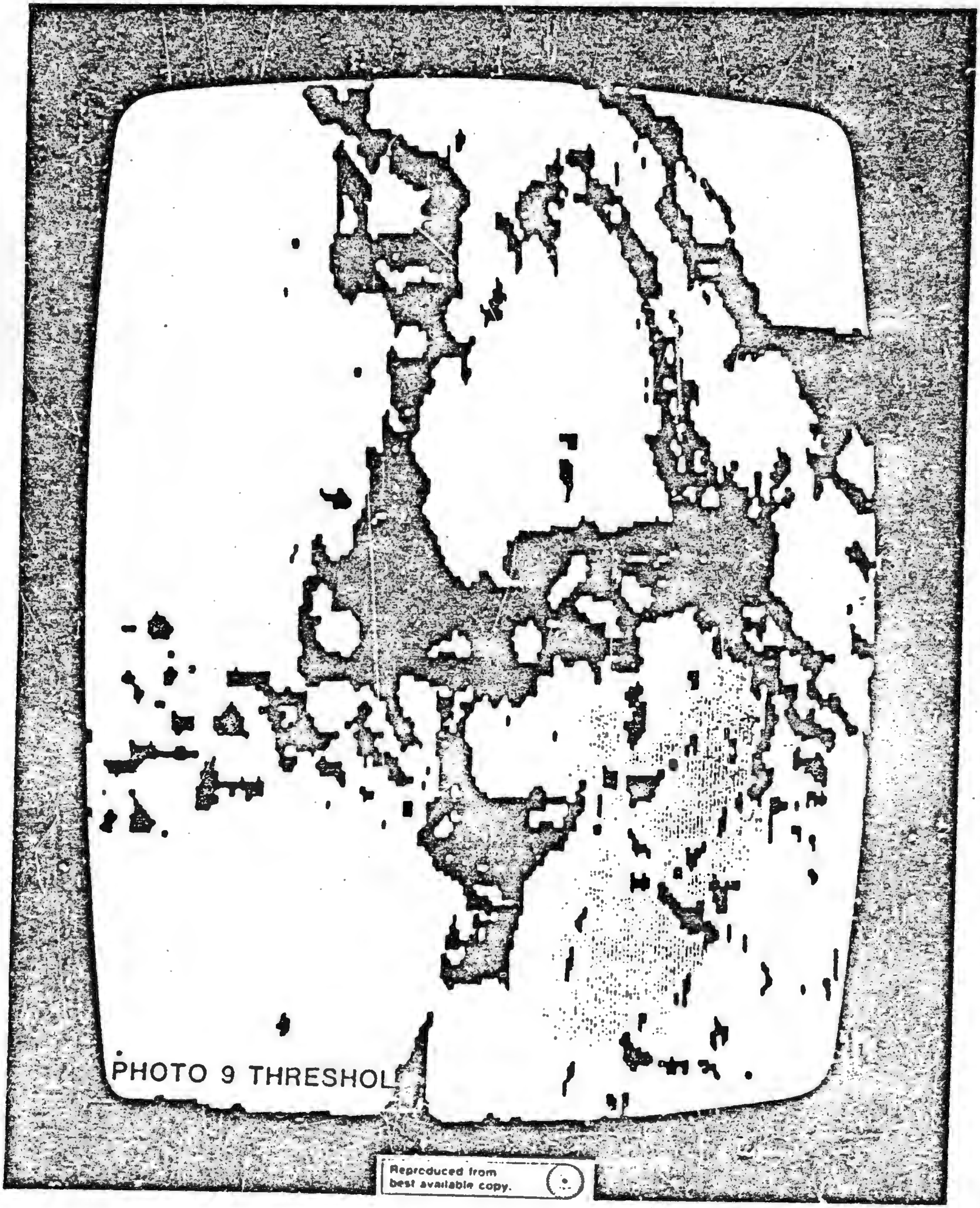
DATA PHOTO 8 - Gradient



DATA PHOTO 9 - Large Pot Hole



DATA PHOTO 9 - Histogram



DATA PHOTO 9 - Threshold

END
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