THE UNIVERSITY OF ASTON IN BIRMINGHAM

THE DEVELOPMENT OF A SYSTEM OF AUTOMATIC INSPECTION FOR SURFACE MATERIAL DEFECTS

Thesis submitted for the degree of Doctor of Philosophy

by Howard Francis Fortescue

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SUMMARY

A prototype has been developed with a view to automating the visual inspection of a range of ring-shaped components. The types of defect which occur in these components are described, and criteria are developed for defect detection which imply 100 micron diameter pinhole porosity as the limit of required resolution.

Potential non-destructive testing techniques are reviewed and an opto-electronic technique selected as appropriate. Opto-electronic scanners are discussed and a linear solid-state photodiode array incorporated in a linescan camera is chosen as a promising solution. The use of this device is described, including : illumination,optics, analogue and digital electronic processing, and interfacing to a microprocessor. Strategies for isolating defect information from the many other variations in the signals are discussed.

At the system component interface, a new model is developed of the scanning patterns of an optical array on a moving inspected surface. This leads to a description of sensitivity variations over scanned areas and a means of predicting dynamic phenomena from static measurements at the limits of the array resolutions.

The technology involved was entirely new to the company which sponsored the project. The importance of the proper treatment of innovation in a project such as this is discussed in terms of the suitable presentation of costs, and convincing demonstrations.

KEYWORDS : NONDESTRUCTIVE TESTING, SURFACE INSPECTION, AUTOMATION, OPTICAL SCANNERS, PHOTODIODE ARRAYS

"Whoever thinks a faultless piece to see
Thinks what ne'er was, nor is, nor e'er
shall be "

Alexander Pope, 1711.

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CHAPTER 1

Introduction

1. a) Introduction

This thesis is concerned with an attempt by an industrial company to solve one of its long-standing problems through the use of a technology which was entirely new to it. The problem was the cost, and to a lesser extent, the unreliability of the visual inspection of cast valve seat inserts (VSIs). These are ring-shaped components which are pressed or frozen into the cylinder heads of internal combustion engines, and upon which the valves seat to form a gas-tight seal. Plate 1.1 shows an example from the range of VSI components, and Figure 1.1 shows the components' positions in an engine.

1. a) (i) The Company

The company involved in the project is Brico Engineering Ltd., a Coventry-based firm which was one of the founder members of the Associated Engineering Group.

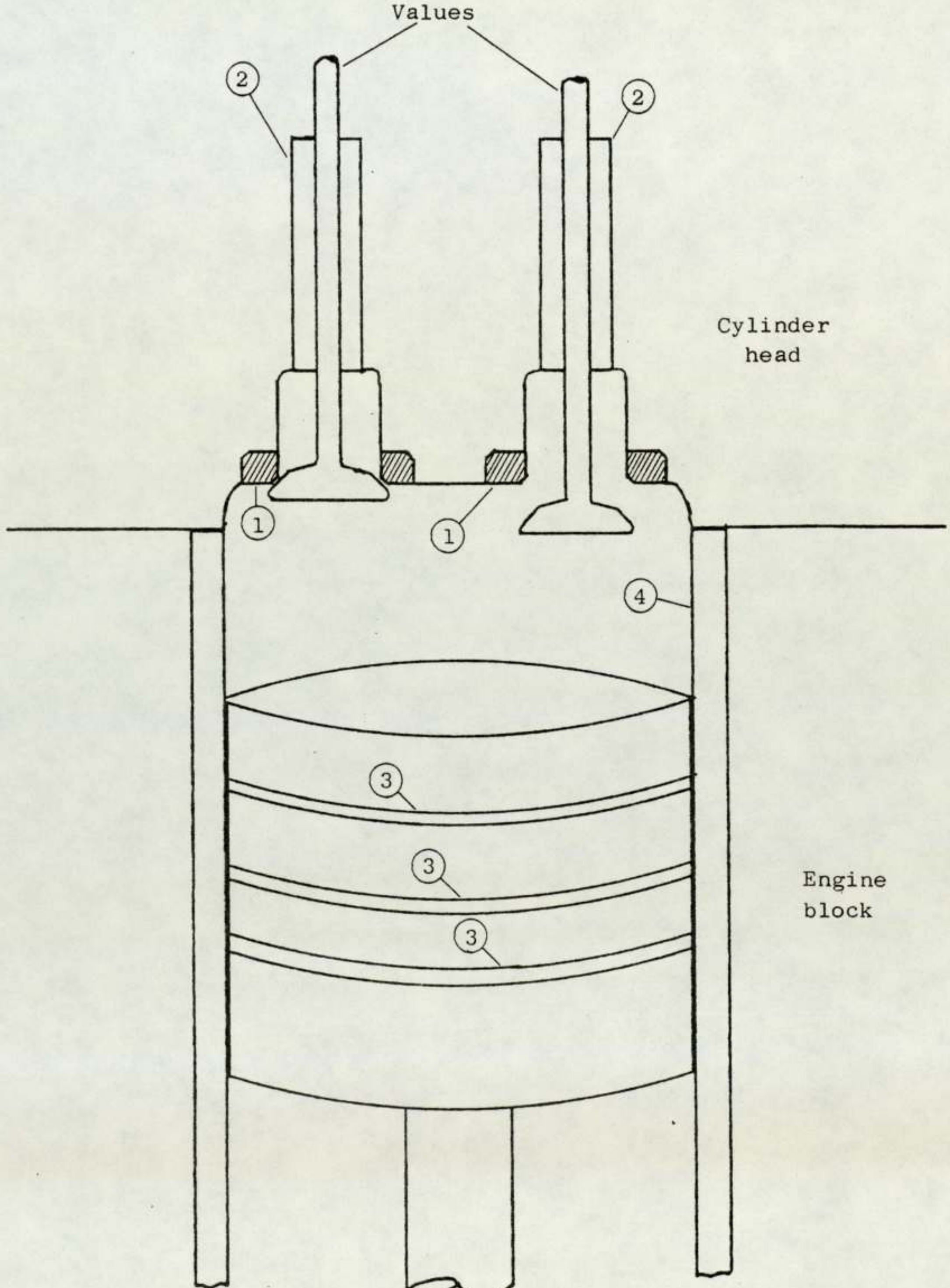
Brico is a medium-sized concern, having approximately 1000 employees at the start of this project in October 1978.

The company's output is largely automotive components which are supplied to a wide variety of manufacturers, both in Britain and abroad. Some of the most important components are shown in Figure 1.1.

1. b) Collaboration with the University of Aston

During 1978, the managing director of Brico received literature from the Interdisciplinary Higher Degrees Scheme (IHD) at the

Figure 1.1. Some Major Components produced by Brico



1. Valve seat inserts
2. Valve guides
3. Piston rings
4. Cylinder liner

University of Aston in Birmingham. In this Scheme, companies are invited to attempt the solution of suitable real problems through the placement of a postgraduate research student who will receive support in his or her research from the University. This joint undertaking is usually financed by the company and the Science Research Council, as was the case with this project. Brico's managing director was interested in the Scheme and requested his managers to submit projects from problem areas. The Quality Control manager submitted the problem which became the subject of this research and thesis.

1. c) Valve Seat Insert Production

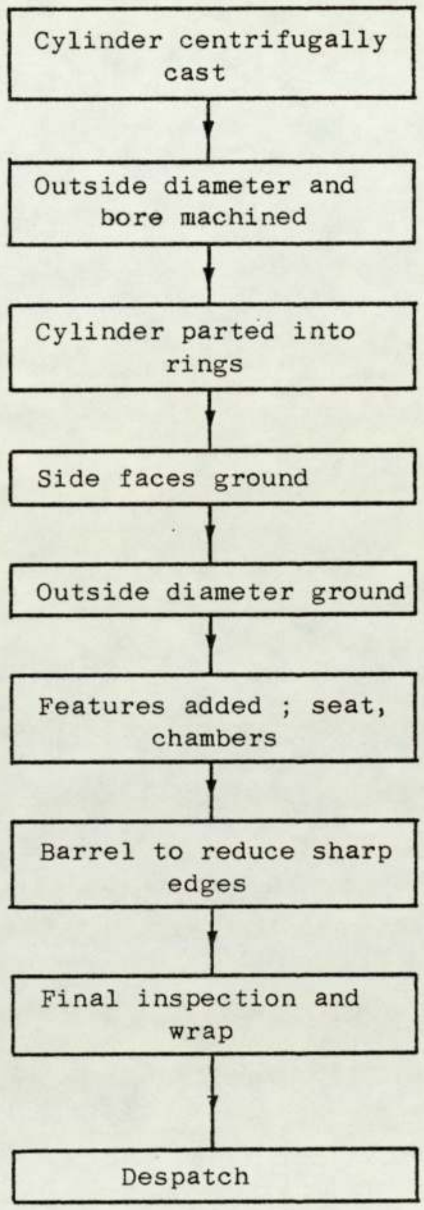
Valve seat inserts are produced by two distinct methods, sintering and centrifugal casting ; this project is concerned with those produced by the latter process.

Sintered components are made from "blanks" produced by compressing powdered metal into the ring shape required, and then heating this until the powder fuses into a solid (below the material's melting point). The blanks are subsequently machined to be within the required dimensional tolerances. Centrifugal casting consists of pouring molten metal into a rotating, cylindrical mould and allowing the material to freeze there. The resulting cylinders are then divided into rings to produce the individual components ; Figure 1.2 shows the steps involved.

1. d) Valve Seat Insert Inspection

The specifications for finished components are normally all shown

Figure 1.2. Major Steps in VSI Production



on the drawings ; an example of one of these is shown in Appendix A. These specifications include : dimensions and tolerances, surface texture, hardness and material composition ; the latter two of these are also shown on Brico material specifications (Appendix A). Levels for which defects in finished materials are acceptable have, in the past, been vague, but during the course of this project, specifications have been agreed with some customers. Figure 1.3 shows a generalised specification based on the appearance of surface material defect. No defects are allowed on the seat face, or on the corners, but some other areas of the component may have up to three 0.75mm diameter defects providing that they are not close together. Cracks are also unacceptable.

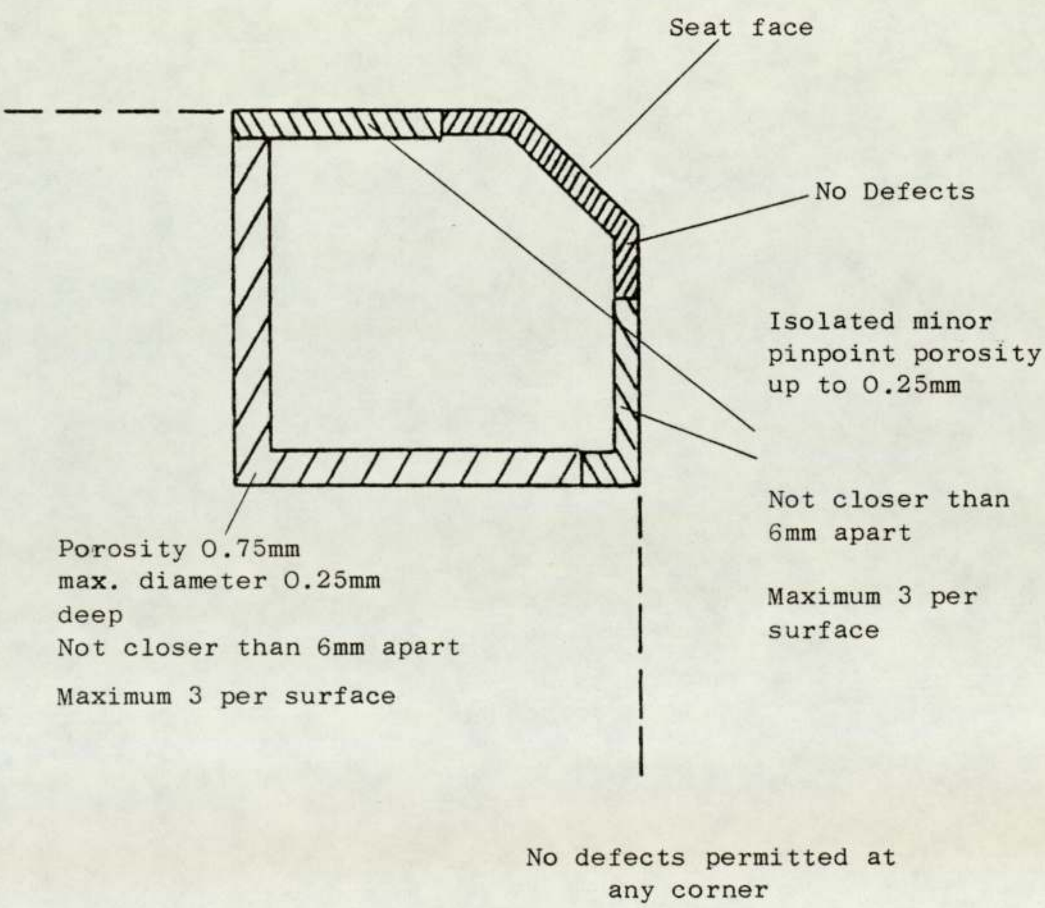
Samples of components are taken on a statistical basis and checked against their specifications for dimension, surface texture, material composition and hardness. Discrepancies may result in the whole batch being checked, and those components which are out of specification being rejected.

All components are visually inspected for other possible defects; these are described in Chapter 2.

1. e) Deficiencies in Visual Inspection

There is a number of reasons why manual inspection is unsatisfactory, the prime one being the high cost. Inspection is a labour-intensive area of industry, and as such, is subject to continually rising costs. Brico is no exception to this, and management felt that there must be a better inspection method, preferably one which did

Figure 1.3. Generalised VSI Acceptance Standard for Surface Material Defects



not involve the employment of personnel. Cost saving was, therefore, the primary motivation for this research.

Another area where manual inspection was felt to be deficient was that of its inability to achieve consistent quality. Although viewers are capable of regularly picking out components with minute defects, occasionally some very large and obvious defects get through the process.

1. f) The Project Brief

The project brief was to develop an automatic system for detecting surface material defects on valve seat inserts. This inspection was to detect defects on any surface and be achieved at a rate of 2000 components per hour.

Surface breaking pinhole porosity was stressed, since it was a perennial problem and since it was felt that this might be the most difficult type of defect to detect.

A cost-effective system was the objective, and one involving techniques which it was hoped might be applied to other components in the future.

PLATE 1.1.

A Valve Seat Insert

CHAPTER 2

The Definition of a Defect

2. a) Types of Defect

Finished valve seat inserts (VSI's) are rejected and scrapped for many reasons. For the purposes of the quality control records at Brico, these reasons are grouped into "material scrap" and "machine scrap". These groupings are useful because they indicate either the foundry or the machine shop as the cause of faults. However, in order to specify the aims of the project, and to provide a proper background, it is necessary to describe defects in more detail. For these purposes, the possible reasons for rejecting components may be classified as follows.

2. a) i) <u>Porosity</u>

This usually appears as black cavities on a finished bright metal surface. The size, spacing and number of these cavities vary greatly (plates 2.1 and 2.2). These defects may appear anywhere on the surface of the component and may be present within the body of the material. They are caused either by the inclusion of foreign matter (solid or gas) in the material as it is cast, or by shrinkage.

During centrifugal casting, foreign matter tends to collect in the bore as it is mostly less dense than the metal itself.

2. a) ii) <u>"Uncleaned-up" condition</u>

This condition occurs when the final operation does not remove material left at the surface by the previous operation. This may be because the component was undersized prior to the final operation, or because the final operation removed too little material. In the latter, rather unusual case, the component could be reworked. The former occurs either when the casting is undersize (casting scrap) or when the previous machine operation removed too much material (machine scrap). With an undersized casting this condition is easily visible, as the rough cast finish is still present (plate 2.3). The defect is less obvious where the previous machining operation has left the component undersized, as the previous finish may be quite bright. However, there is usually a difference in texture and also in the dimension (plate 2.4).

2. a) iii) Tool damage

When a tool has finished its operation, it often tracks the surface of the component as it retracts, occasionally producing a groove. Several other types of damage occur during machining operations, such as broken edges and very rough finishes (plate 2.5).

2. a) iv) Missed operations

If a machine operation is missed it is usually a feature such as a radius or a chamfer which is omitted. Such components are unserviceable, but can be reworked providing this does not disrupt production.

2. a) v) Cracks

Cracks in VSI's are usually radial and can be caused in casting or machining, usually grinding, or by a combination of these. They are not easy to see, but can be detected by other methods of non-destructive testing (NDT)(see Section 3bv).

2. a) vi) Dimensions

Finished components which are undersized (i.e. below the minimum dimension of the specified tolerance) on any dimensions are scrap. Oversized components can usually be reworked. (For tolerances see the Brico drawing in Appendix A).

2. a) vii) Material composition

There are detailed specifications for the composition of each of the alloys from which VSI's are made (Appendix A). The composition is checked at the foundry and again when samples are taken at the main site.

2. a) viii) Hardness

The hardness of finished components is specified and checked against Rockwell and/or Vickers hardness scales (Appendix A).

2. a) ix) Surface texture

The surface texture of VSI's is specified on the drawing, usually in terms of the surface roughness measure Ra, (see drawing in Appendix A).

2. b) The Rationale for Concentrating on Porosity

At the initiation of the project the brief was to develop an automatic system for detecting and rejecting surface material defects. These include surface breaking porosity, cracks and uncleaned up condition due to undersized castings. Investigations concentrated on porosity for several reasons : cracks in VSIs were so rare that they did not consitute a problem (1). If cracks were to become a problem there are eddy current systems available which could be adapted to detect them.

The uncleaned up condition revealing a rough cast finish is so similar to gross areas of porosity that it would be easily detected by any system which could detect porosity. Further, if a system could be developed which would detect pinhole porosity then it seemed likely other defects such as machine damage, missed operations and even large cracks could be detected. Porosity was also the main problem in VSI production, and also gave rise to most customer complaints (1). Improved foundry practices have reduced the incidence of porosity over the years but have not completely eradicated it and are unlikely to do so in the foreseeable future. This is particularly noticeable with the more highly specialised alloys, whereas machine scrap and undersized castings can be regarded more as correctable mistakes.

2. c) Inspection Criteria for Porosity

Customers require "no surface material defects" on the whole of, or at least part of each component supplied to them. Brico has no written specification from most of its customers covering surface material defects but it is assumed, and it is also the practice that there should be none.

A few customers have produced specifications for those defects and, although some quite large defects are allowed on unimportant surfaces, there are always areas where "no defects" applies.

These requirements are based on the experience and intuition of customers. They feel that if there are no surface defects, then the probability of internal defects is low, particularly near the surface where they may be important. Customers also feel that components with defects may fail in service (1). This rejection criterion is supported by their experience that if only parts with no defects are used, then there are few, if any failures attributable to those parts. This means that the requirement for no surface material defects is either exactly correct or too stringent. The latter seems more likely.

It is very difficult to measure the depth of porosity and would be practically impossible with production quantities. A few customer acceptance standards do state the dimensions of defects on non-critical surfaces, including the depth. In practice it is so difficult to interpret these standards accurately that viewers either reject any surface defects which approach the area indicated in the standard, or simply apply the "no defects" principle and reject them all.

Although "no surface material defects" may seem a sensible requirement, a closer examination will show that it, by itself, is meaningless. This difficulty is best explained by the simple example of examining an area of apparently defect-free steel. A close examination with the naked eye in good light reveals "no defects" ; if the sample is now examined under a magnifying glass or a microscope, then previously unobserved "defects" may appear. Clearly, if the magnification is increased enough, any specimen (except, perhaps, a theoretically perfect single crystal) will reveal its "defects" (see plate 2.6, a, b and c).

There are two important and distinct points here. The first is that it is necessary to specify precisely any inspection method by which defects are to be detected in order to state that an inspected part is defect free. The second is that it is necessary to decide what size and type of defect should cause a part to be rejected, given that any piece of steel will reveal some defect if examined closely enough. These two points are stated from a visual inspection stance, but they are equally true if a component is examined from an electrical or metallurgical viewpoint.

Ideally, the second of the above points should be closely related to the final purpose (2). In practice, the ideal is seldom, if ever achieved. It is reasonable to look at the function of the components solely from the Brico point of view. In this case, the purpose which the component fulfills is to be saleable to a motor manufacturer. The component must, therefore, only meet the quality standards of the customer, regardless of the basis of that standard.

2. d) Fitness-for-purpose versus Visual Criteria

An alternative to basing the investigations of the project on customer requirements would have been to carry out a comprehensive fitness-for-purpose study on defective VSI's. This was not undertaken for the following reasons :

Present customer requirements are either correct or too stringent. This means that a detailed fitness-for-purpose study would imply either the same standards as now, or less stringent ones. Customers would see this as a lowering of quality standards and it would be very difficult and costly, if not impossible to persuade them to accept the new standards.

Whatever new standards a study revealed, the original problem of automating the inspection process would still have to be solved.

In view of the above, it was felt that the time and expense which would be required to perform a fitness-for-purpose study could not be justified.

2. e) The Minimum Size of Pinhole Porosity which should be Detected

The question is now "What is the minimum size of pinhole which the automatic system will be required to detect ?" The inspection criteria above imply that this is the minimum size which the human eye can see. In fact, one of the few written inspection standards which outlines the acceptance level of casting defects for VSI's states no surface defects "based on normal (no magnification) visual inspection" (3).

The problem now becomes one of deciding what is the minimum size of pinhole that the eye can see. Lighting is good and fairly consistent in the inspection areas at Brico, but individual differences between viewers, and also different surface textures and reflectances affect what can be seen. VSI's with a variety of different sized surface defects were shown to inspectors and other quality control staff, including the factory chief inspector and the quality manager. The question asked was "Which is the smallest defect you can see with the naked eye ?" It was generally agreed that a black hole 100 microns (.004") diameter on a bright metal surface can just be seen with the naked eye in a good light.

This 100 micron diameter criterion is a gross generalisation, and many assumptions have been made in arriving at it.
However, it was necessary to make a decision at an early stage as to what resolution would be required of any automatic system. This may seem an arbitrary decision, but as long as the limitations implicit in its statement are realised, it is well justified.

Those who decided on the 100 micron diameter defects were given a

VSI and were told that it had defects on a particular face and asked to find the smallest they could see. This is a very different situation from the one in which viewers normally operate. The main difference is the time allowed to scan for defects, a typical production inspection time, is about 1 second for one VSI ; the more leisurely the approach, the more detailed the inspection. Repeated scanning was possible and most selected the 100 micron defect after about 10 seconds. Having once found the defect, it is relatively easy to relocate. This highlights another factor which is the inspector's prior knowledge of the defect. In fact, several of those who had selected the 100 micron defect as being the smallest they could see, subsequently found that they could perceive a 50 micron hole after it had been shown to them under magnification.

For these and other reasons it was felt that the criterion set was very strict, and that an isolated pinhole 100 micron diameter would almost certainly pass normal inspection unnoticed ; also that if necessary, it would be easier to relax this criterion in future than to tighten it.

A number of minute defects which are close together may appear as an area of contrasting texture or colour, and therefore may be more easily visible than a single defect, whereas an automatic instrument made need to scan each individually. Also, there are considerable differences between the eyesight of individuals.

Taking all these factors into account, and also the need to provide a simple criterion which would be acceptable to quality control staff, the 100 micron minimum visible defect was decided upon.

The discussion so far assumes that the defects are round ; the shapes vary, but most defects this size appear as points of black. The contrast between the defect and background is, of course, important. The surface used to decide the criterion was of brightly ground Alloy 52 (high chrome content) (Plate 2.2) with a variety of pinholes and other porosity defects caused during casting. The contrast here is very much better than for a similar defect on a dull alloy such as Alloy 8. The contrast is dependent on the surface reflectance, which depends on the alloy as stated, and on the machining process and surface texture. Generally speaking, the rougher the surface, the less the reflectance, though for the same roughness (Ra value) ground and turned surfaces may have different reflectances (4).

One must bear in mind the above factors together with the following section on eye performance when considering a 100 micron defect as the smallest visible.

2. f) Eye Performance

The resolving power of the eye is known as Visual Acuity (VA) and is defined in terms of the minimum angle, subtended at the pupil, resolvable by the eye. The value of Visual Acuity is given by the reciprocal of this angle measured in minutes of arc. Thus, if the minimum resolvable angle was 2', the VA would be 0.5, and the smaller the angle, the greater the VA value.

The normal value of Visual Acuity for a person with good eyesight is 1, i.e, an angle of 1' can be resolved (5) when the object is focused on the fovea which is the most sensitive region of the retina.

Visual activity falls off linearly as the image moves away from the fovea towards the periphery (6). It is also affected by the intensity of the light from the object, a brighter object producing a higher VA up to a saturation level (7). Visual Acuity also varies between individuals, as does and physical parameter. The near point, which is also subject to individual variations, is the closest distance to the eye where an object can be sharply brought into focus. This is typically about 250mm (8). Thus, the minimum size of target resolvable by an eye with a VA of one and a near point of 250mm is approximately 70 microns, which is of the same order as the 100 micron limit chosen.

The normal distance from an object to eye during visual inspection is about 400mm and for a Visual Acuity of 1, this yields a value of 120 microns for the smallest resolvable object. This again is of the same order as the 100 micron limit.

Another important question is "How quickly can the eye scan with this resolution?" To answer this it is necessary to examine how the eye actually scans a surface during an inspection task. The eye does not scan continuously, it fixates a particular area for a time and then moves quickly to another area and fixates there, and so on. These movements are known as saccadic eye movements, or saccades. Fixation times are rarely less than 200ms. The area round the centre of fixation from which useful information can be gained is known as the useful area of view, or the visual lobal area which is eliptically sloped with the longer axis horizontal. For the maximum resolution which is required, this area is that covered by the fovea and therefore subtends and angle of only 2^{o}. For detection of gross defects, this area may subtend an angle of as much as 120^{o} (6).

The surface area of a small VSI, 40mm diameter, 3mm radial thickness and 9mm height is $\approx 3{,}000mm^2$ (e.g. VS 2490). If this could be examined in the most efficient possible series of fovial fixations, each of area $150mm^2$ (2^o arc at 400mm) then 20 fixations would be required. This optimistically low number of fixations would take 4 seconds, which is four times as long as is actually taken to inspect each VSI. This calculation is both superficial and approximate, but approximations have been used which give a minimum result. The probable explanation for this discrepancy in inspection times is that part of the surface is scanned with maximum resolution and the rest with reduced resolution.

This supports the suggestion by senior quality control staff that a single pinhole 100 microns diameter, although just visible on close inspection, would probably be missed under normal viewing conditions.

2. g) Summary

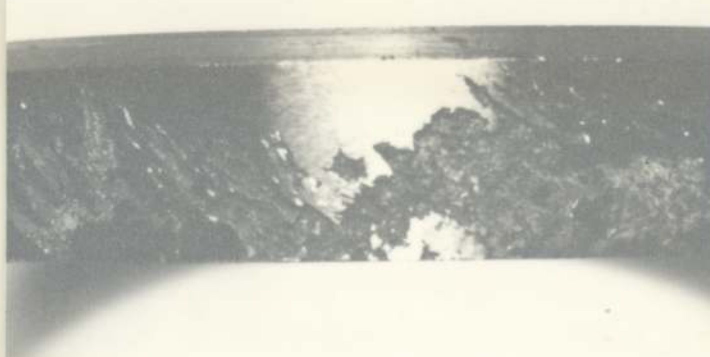
There are many different types of defect which can cause rejection of VSI's, as with any other components. The particular type of defect upon which this thesis concentrates is surface-breaking porosity which appears as a black area on a bright metal surface. This choice was inherent in the project brief and was largely influenced by customers' acceptance standards. Having decided on the type of defect, the minimum size required to be detected was specified as 100 microns diameter. This is intended as a guide to the maximum sensitivity of any proposed system, and again stems from customers' specifications of "no visible defects", together with an attempt to establish the magnitude of the smallest defect visible to the naked eye.

Generally speaking, any defect smaller than 100 microns diameter cannot be seen. The implication is that if it cannot be seen it does not exist. This is justified in that defects smaller than 100 microns diameter have never been detected and components accepted on this basis provide satisfactory service.

PLATE 2.1. A defective VSI showing gross porosity on bottom face

PLATE 2.2. A defective VSI showing porosity in the bore

PLATE 2.3. A defective VSI showing the "uncleaned up" condition due to an undersized casting





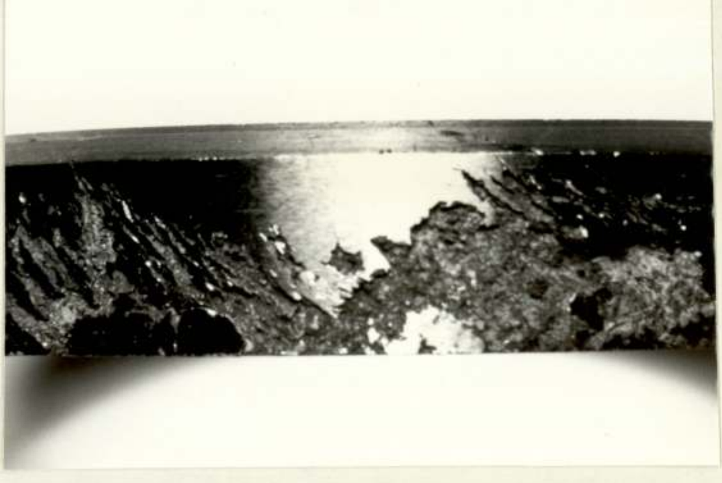


PLATE 2.4. A defective VSI showing "uncleaned up" condition due to machine error

Plate 2.5. A defective VSI showing tool damage

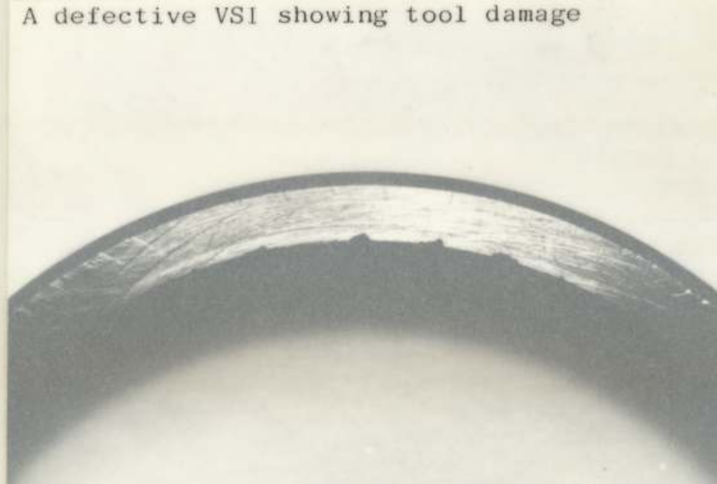
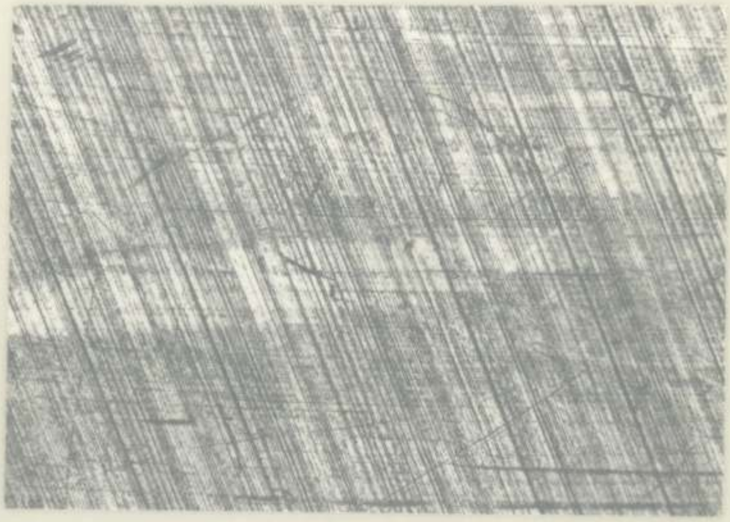


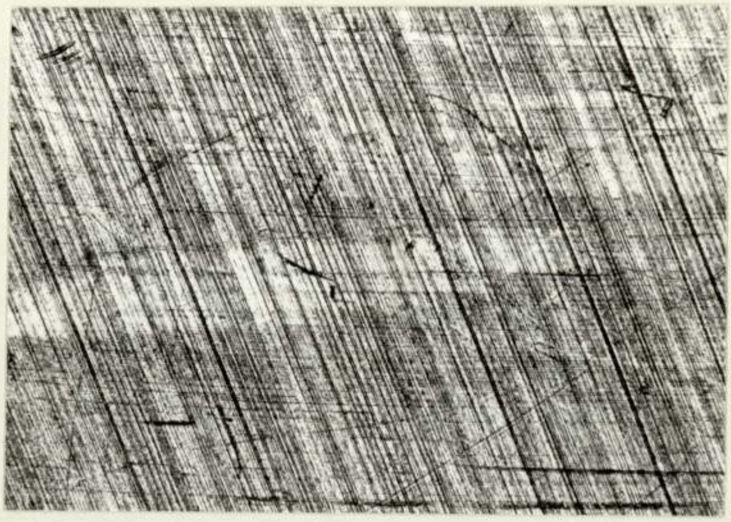
PLATE 2.6. An apparently defect-free metal surface shown at three different magnifications

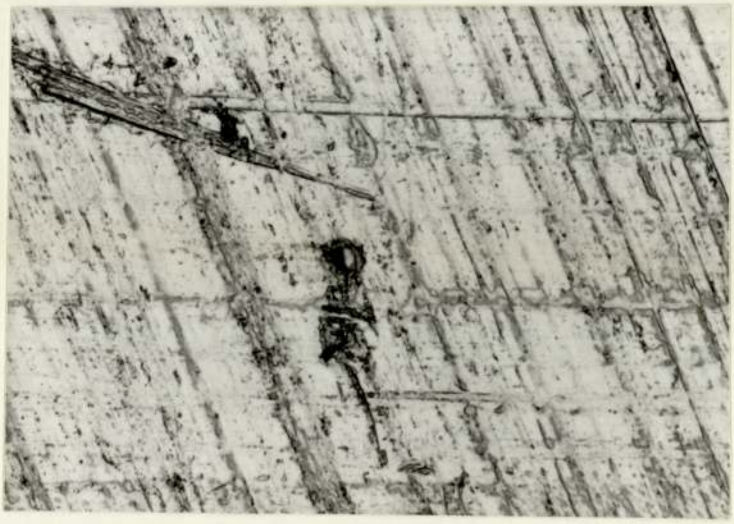
(a) 1x



(b) 10x

(c) 400x





CHAPTER 3

Non-Destructive Testing

3. a) Introduction

This chapter reviews and appraises those non-destructive testing (NDT) techniques relevant to surface inspection. Only the eddy current and opto-electronic techniques seem capable of development into systems for automatic inspection of valve seat inserts. Of the two, the eddy current technique is incapable of detecting 100 micron diameter pores. Consequently, the opto-electronic technique was selected as offering the best prospect of solving this particular inspection problem.

General information on NDT can be obtained from the NDT handbook (9), and from Non-Destructive Testing (2).

3. b) Non-Destructive Testing Techniques

3. b) i) <u>Optical inspection aids</u>

The current viewing method for finished components is described in Section 1. d) and this uses unaided eyesight. The use of magnifiers is invalid here since only defects which are clearly visible to the unaided eye are rejected.

Other types of optical aid commonly used in industry are projectors for checking shape in outline and boroscopes for examining otherwise inaccessible areas such as the inside of an engine. Flexible fibroscopes, which are even more versatile, are now available for viewing inaccessible areas. These fibre optic bundles have an imaging lens at the object end, and can have an eyepiece or may be coupled to a television camera at the other (10).

3. b) ii) Liquid or dye penetrant techniques (11)

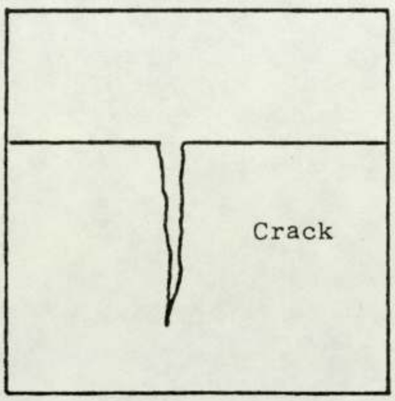
These are methods of finding small surface-breaking defects such as cracks and voids in metallic components by enhancing their visibility. The technique involves soaking the metal surface with dye penetrant which then seeps into any cracks, etc. The excess penetrant is subsequently removed, leaving the dye only in the cracks, and the surface is covered with a light-coloured absorbent material called developer. After a time, the dye seeps out of the crack into the developer, giving a visual indication much wider than the crack (Figure 3.1). Many different types of dye penetrant and developer are available, including fluorescent dyes for viewing under ultra violet light, and dyes which can be sprayed electrostatically to assist deposition. All these methods rely on the inspection which follows development.

3. b) iii) The magnetic particle technique

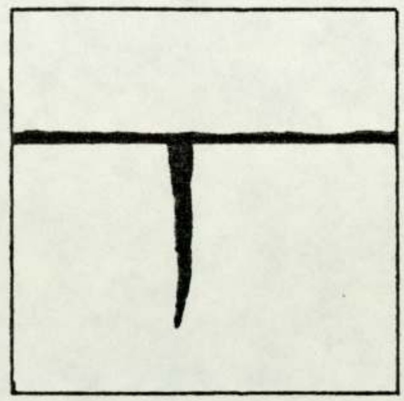
This is a very sensitive method of detecting both cracks and sub-surface defects in ferromagnetic materials (12).

The method is to induce a magnetic field in the material at right angles to any crack which is to be detected. Where the magnetic flux is interrupted by a discontinuity, there is what is known as a leakage magnetic field at the surface, and it is this which is detected. The surface is covered with minute, highly mobile magnetic particles and these congregate around any leakage magnetic fields and therefore around discontinuities (Figure 3.2). The magnetic particles may be in fine dry powder form or, more usually, suspended in a liquid such as paraffin. The magnetic particles are sometimes coated with fluorescent material and the viewing is performed under ultra violet light. This

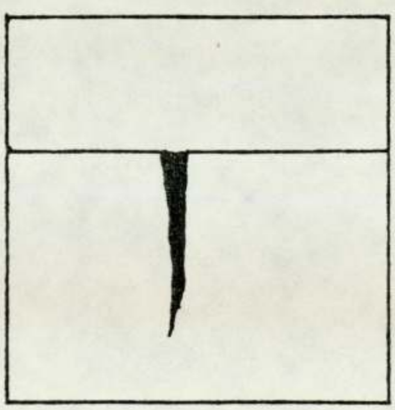
Figure 3.1. Mechanism of Penetrant Flaw Detection



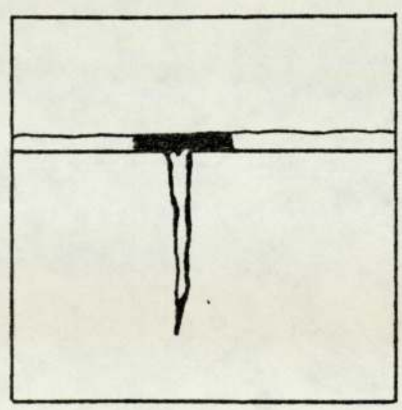
a) Cleaned surface



b) Penetrant covered

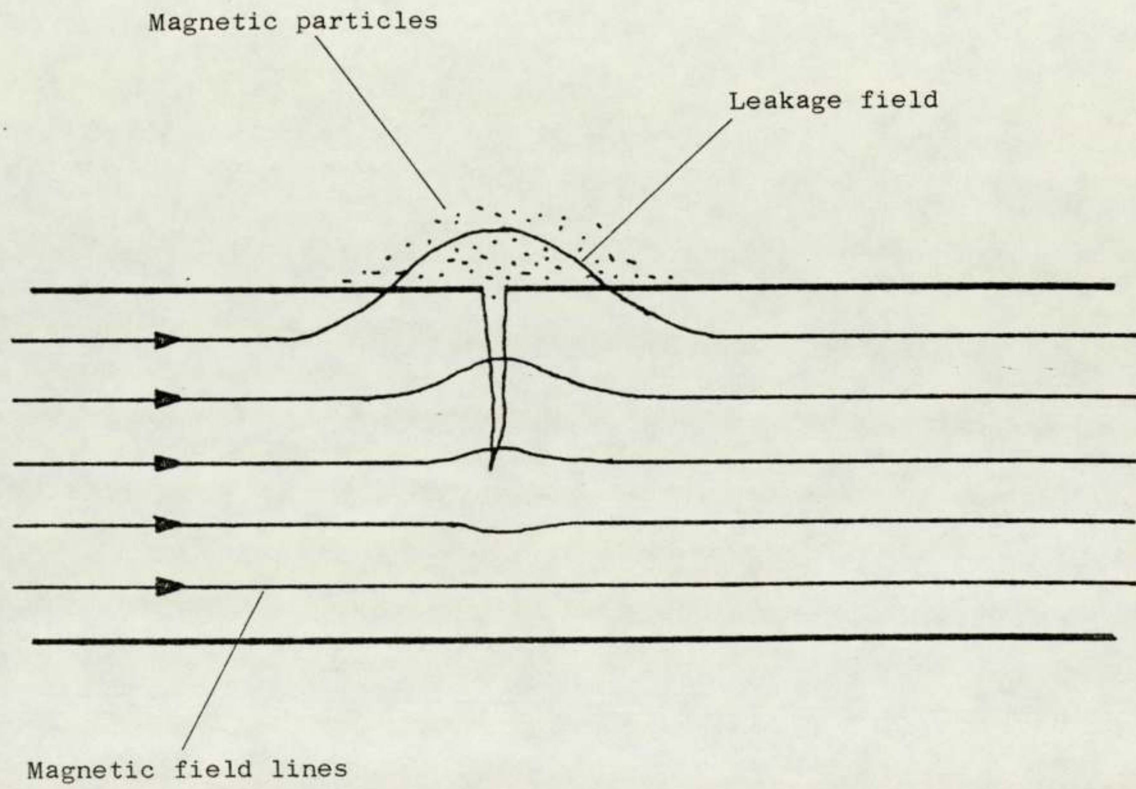


c) Excess penetrant removed



d) Developer applied

Figure 3.2. Crack Detection by the Magnetic Particle Technique



method is a very sensitive one but still relies on a skilled viewer who must detect and interpret the discontinuities.

3. b) iv) <u>Flux leakage techniques</u>

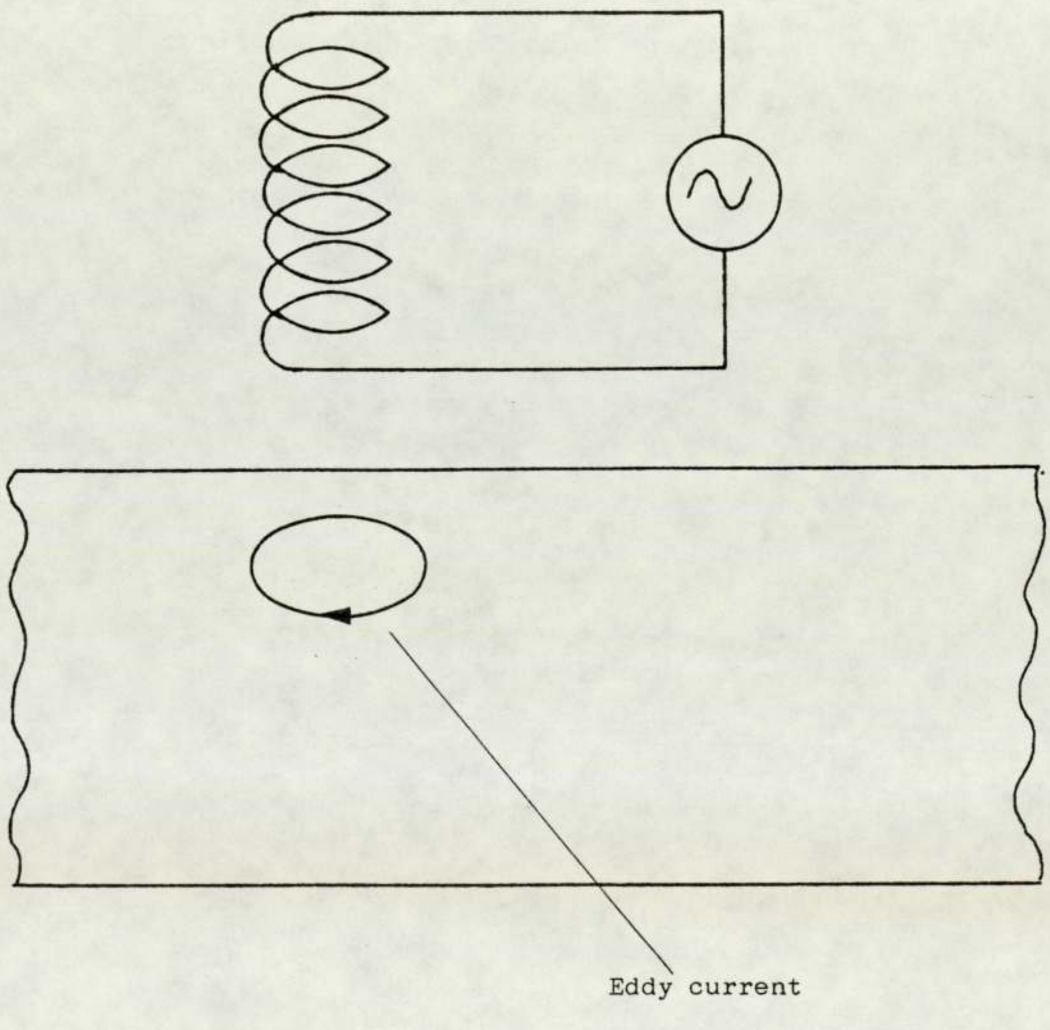
Leakage magnetic fields (Figure 3.2) can be located by systems employing magnetic recording tape or electromagnetic probes (13). The former system utilises a rubber-based magnetic tape which is brought into close proximity with the magnetised stock and records any leakage fields. The tape then passes over a playback head which retrieves the magnetic information. This technique has been used in the steel industry, where its ability to operate on scaled surfaces is advantageous.

3. b) v) <u>Eddy current techniques</u> (14)

Eddy currents are loops of electrical current which have been induced in a conducting material. They are induced by a changing external magnetic field which they oppose. In eddy current test equipment, the external magnetic field is produced by an alternating current in a coil placed near to a metal surface (Figure 3.3). The resulting eddy currents oppose the magnetic field of the exciting coil and the extent of this opposition is measured electronically. The effect of this is best seen by considering the effect of examining sound and cracked samples under a coil. In the sound sample, complete eddy current loops are formed, but in the cracked sample, these loops are interrupted. In the latter case, there is less opposition to the changes in magnetic fields.

The frequency of the alternating current is an important parameter. For a high frequency signal, a small coil is used giving sensitivity

Figure 3.3. Principle of Eddy Current Inspection



to small defects over a small surface area with little depth of penetration. At low frequencies, a larger coil is used and this is not so sensitive to small defects, but covers a larger surface area and gives better depth penetration. The coil may be in a probe for examining one surface, or may surround a component such as a bar or tube

3. b) vi) Ultrasonic flaw detection (15)

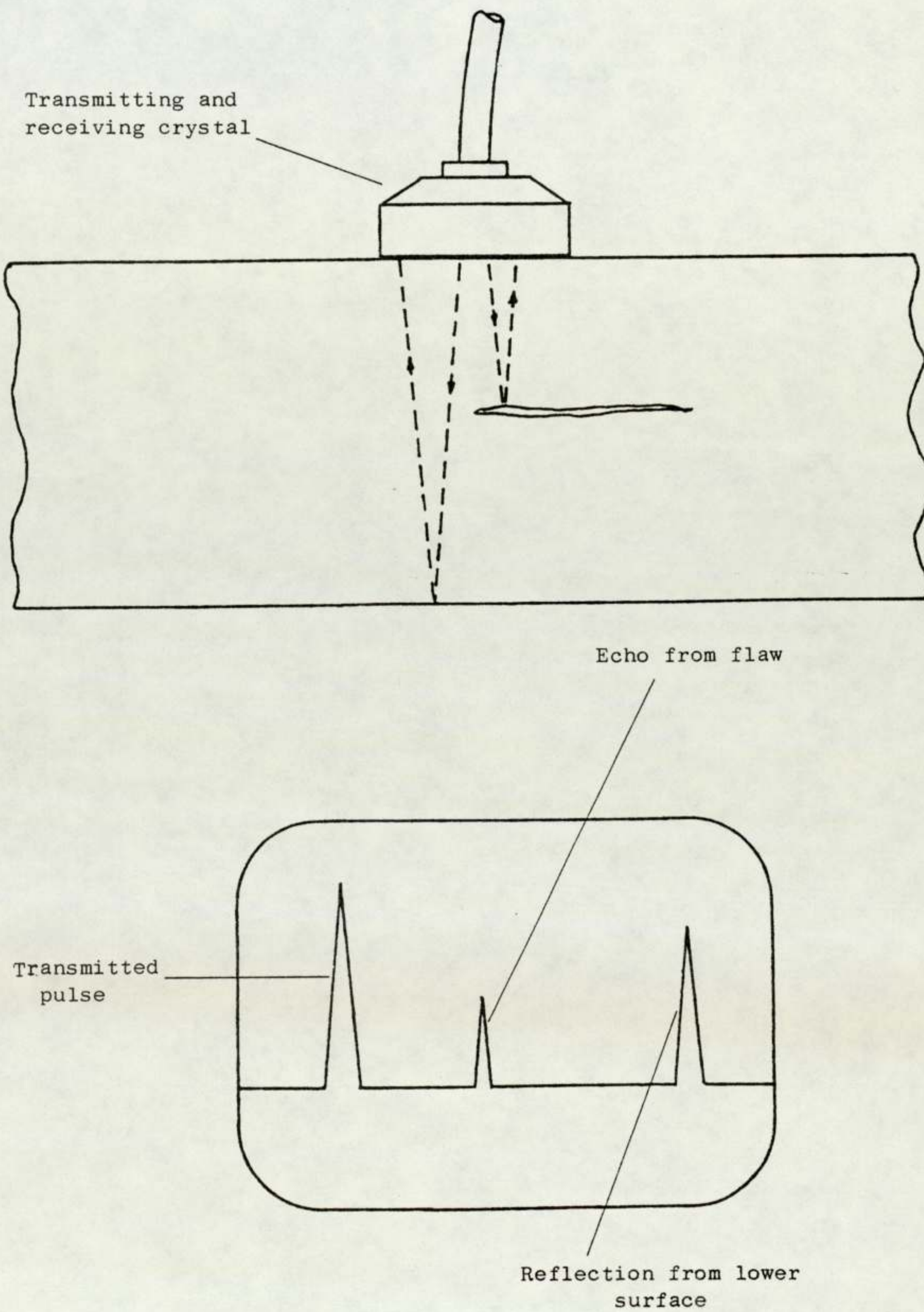
Sound waves having frequencies above the upper limit of the audible range (20kHz) are known as ultrasonic waves.

The ultrasonic frequencies used in NDT are usually in the range 0.5 MHz to 20MHz. These waves are produced by piezo-electric crystals such as quartz, which generate an alternating strain when an alternating voltage is applied. The waves used may be longitudinal (compression), transverse (sheer), surface (Rayleigh) or cause the whole of a thin component to vibrate, i.e. plate (Lamb) or bar waves.

Ultrasound can be used to detect discontinuities in any homogenous material through which the waves will propagate ; it also has several other applications, such as thickness measurement.

There are two basic methods for detecting discontinuities within material : transmission and reflection. In transmission, the detector and transmitter are on opposite sides of the material. If the material contains a flaw, then the received wave is attenuated more than for a homogeneous sample. In the reflection method, the transmitter and receiver are on the same side of the material and any flaw is detected by the energy it reflects back to the receiver (Figure 3.4).

Figure 3.4. Ultrasonic Flaw Detection by the Pulse Echo Method



Ultrasonic methods are ideally suited to detecting such flaws as laminations in rolled plate, but are not so appropriate for surface porosity. A complication with ultrasound is the need for a couplant between the probe and test piece. This must be a material through which the ultrasound propagates, such as a grease, oil, or sometimes, water. As an air gap is unsatisfactory, this can make automation difficult.

3. b) vii) Radiography

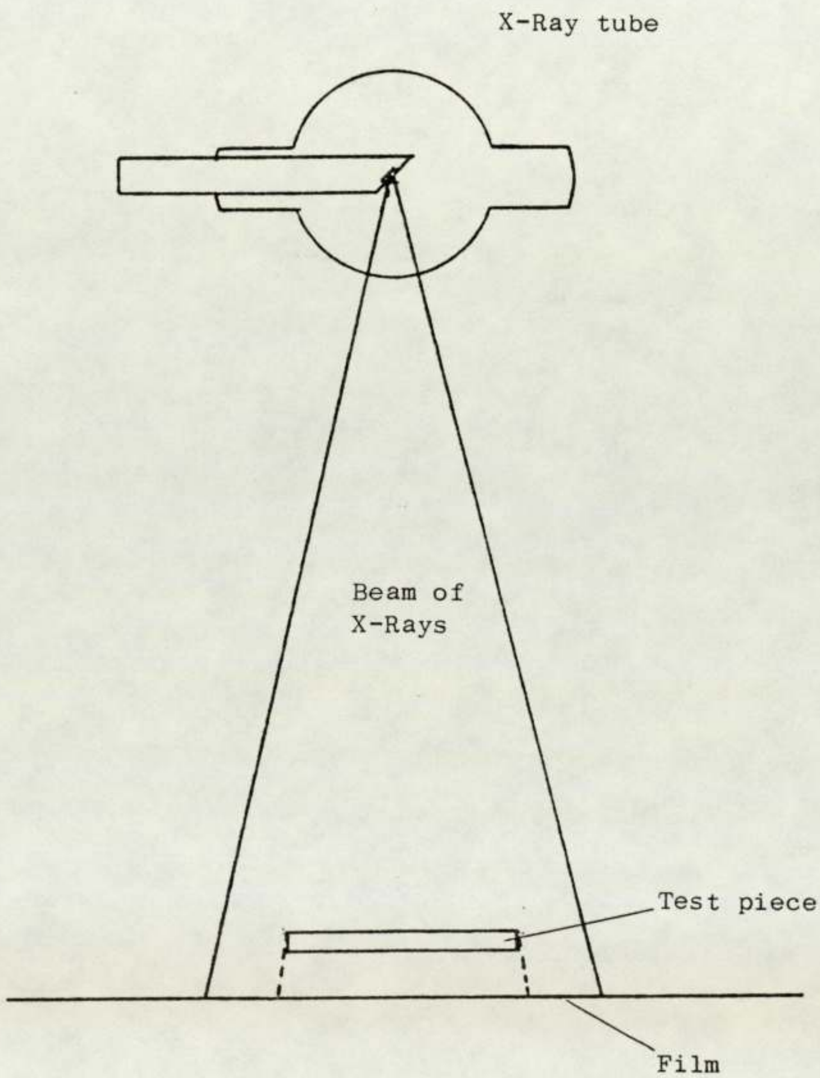
A wide range of X- and Gamma ray techniques is used in NDT. One of the most common is radiography (16) in which a test sample is arranged between an X-ray source and a photographic film (Figure 3.5). The X-rays penetrate the sample and expose the film which is then developed. The exposed film is darkest where X-rays have penetrated the target most easily and light where they have been blocked. If the test object were a flat plate with no discontinuities, then the film would be uniformly exposed. A cavity within the plate would produce a dark area on the film from which an experienced radiographer could interpret the nature and plan dimensions of the defect.

3. b) viii) Opto-electronic techniques

An opto-electronic device is one which converts incident light into electricity or vice-versa. This definition is usually relaxed such that the term light includes not only visible radiation but also near infra-red, and sometimes ultra violet radiations. This thesis is concerned mainly with detectors, and the term opto-electronic is used to refer to these.

Opto-electronics can be applied either to aid visual inspection

Figure 3.5. Simplified Arrangement for producing a Radiograph



or to replace it, but is inevitably restricted to surface defects. The electrical signal produced by an opto-electronic device may be reconstituted as a visual display, as in a closed circuit television (CCTV) system, or it may be processed and fed to some decision-making device which is often a computer. To deal briefly with the former case, it has been found that some inspection tasks are better performed if the inspector views the sample(s) on a CCTV screen rather than directly or with conventional optical magnification (17). There may be many reasons for this, for example that the inspector operates in a more ergonomically acceptable environment. An extreme case of this is the sorting of good potatoes from bad ones and other debris, from a CCTV screen.

Where opto-electronic signals can be processed electronically, and a device can be used to make a quality decision, then the human viewer can be eliminated and full automation is possible.

There are four types of opto-electronic device currently available which can be made sensitive enough to detect the 100 microns diameter minimum defect, given sufficient contrast. These devices are television cameras, flying spot, flying field and solid state scanners, which are discussed in Chapter 4.

3. c) Applicability of Various NDT Techniques to Automatic Detection of Surface Pinhole Porosity.

It is first necessary to consider the criteria which must be met in order to satisfy the project requirements ; these are twofold. Firstly, the NDT technique selected must be able to detect the type of defect involved in this project. Secondly, the method must be capable of automation (see Table 3.1). Only opto-electronics can meet both these requirements, although an eddy current system which was tested came close to detecting the small pinholes, and could certainly be automated.

Viewers using optical aids would out-perform the quality criteria with no associated advantage. Similarly, penetrant and magnetic particle methods would assist viewers to detect cracks and small defects but would not lend themselves to automation unless coupled with an opto-electronic system. Although there might be ways of increasing the sensitivity of an opto-electronic system to particular types of defect, it is first necessary to develop that system.

Flux leakage techniques are not appropriate for detecting surface porosity as the magnetic flux tends to pass round the defect rather than produce a significant leakage field. This is evident when magnetic particle tests are performed, which easily detect the leakage fields from invisible cracks but fail to reveal 100 micron and larger porosity.

Radiography is inappropriate here because it would involve the use of large quantities of film and it does not lend itself to automation, nor can it detect defects of this size on VSI's.

Ultrasonic devices are not suitable for detecting this type of defect on the surface of a component without extensive development, particularly since the minimum size of defect currently detectable is approximately 1mm.

TABLE 3.1. : Applicability of Various NDT Techniques

NDT Technique	Is the technique suitable for automation	Where can flaws be detected	Detect 100 micron minimum defect	Most appropriate application
Optical inspection aids	No (1)	Surface only	Yes	Minute or inaccessible flaws where only a small area requires inspection
Penetrants	No (1)	Surface only	Yes	Cracks
Magnetic particle	No (1)	Surface and subsurface	Not consistently	Cracks in ferromagnetic materials
Flux leakage	Yes	Surface and subsurface	Not consistently	As magnetic particle(3)
Eddy current	Yes	Surface and subsurface (2)	Not quite	Cracks in electrically conductive materials
Ultrasonic	Possibly	Internal and surface	No	Laminations
Radiography	No	Internal and surface	No	Voids with a large dimension perpendicular to the surface
Opto-electronics	Yes	Surface only	Yes	Flaws which can be illuminated to give reasonable contrast

1. Could possible be automated with an opto-electronic system
2. Penetration and sensitivity depend on frequency and coil arrangement
3. One magnetic tape method can operate on scaled surfaces.

Eddy current techniques have been developed primarily for crack detection, but the technology has reached such a high level that it was felt that a sensitive system might be capable of detecting the required size of pinhole porosity. Eddy current equipment manufacturers supported this view and some tests were performed. A set of test pieces was made up by spark eroding holes in sound valve seat inserts and a full report of these tests is given in Appendix B. The main conclusion in terms of sensitivity was that a hole must be larger than 380 micron diameter (280 micron deep) in order to be reliably detected anywhere on a surface. It was felt that this was not sensitive enough as it fell short of the 100 micron defect criterion. Manufacturers and users of opto-electronic systems claim resolution surpassing the 100 micron criterion (see Chapters 4 and 5), and these systems, like eddy current, can be readily automated.

An additional reason why an opto-electronic approach emerges as the most suitable system for detecting surface pinhole porosity is the origin of the rejection criteria for this type of defect. These defects are important only because it is necessary to satisy customers' stringent visual inspection standards, as explained in Chapter 2. These visual standards are based on the performance of the unaided human eye, so it is likely that a system which is closely analogous to the eye will meet the same criteria. The eye is receiving information in the form of reflected and scattered light from the surface of the component, the brain is processing this information and making a quality decision. An opto-electronic system performs the same operations and so can most readily meet the same criteria.

In summary, the project requires a system capable of detecting the 100 micron "minimum defect" and of being automated. Only an opto-electronic system can meet both requirements, although a sensitive eddy current system very nearly reaches this minimum defect requirement and certainly can be automated.

CHAPTER 4

Opto-Electronic Scanners

for Flaw Detection

4. a) Introduction

The project brief has been refined to the solution of the problem of automatically detecting minute black holes on the bright metal surfaces of components. Chapter 3 points to an opto-electronic solution of the sensor part of this problem. This simply means measuring reflected or scattered light from the bright surface, and producing an electrical output which can indicate the presence of a defect.

4. b) The Requirement to Scan

If any area much larger than the defect to be detected is examined in one step, any slight variation in the dimensions or reflectance of that large area may produce a signal variation greater than that produced by the defect.

In order to detect minute defects, a surface must be divided into smaller elements with areas of the same order of magnitude as the defect. The element area required will also depend on surface texture, reflectance variations and other noise (see Chapters 5 and 6).

To examine the whole surface these elements must be interrogated sequentially, i.e. the surface is scanned in some way. This may be done electronically or mechanically and there are four types of device capable of doing this. These are : 1. Television cameras ; 2. Flying field scanners ; 3. Flying spot scanners, and 4. Solid state arrays.

4. c) i) <u>Television cameras</u>

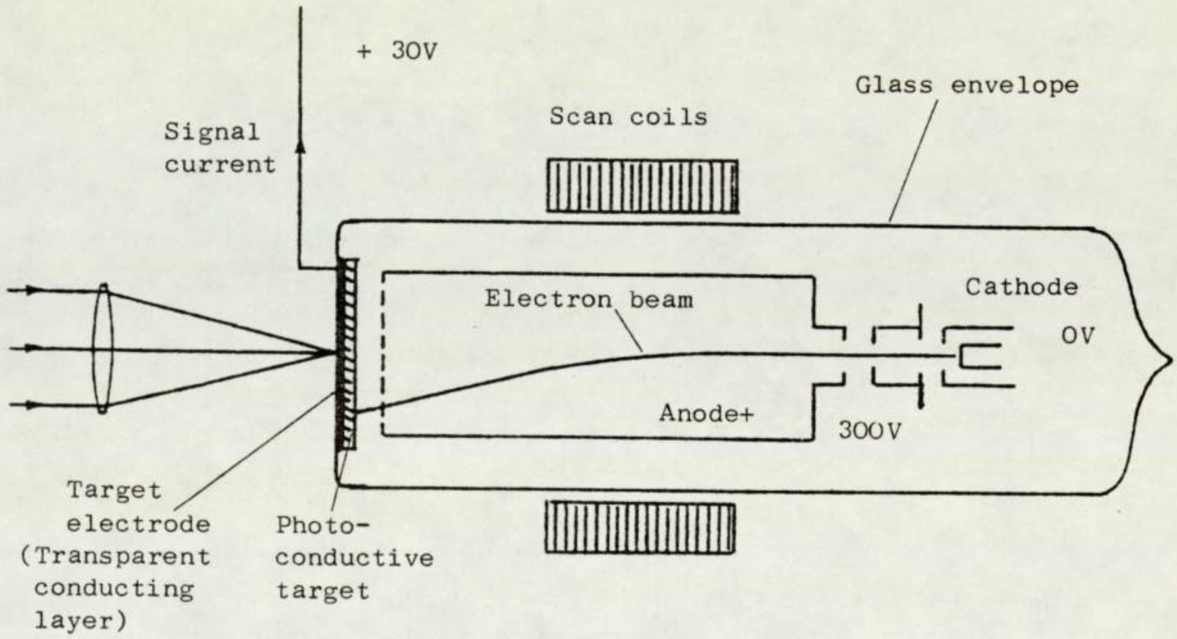
The basis of modern television cameras is the vidicon tube (18).

Many variations exist (19), but the basic device operates as follows :

An image is focussed onto the photoconductive target through the glass envelope and the target electrode, which is at a potential of 30V (Figure 4.1). Where light falls on the target causing it to conduct, a positive charge distribution is built up on the other side, This charge is cancelled by a scanning electron beam, and the current so produced is detected at the target electrode and constitutes the video signal. The scanning electron beam is produced in the same way as in a normal cathode ray tube, and is accelerated towards the target by a 300V anode potential. The electron beam scans the target in a raster, usually under the influence of deflecting coils.

After the beam has sampled a point on the target, light falling on that point causes charge to build up again until the beam returns to re-sample it. Thus, light is integrated for the whole of the time between scans (the frame-scan time) giving high sensitivity.

Figure 4.1. Simplified Representation of a Vidicon Camera Tube



Several target materials are available with different spectral responses (18).

4. c) ii) Flying field scanner

In this type of scanner, an image of the field of view is mechanically scanned across a sensitive detector. This mechanical scan may be performed by : a rotating mirror or mirrors, a vibrating mirror, a rotating prism or a drum of lenses.

Figure 4.2 shows a simple arrangement. As the 45^{o} mirror rotates, successive points on the line (A B) are focussed onto the detector. This scan is of one line, and it is necessary either to move the scanner or the object in a direction perpendicular to A B in order to interrogate a two dimensional area.

4. c) iii) Flying spot scanner

A flying spot scanner causes a very bright spot of light (usually laser) to scan a line across the surface, and the reflected, scattered or transmitted light is detected. Figure 4.3 shows one configuration.

The photomultiplier detector is constantly exposed to the whole area of the surface to be scanned, but receives a signal only from the point which is illuminated by the flying spot. A sensitive photomultiplier tube is usually used because of the low light level received.

The light detected may be a specular reflection (as shown in Figure 4.3), scattered or transmitted light. Detectors may be employed for any combination of these.

Figure 4.2. Flying Field Scanner

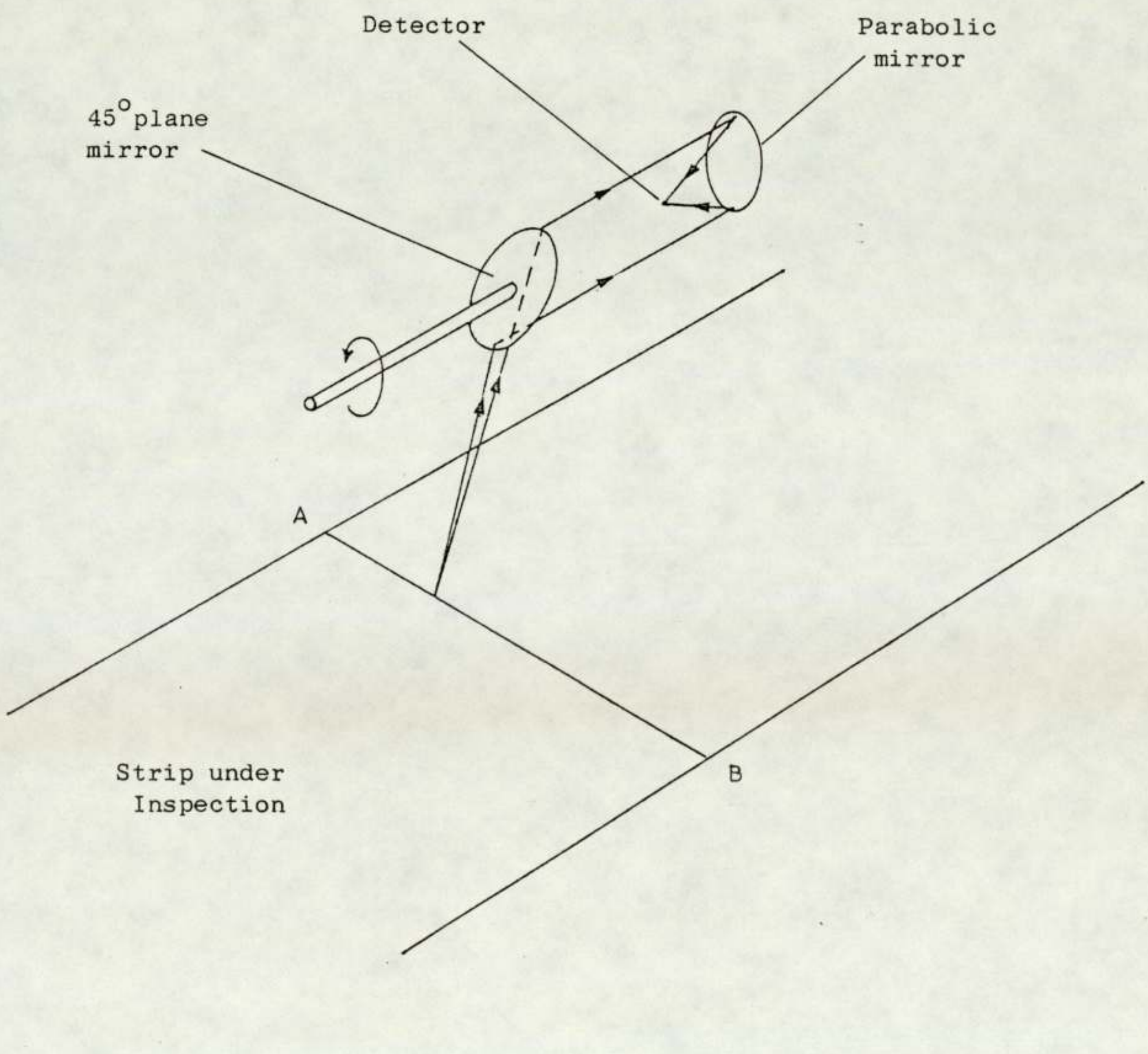
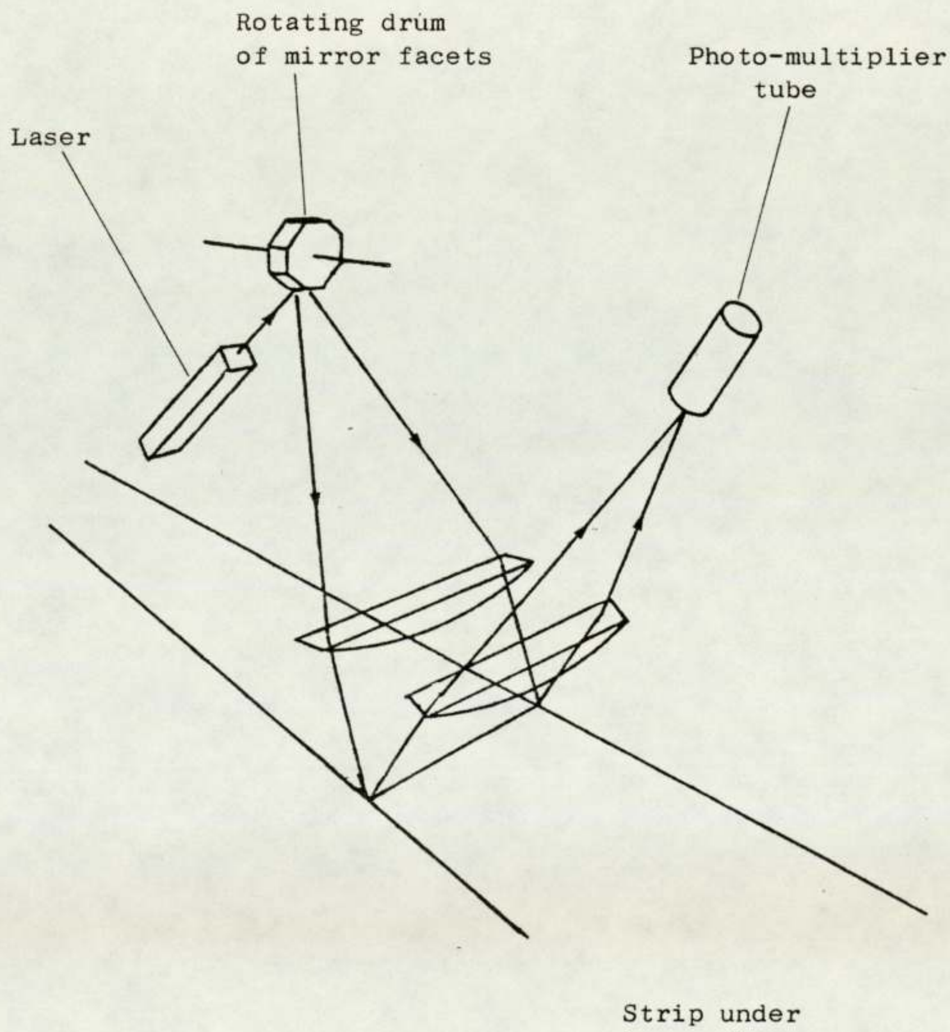


Figure 4.3. Flying Spot Scanner : as developed by the Sira Institute



4. c) iv) Solid state arrays

Cameras using solid state arrays focus the required image directly onto the array of photosensors. The array is normally linear or matrix and is on the same piece of silicon as some of the processing electronics. The output from the array is an electrical analogue of the spatial distribution of light exposure on the array. There are normally too many elements in an array for each to have its own output pin, and so the signals are output serially onto a common video line.

Linear arrays are simply scanned from end to end repeatedly, whilst matrix arrays are scanned in raster fashion, though there are some variations from these patterns.

After each element is read it integrates the light falling on it until it is read again on the next scan, and so on indefinitely.

4. d) Scanner Application Areas

Each of these scanners has its own merits which have been most highly developed in its own fields of application. As such, it is difficult to compare their performance.

In order to put into perspective those performance characteristics which can be compared, it is useful to know the fields in which the different scanner types find most widespread or highly developed use. These areas of application are summarised in Table 4.1.

TABLE 4.1. : SCANNER APPLICATIONS

TELEVISION CAMERAS

1. Television broadcasting
2. Closed circuit television (CCTV)
    a) Industrial inspection and recording
    b) Medical
    c) Security surveillance
    d) Home video.
3. Automatic inspection (computer linked)
4. Remote sensing of the earth's surface.

FLYING FIELD SCANNERS

1. Thermographing
    a) Remote sensing of the earth's surface
    b) Buildings and other installations - energy saving
    c) Machine-fault detection
    d) Medical
2. Optical
    a) Automatic inspection of moving strip in industry
    b) Remote sensing of the earth's surface

FLYING SPOT SCANNERS

1. Automatic inspection of moving strip in industry
2. Cylinder bore inspection
3. Telecine

TABLE 4.1. : SCANNER APPLICATIONS

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    c) Machine-fault detection
    d) Medical
2. Optical
    a) Automatic inspection of moving strip in industry
    b) Remote sensing of the earth's surface

FLYING SPOT SCANNERS

1. Automatic inspection of moving strip in industry
2. Cylinder bore inspection
3. Telecine

TABLE 4.1. CONTINUED

SOLID STATE ARRAYS

1. Automated inspection

    a) Dimension gauging

    b) Volume measurement

2. Optical character recognition - bank cheques

3. Closed circuit television - security surveillance

4. Telecine

4. d) i) Television camera applications

In broadcasting, demand for better quality or smaller television cameras continually stimulates design (20, 21, 22, 23).

In the field of remote sensing of the earth's surface, design criteria differ from those in broadcasting, but improvements in equipment are often complementary.

Closed circuit television (CCTV) systems are used in security systems, medicine and industrial inspection. Usually these are not required to have the same very high standard of picture quality as broadcasting systems. Television cameras can be linked to computers to produce fully automatic part inspection positioning and orientation systems (24, 25), but high resolution is not always advantageous as too much data can be produced for useful digital processing.

4. d) ii) Flying field scanner applications

The greatest merit of the flying field scanner is that the sensor can be chosen with a particular spectral response. The responses of different sensors extend from the visible well into the infra-red (18). This infra-red response is extremely valuable in the remote sensing of the earth, where intricate multi-wavelength pictures can be composed using a number of scanners or more than one detector in one scanner.

There is also the capability with flying field scanners of calibrating the video signal against a standard source (or sources) at the end of each scan.

Infra-red scanners are now available in compact camera form for thermographing buildings and industrial installations to trace heat losses and also for examining machines which may show faults by uneven or excessive heat emission (26).

Analogous principles can be utilised in medical diagnoses by monitoring the emission of body heat. Some sensitive detectors require to be cooled (usually with liquid nitrogen) to reduce thermally produced noise ; this is an unwelcome practical complication in some applications.

Flying field scanners have been used successfully for flaw detection. For example, in tinplate manufacture where black defects of 1mm can be detected on a 1m wide strip at speeds up to 2.5 ms^{-1} (17).

4. d) iii) Flying spot scanner applications

Flying spot scanners have been developed which operate either at higher resolution or speed than flying field scanners. These are successfully used in the steel industry for detecting flaws in moving strip (17). A specialised flying spot laser scanner has been developed for examining cylinder bores for defects and quality of surface texture in the motor industry. A further application of this type of scanner in flaw detection has been in the detection of flaws in transparent plastic and glass (27).

In the field of broadcasting, the conversion of cine film to television signals is performed by a device known as "telecine" which employs flying spot scanners.

4. d) iv) Solid state array applications

One of the main areas of development in the field of solid state arrays is in the number of elements. A matrix CCD array is now available with 385 x 576 picture elements for use in 625-line television (28). Although this device is compatible with current television systems, and has a number of points to recommend it, such as its size and robustness, picture quality does not compare with current studio cameras. While developments continue, initial applications are likely to be in home video, electronic news gathering (ENG) and CCTV.

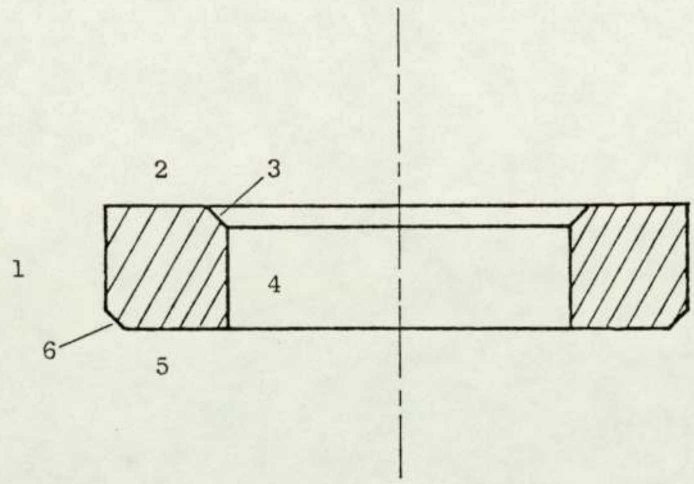
Solid state arrays currently find their major applications in industry where a relatively cheap, robust sensor is needed. These applications include dimension gauging, flaw detection and volume measurement of moving materials (29, 30). Linear arrays are also used in optical character recognition (OCR), e.g. in reading the numerical data on cheques and also in facsimile scanning. Recently, long linear arrays have been incorporated in telecine devices in place of flying spot scanners.

4. e) Advantages and Disadvantages of Scanner Types in Valve Seat Insert Inspection

The following section examines the relavent merits of the different systems with respect to the problem of flaw detection in valve seat inserts (VSI's). Much of this will be relevant to any similar problem of component inspection.

Figure 4.4 shows a diametral section through a simple VSI. All the

Figure 4.4. A Diametral Section of a VSI



Facets

1. Outside diameter
2. Top face
3. Seat
4. Bore
5. Bottom face
6. Chamfer or other feature

facets must be examined for defects, and because of its ring shape, the component must be rotated in order to check the whole circumference. Line scanning a surface perpendicularly to its direction of motion gives area coverage ; thus there is no need to use an area scan device. In fact, the long framescan time which would be involved is disadvantageous since the image must be kept stationary (or very nearly so) for its duration in order to avoid distortion. To overcome this problem it would be necessary to index the component round or strobe the light in synchronisation with the framescan.

In contrast to vidicon tubes, solid state arrays are robust and have long lifetimes. (Solid state arrays - 10^4 to 10^5 hours ; vidicon tubes - a few thoudand hours). Solid state arrays do not use high voltages as do vidicon tubes, but are currently much more expensive.

Cost and mechanical size must be seen in the context of a system which will require more than one scanner (possibly as many as six) in order to check all the facets shown on a diametral cross-section (Figure 4.4). Another important constraint is the inspection rate which must be of the order of one second per component in order to maintain throughput.

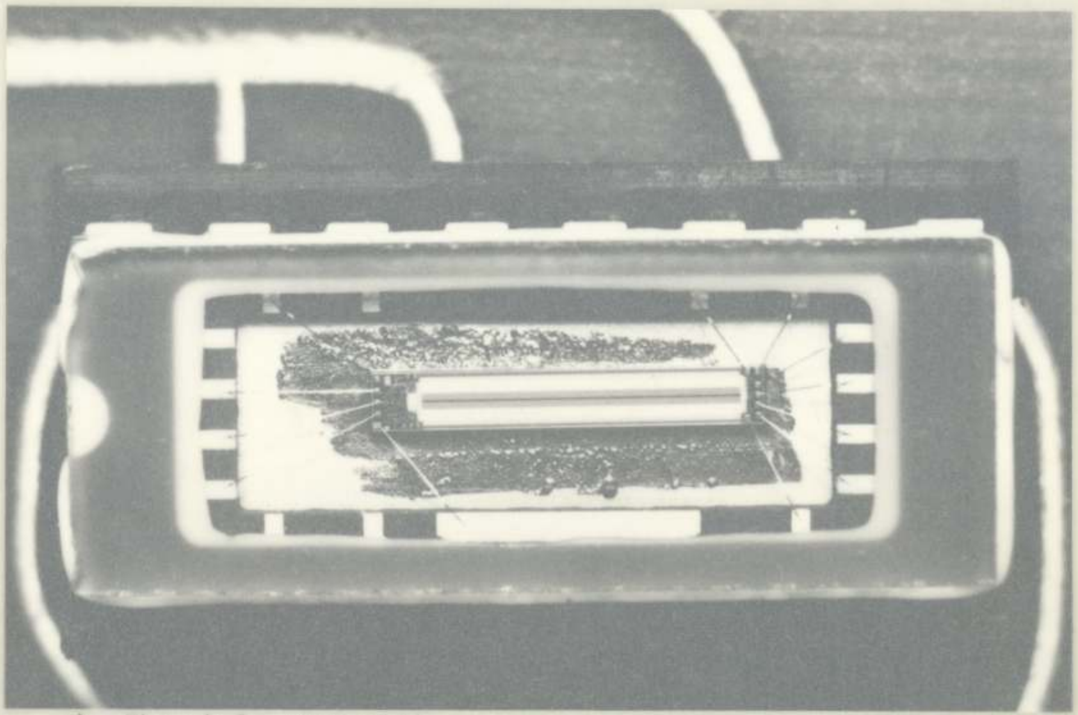
Mechanical line scanners with the appropriate speed and resolution are large, complex and costly compared to solid state line scan devices. The latter are also more easily interfaced to digital electronics than the other types of scanner (31).

There are various types of solid state array, the major ones being : photodiode ; charge injection devices (CID) and charge coupled devices (CCD). For any practical application, device selection must be on the basis of cost and ease of use for adequate performance (29).

Of the solid state line scan devices available, a general purpose photodiode array currently offers adequate resolution and speed at the lowest cost.

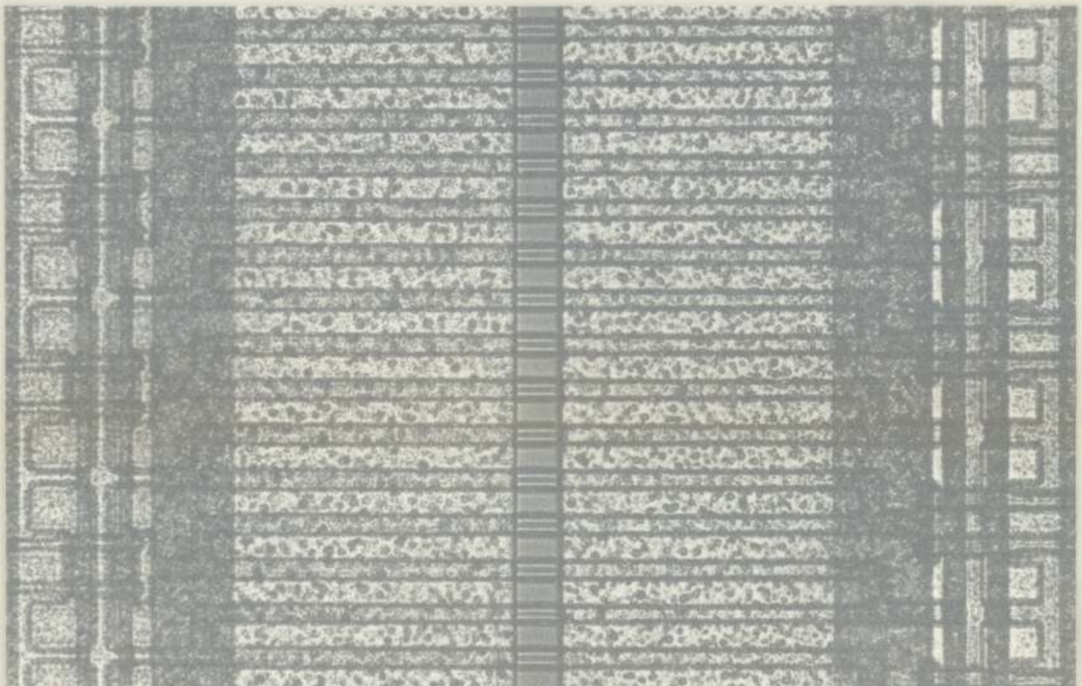
The device selected for a feasibility study and subsequent use in a prototype system was a Reticon RL256G photodiode array having 256 elements on 25 micron centres (Plate 4.1).

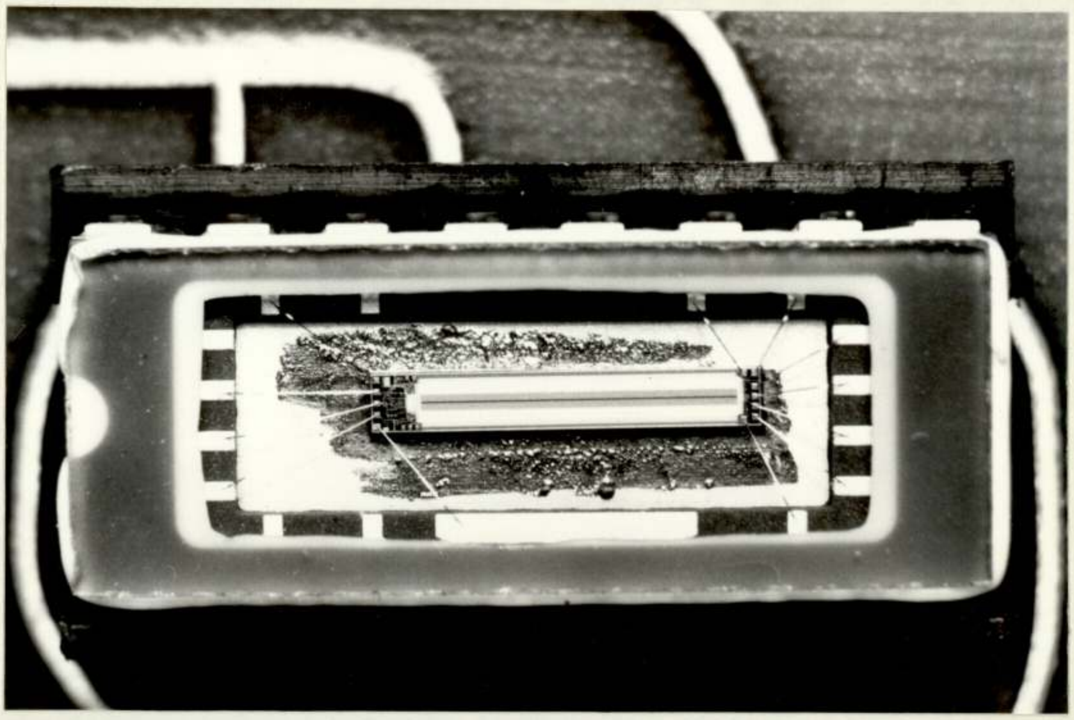
PLATE 4.1. A Linear Self Scanned Photodiode Array

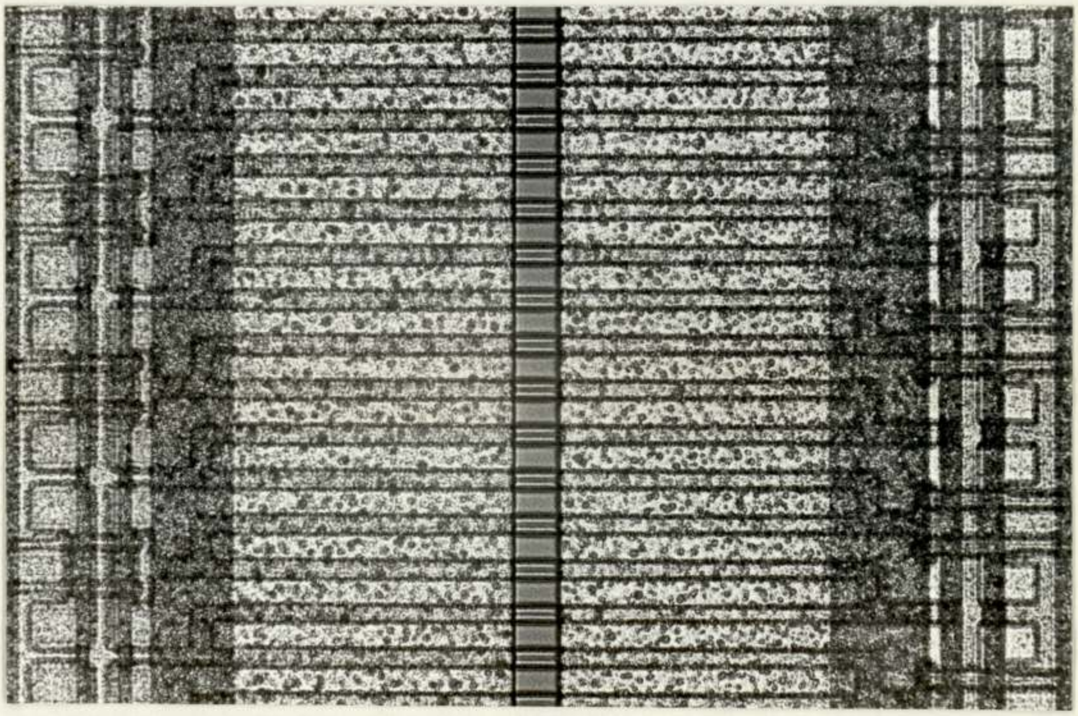


a) The whole component

b) The Photodiodes







CHAPTER 5

Linear Solid State Optical Arrays

5. a) Light Measurement

There are two systems commonly used for the measurement of light : the Photometric and Radiometric systems. The names and units of equivalent quantities differ as do their fields of application. Photometry is used in the field of Illumination Engineering where the defining factor is the effect on the human eye of light, which is measured in lumens. Conversely, Radiometry is employed in the field of optical Radiation Physics where light is measured in watts, and its effect on the human eye is not fundamental. Table 5.1 shows the major radiometric and photometric quantities and their definitions. Radiometric quantities are used in this thesis. The transformation of radiometric quantities into photometric involves the integration over all visible wavelengths of the product of the radiometric quantity and the spectral efficiency of the human eye, taking into account spectral distribution

Table 5.1. Radiometric and Photometric Quantities (32, 33)

Radiometric quantity	Unit	Definition
Radiant flux " power	W	Power
Radiant energy	J Ws	Energy. Radiant flux x time
Radiant intensity	WSr^{-1}	Radiant flux per unit solid angle
Radiance	$Wm^{-2}\ Sr^{-1}$	Radiant flux per unit solid angle per unit area
Irradiance	Wm^{-2}	Radiant flux per unit area of receptor
Radiant entrance	Wm^{-2}	Radiant flux per unit area of emitter
Irradiation (exposure)	Wsm^{-2} Jm^{-2}	Radiant flux per unit area of receptor x time

Table 5.1. continued

Photometric quantity	Unit	Definition
Luminous flux	lm Lumen	Power
Luminous energy	lm.s	Energy, luminous flux x time
Luminous intensity	$lm.Sr^{-1}$ Cd Candela	Luminous flux per unit solid angle
Luminance (photo-metric brightness)	$lmm^{-2}Sr^{-1}$ $Cd\ m^{-2}$ Nit	Luminous flux per unit solid angle per unit area
Illuminance (Illumination)	$lm\ m^{-2}$ lx Lux	Luminous flux per unit area of receptor
Luminous exitance " emittance	$lm\ m^{-2}$ lx	Luminous flux per unit area of emitter
"Exposure" (Illuminance x time)	$lmsm^{-2}$ lx s	Luminous flux per unit area of receptor x time

Note on Table 5.1.

A lumen is defined as the flux emitted within unit solid angle of one Steradian by a point source having a uniform intensity of one candela.

In the field of photography, the common logarithm of "Illuminance x time" is called exposure.

5. b) The Photoelectric Effect

The photoelectric effect is the excitation of electrons by photons into a state where they can contribute to conduction from a state where they could not. This can occur under such varying conditions that the effects may seem altogether different. A photomultiplier tube and a solid state photodiode both depend on this fundamental process.

5. b) i) Photomultiplier Tube

In a photomultiplier tube, sufficiently energetic incident photons cause electrons to be ejected from the photocathode. These electrons are accelerated towards another electrode, called a dynode, at a positive potential relative to the photocathode where secondary emission of elctrons occurs. These electrons are accelerated towards a further dynode, and so on, giving an avalanche effect. As many as fourteen dynodes may be used before the electron current is collected at the anode, and detected.

The energy E of a photon of frequency f is given by E = hf where h is Planck's constant. For any surface there is a minimum energy Eo which must be supplied by the photon in order to eject an electron. If hf > Eo photoelectrons can be produced, and any excess photon energy is given to the photoelectron as kinetic energy K.

$$K_{max} = hf - E_o$$

where Kmax is the maximum possible kinetic energy of a photoelectron ; the majority will have less kinetic energy because of collisions within the material before ejection (34).

5. b) ii) Solid state photodiodes

Electrons in a semi-conductor such as silicon occupy energy states which are divided into two bands, the conduction band and the valence band, with no allowed energy states in between. Only the conduction band electrons are mobile and can contribute to conduction. At room temperatures electrons are thermally excited into the conduction band leaving gaps in the valence band called "holes" which are positively charged and can also contribute to conduction. Excitation of electrons from the valence band into the conduction band is known as electron-hole pair production and can be brought about by the absorption of a photon. There is an energy gap between the valence and conduction bands ($Eg \approx 1.1eV$ for silicon) and a photon must have energy greater than, or equal to this energy gap in order to excite an electron across it (35).

Electron-hole pairs which are produced in a reverse biased P-N junction separate and are accelerated across the junction to constitute a current. Mobile charge carriers, electrons or holes generated near the diode junction must diffuse to it in order to be accelerated across and contribute to this current.

In a photodiode, thermal and photon excitations produce this current, the constituents being called, respectively, dark (leakage) current and photocurrent (or light current). Radiant flux can be measured by using the photocurrent which is proportional to the number of photons with sufficient energy ($hf \geq Eg$) incident in unit time.

5. c) Linear Solid State Arrays

There are two main types of photosensor available in linear arrays : photodiode arrays, and the more recently developed charge coupled devices, CCD. A hybrid of the two also exists which, it is claimed, incorporates the best features of both, known as the Charge Coupled Photodiode Array (CCPD).

5. c) i) <u>Linear self-scanned photodiode arrays</u>

The photodiode array consists of a narrow, photosensitive strip along which are rectangular photodiodes (Figure 5.1). Each photodiode is connected through a metal oxide semi-conductor (MOS) switch to a common video output line. These switches are operated by an internal shift register, thus causing the information from each diode to pass to the common line serially. At each scan of the array, the radiant energy incident on each diode since the previous scan is measured. This is achieved by topping up the charge on the capacitence associated with each photodiode, and measuring the top-up required (Fig. 5.2). Between one top-up and the next, the charge is removed by a photo-current at a rate proportional to the radiant flux on the photodiode. Thus, the output shows the integrated light (with respect to time) or radiant energy on each diode between scans.

5. c) ii) Linear self scanned charge coupled optical arrays

Figure 5.3. shows a simplified longitudinal section of a CCD array. Photoelectrons which are produced in the substrate by incident radiation, gather under the electrodes. After light has been integrated for the desired time and packets of electrons have gathered, these packets are moved to a second, shielded array of electrodes parallel to the first. The first array of electrodes continues to collect photoelectrons which are later removed by the same process (the packets of electrons correspond in magnitude to the integrated light). The charge packets under the second array of electrodes are then moved along this array, at the end of which a high capacitance device detects the magnitude of each and converts it to a video signal. The limits of a charge collection site may be defined by the electrode, or by diffused channel stops.

Figure 5.1. Part of the Array ; the photodiodes are shaded.

Numerical dimensions are those of a Reticon RL256G Array

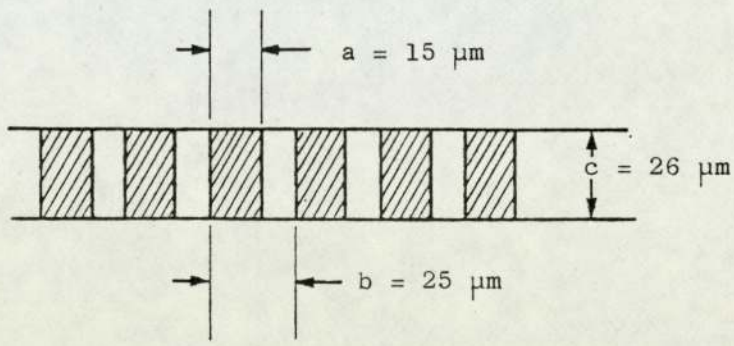


Figure 5.2. Simplified Circuit showing Part of the Array

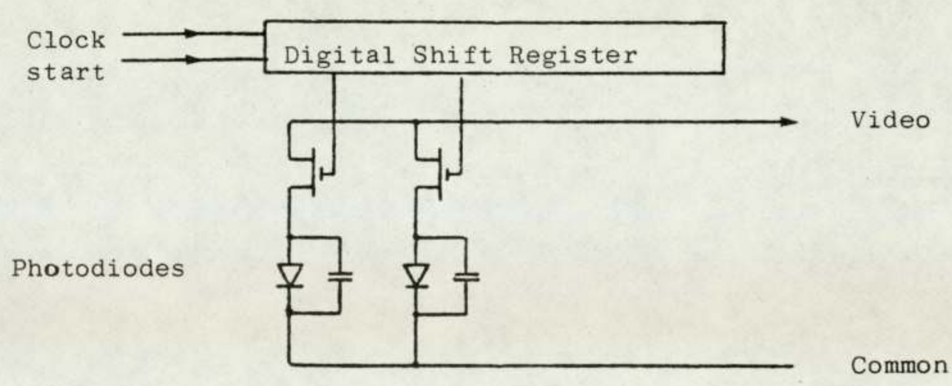
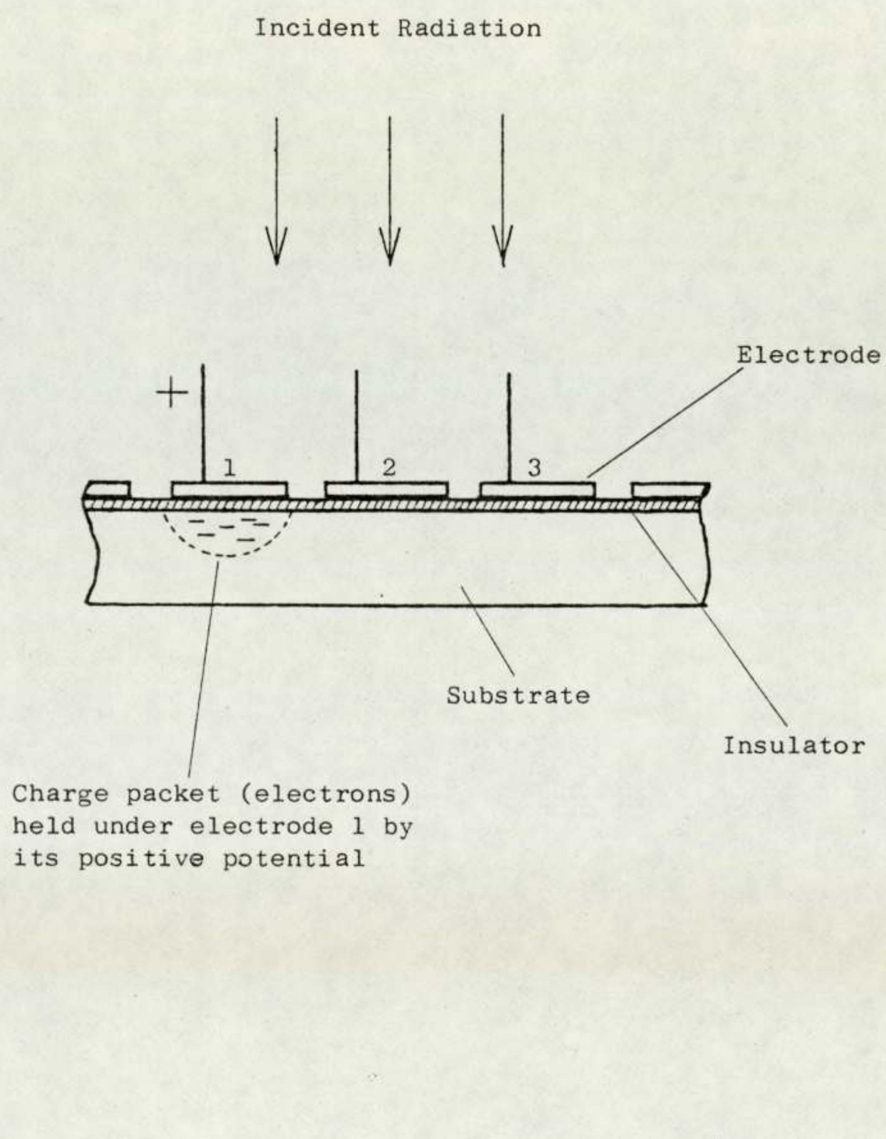


Figure 5.3. Simplified Longitudinal Section of a Linear CCD Optical Array



5. c) iii) Mechanism of shifting charge packets

In Figure 5.3 a packet of electrons held under electrode 1 by a positive potential can be moved to electrode 2 by reducing that potential and increasing the potential on 2. The packet can then be moved to electrode 3 by the same process. For the flat electrode shown, a three-phase clock is used, but electrodes designed to attract electrons to one site can be used with a two-phase clock (36).

5. d) i) Spectral response

The spectral response of a silicon diode is shown in Figure 5.4. The long wavelength cut-off occurs because protons do not have sufficient energy to excite electrons across the band-gap into vacant states. A proton of wavelength 1 micron has energy 1.24eV and the energy gap for silicon is 1.1eV. The short wavelength cut-off occurs because the protons are so energetic that they excite electrons into conduction states very close to the surface. Since the crystal lattice is disrupted at the surface, the distance the charge carriers diffuse before recombination is very short, and very few reach the diode junctions.

Light sources are often defined by their colour temperature (e.g. 2870K). This is the temperature of a black body radiator of the same chromacity as the source.

5. d) ii) Sensitivity

Any silicon photosensor has a particular sensitivity which can be expressed as the quantity of charge produced per irradiation. The sensitivity of the elements in the RL-256G array is shown in Figure 5.5. This is the responsivity of one element to a particular light source.(test source Figure 5.4).

Figure 5.4. Relative Spectral Response of a Silicon Photodiode (solid line). Dashed curve shows the spectral distribution of the light source used to determine the responsivity shown in Figure 5.5.

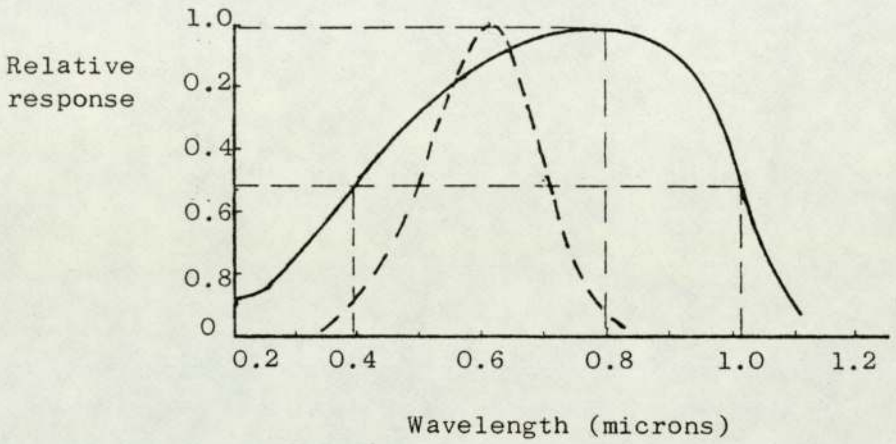
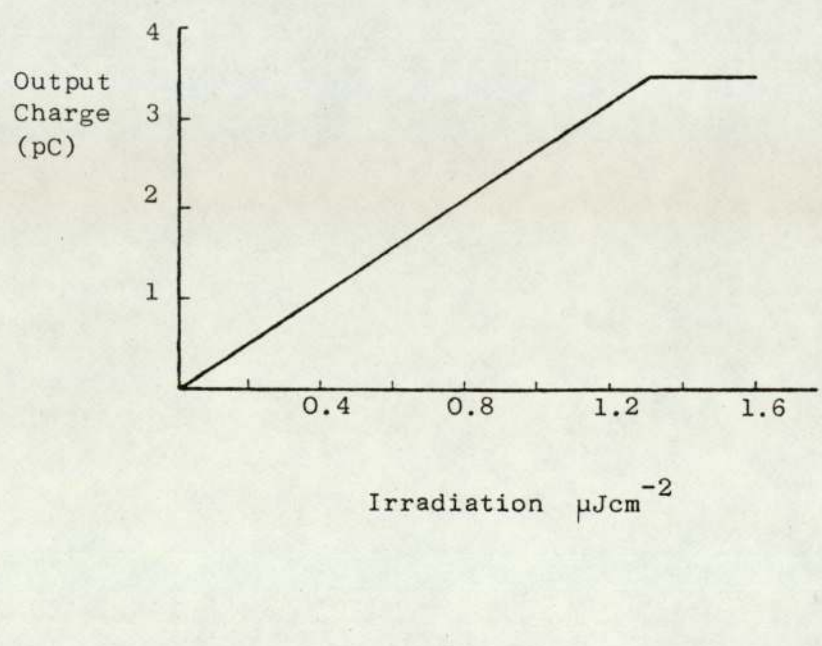


Figure 5.5. Responsivity of One Photodiode in the Array



Responsivity depends on the spectral distribution of the source ; narrow band radiation with mid-wavelength of 0.8 micron will yield a responsivity approximately double that of radiatons with mid-wavelengths of 0.4 microns or 1.0 microns (Figure 5.4).

Implicit in the responsivity as quoted in manufacturers' data is the area of the photosensor, and responsivity increases in direct proportion to this area. The responsivity of most solid state photosensors depends on the responsivity of silicon. For a 2870K tungsten source, this is typically $100\ \mu A\ \mu W^{-1}$ or $100\ \mu C\ \mu J^{-1}$ which is independent of area (37).

Responsivity can be related to the Quantum efficiency of the detector which simply defines the ratio of charges produced and the number of incident photons

$$\eta = \frac{\text{number of electrons produced}}{\text{number of incident photons}} \text{ (in the junction)}$$

5. d) iii) Further important array parameters

N.B. When specific numerical values are quoted, they refer to the Reticon RL256G self-scanned photodiode array or similar devices.

Irradiance is the product of incident light flux and the time for which this is integrated. Varying these two parameters yields two distinct ways of changing the charge output of a sensor. The first is to increase the light intensity and the second is to increase the integration time which is controlled by the switching electronics. Integration time is the time between the start of the scan pulses, and its minimum value is the product of the number of diodes N and the time required to sample and recharge each diode ; this is typically one clock period, say T, of an external single-phase clock. The integration time can be increased by adding a blank period between the end of the scan pulse and the next start of scan. A third method of increasing output is to select a light source, the spectral distribution of which matches the spectral response of the photodiode.

The leakage current of photodiodes is known as dark current, and appears as a background signal which increases in proportion to the integration time. The dark current is temperature sensitive and can be reduced by cooling. It is typically 1 per cent of saturation signal at room temperature, with a 30ms integration time.

Switching signals which break through into the video line are largely removed by differencing the video output with that of a dummy array. The dummy array is shielded from light but picks up the same switching transients as the photo array and the differencing of the two signals leaves a residual noise of less than 1 per cent (38).

Amplified noise may contribute another 1 per cent of saturation signal, giving a total noise of the order of 1 per cent for integration times of a few ms. The uniformity of response between individual diodes is typically $\pm$ 4 per cent (maximum 8 per cent) and is dependent on wavelength, being greater at longer wavelengths.

5. d) iv) Crosstalk and interdiode photons

Crosstalk is the response of one photodiode to light falling on an adjacent one. It may be as high as 15 per cent for diodes on 25 micron centres, but is less than 5 per cent for larger diodes (100 micron centres)(5E). Crosstalk is due to charge carriers diffusing to the wrong diode. The deeper in the substrate the charge carrier is produced, the further it has to diffuse, and the more chance there is of it arriving at the wrong diode. Thus, crosstalk increases with increasing wavelength.

Photocharges produced in the region between two diodes, which may constitute 40 per cent of the photosensitive area of the array will tend to arrive at the nearest possible photodiode, but some diffuse the other way, producing a response along the array length as shown in Figure 5.6 (38).

5. e) Scanning Patterns of Solid State Optical Arrays

Solid state optical arrays are used extensively as the light sensors in linescan cameras. The lens of a linescan camera casts a real image of the required object or surface onto the array. This situation can be described in image space where the surface is projected onto the array elements, or in object space where the elements are considered to be projected onto the surface. These two representations are equivalent, and the latter is used in the following discussion. The dimensions of these projected elements on the surface are given by the quotient of the real element dimension and optical magnification.

For a stationary surface (relative to the array) an element receives light only from its projected element area (Figure 5.7). When the surface is moving, light is received from a scanned strip which is generated by the movement of the projected element area across the surface (Figure 5.8a).

Figure 5.6. Idealised Relative Response of Photodiodes along the Array Length. The plateaux correspond to the positions of the Photodiodes

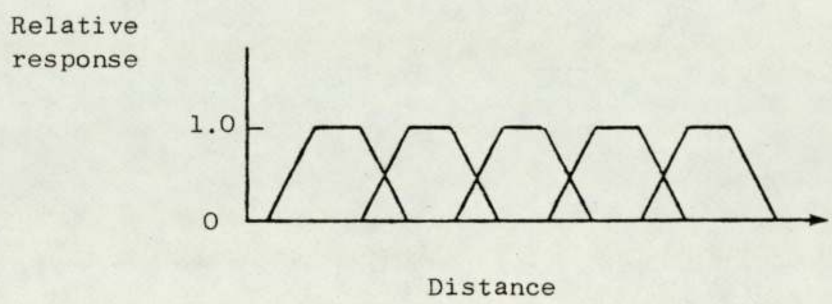


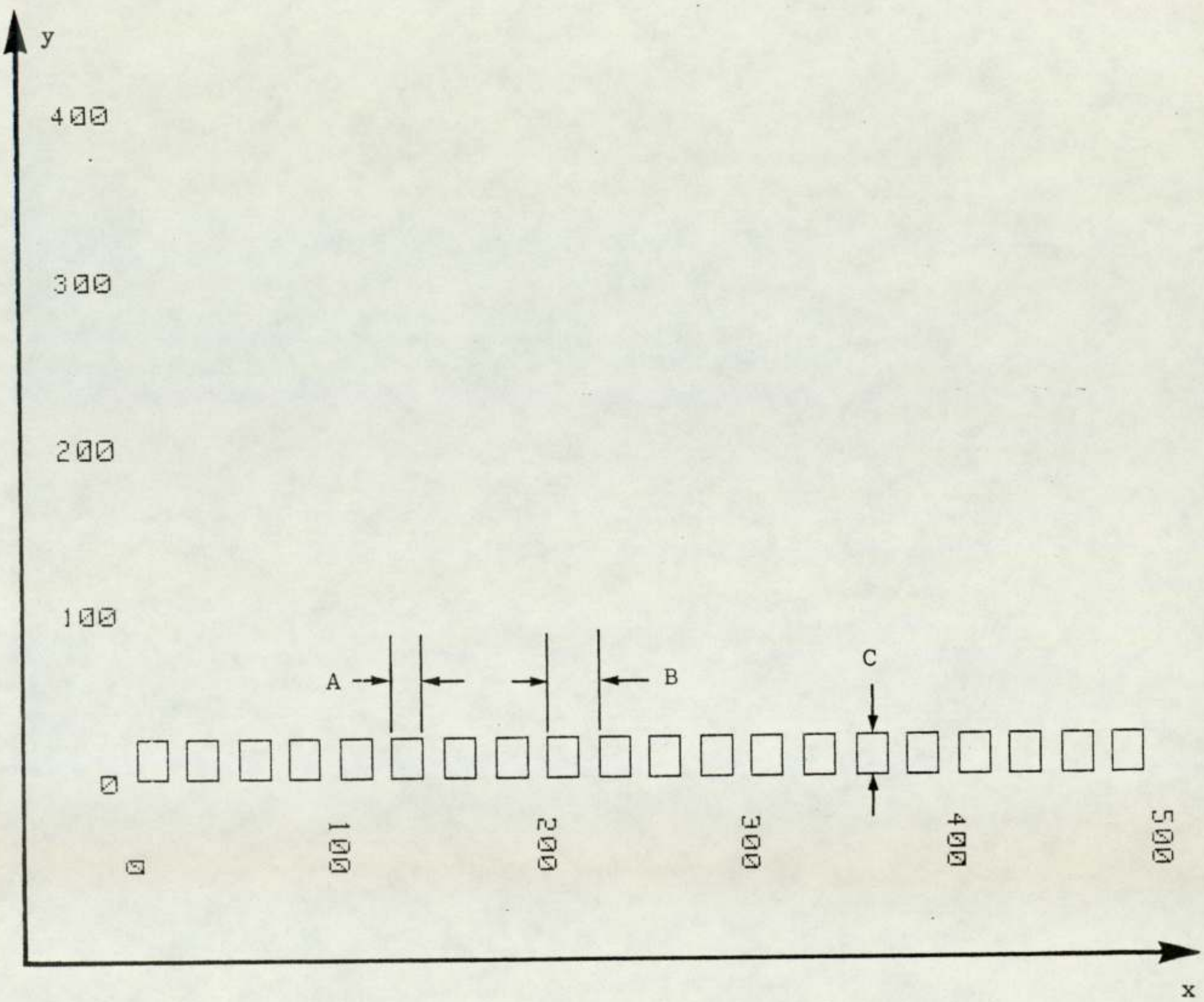
Figure 5.7. A Projection of Array Elements onto a Surface (Static)

A = Projected Diode Length

B = Projected Diode Pitch

C = Projected Diode Width

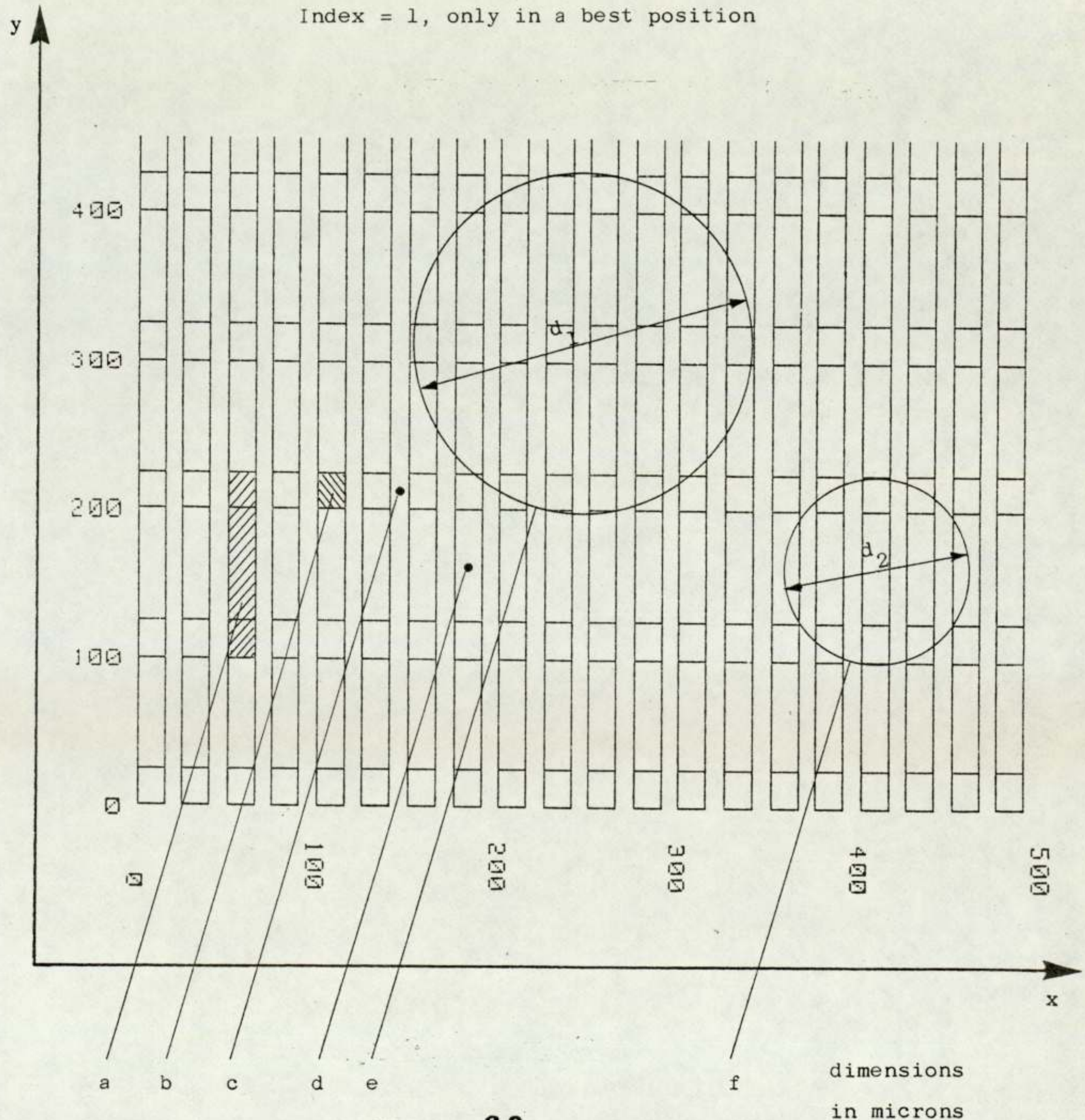
Dimensions in microns



For clarity the elements are considered as the diode areas only, although the whole strip is photosensitive.

Figure 5.8. A Projection of Array Elements onto a Surface (Dynamic)

a) A scanned strip; the area from which one photodiode receives light during one scan.
b) The overlap area of consecutive scanned strips
c) One of a set of "worst" positions for defect centres
d) " " "best" " " " "
e) The Minimum size of defect which will always give Area Index = 1, even in a worst position
f) The Minimum size of defect which can give Area Index = 1, only in a best position



Each scanned strip has an overlap area at each end (which is equal to the projected element area) from which light is integrated on consecutive scans (Figure 5.8b). This occurs because signal information from the nth scan is delivered and the sensor is reset to start compiling the signal for the (n+1)th scan within a single clock period. The clock period is short compared to the integration time, so the projected element displacement is negligible compared to the length of the scanned strip.

The distance moved by the projected element during the integration time t_i is the scan displacement S and this is equal to the product of the integration time and the speed with which the surface is moving, v.

$$S = v \cdot t_i$$

Scan displacement S is independent of magnification m since it is equal to the displacement of the principal axis of the optical system.

The total length of the scanned strip is S + C (Figure 5.9a) and its width is A, where A and C are the dimensions of the projected element area. The scanned strip pitch is B, which is the projected pitch of the array ($A = a/m$, $B = b/m$ and $C = c/m$ where a, b and c are dimensions of the array (Figure 5.1)).

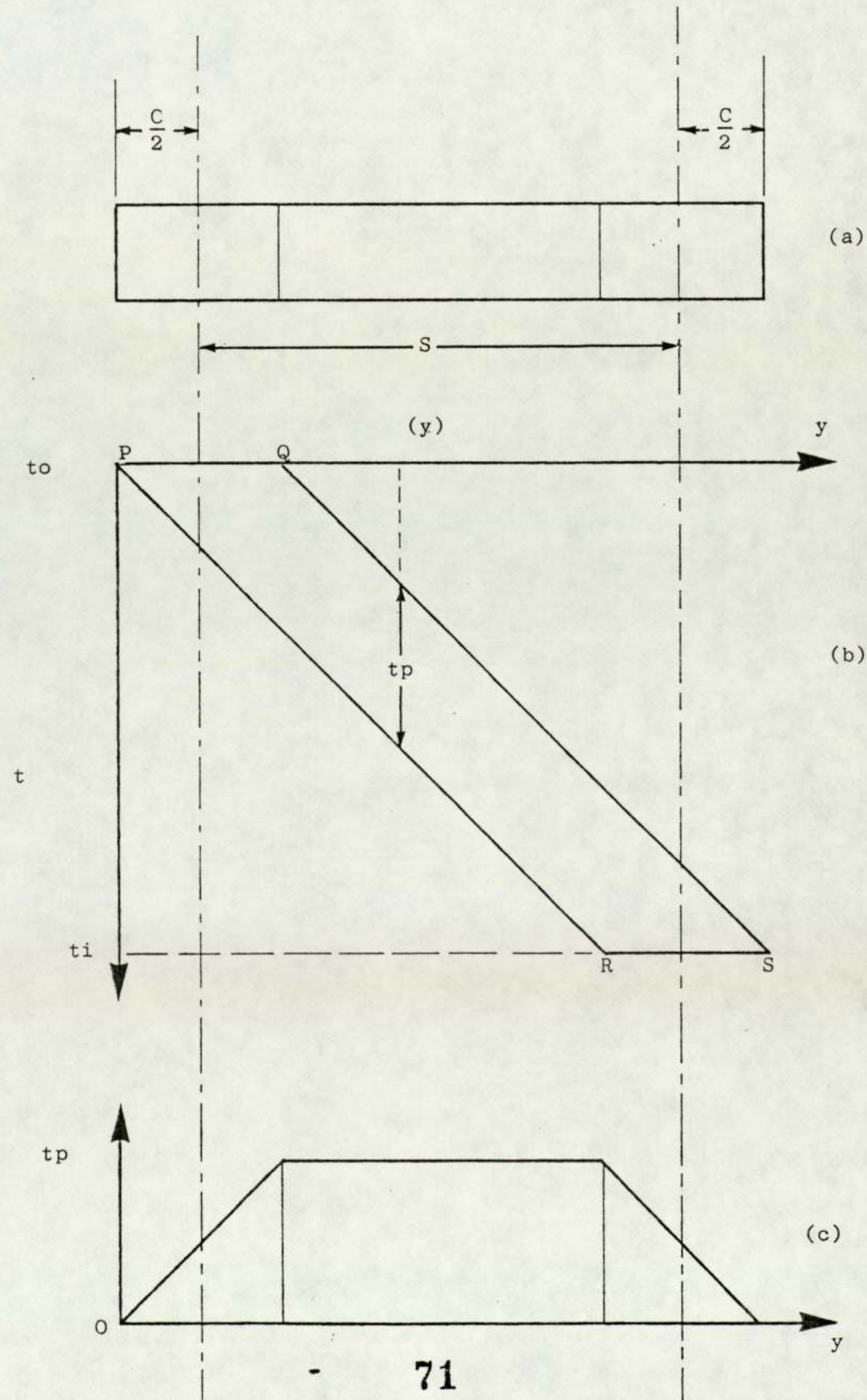
Where numerical values are given for dimension, they refer to a Reticon RL256G self-scanned photodiode array. Many other arrays, both charge-coupled and photodiode have dimensions of the same proportions.

5. e) i) Sensitivity in overlap areas of scanned strips

The light received from the overlap area at the end of each scanned strip is shared between the consecutive scans. Figures 5.9 a and b show

Figure 5.9. Spatial and Temporal Representations of an Array Element

(a) Scanned strip
(b) Displacement/Time representation of element position
(c) Displacement/Point integration time



such a strip and a space/time representation of the position of the projected element. PQ is the element position in y space at t_o, the beginning of the integration time, and RS is its position at the end time t_i. The interval t_p is the time for which any part of the element is projected onto a point (y), and is the integration time for that point on the surface. The point integration time t_p falls linearly in the overlap area at the end of each strip (Figure 5.9c) and therefore sensitivity falls correspondingly.

5. e) ii) CCD and SSPD scan pattern differences

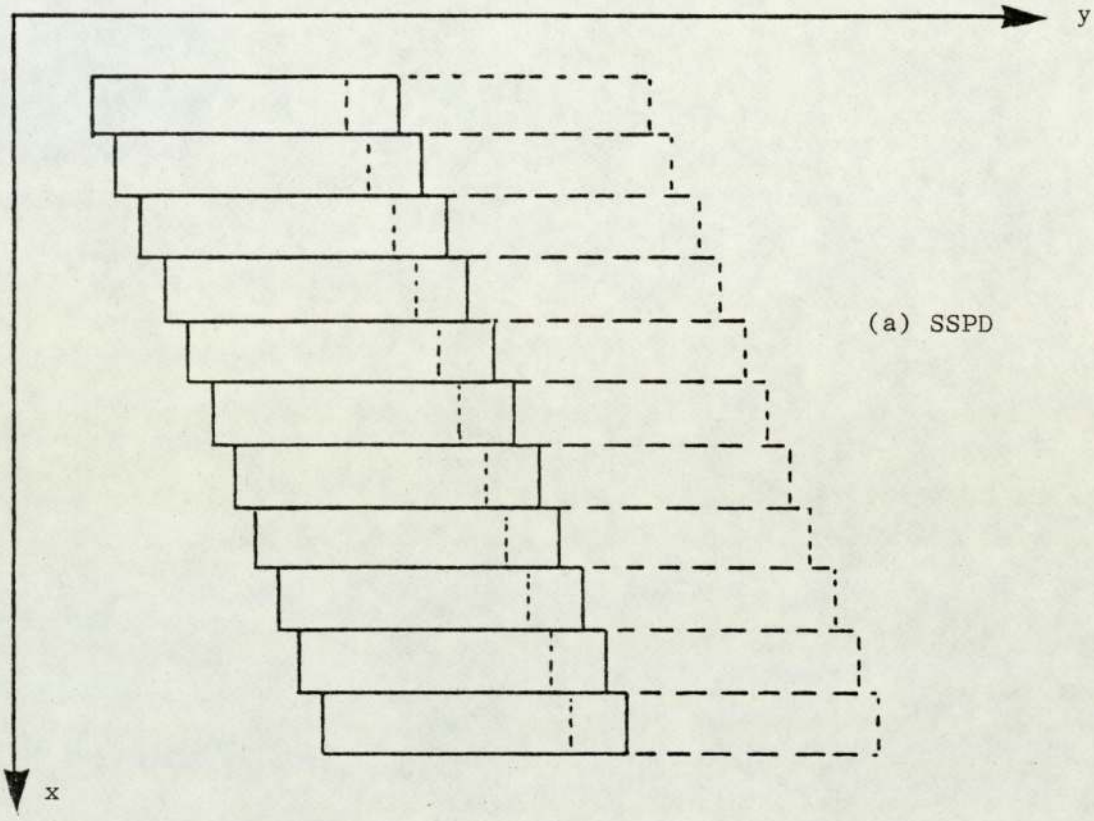
Because the photdiodes in an array are sampled and recharged serially, there is a delay of one clock period between the start of light integration for each subsequent diode. If the array is being scanned continuously so that the first diode is sampled as soon as possible after the last, then on one scan, the delay between the start of light integration for the first and last diodes will be very nearly the integration time. This means that the projected scan strips are staggered as shown in Figure 5.10a. Conversely, the signal information in the form of charge packets in a linear CCD array is transferred simultaneously in parallel to a shielded storage array. The areas from which elements integrate light are thus not staggered (Figure 5.10b).

The stagger of projected scanned strips is exaggerated in Figure 5.10a by showing a small number of elements. In practice, where an array of perhaps 256 elements is used, the delay between adjacent strips will be $\frac{1}{256}$ x integration time, and this can normally be discounted when considering a defect covering a small number of elements. Stagger is only likely to be a problem where resolution in the y direction better than the projected scan strip length is sought,

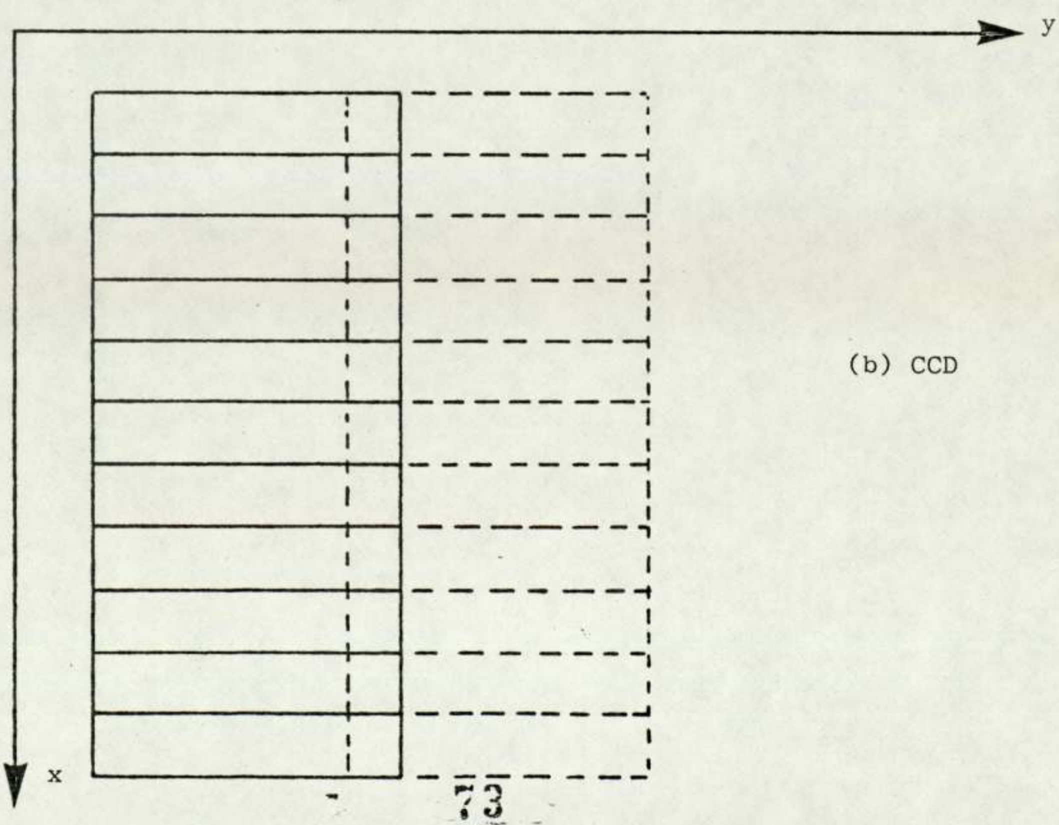
Figure 5.10. Scanning Patterns of Solid State Arrays

(a) Scan pattern of a self-scanned photodiode array (SSPD)

(b) Scan pattern of a CCD array - no stagger



(a) SSPD



(b) CCD

and some y spatial dependence is important over the whole array length (or a considerable proportion of it).

5. e) iii) <u>Contrast and defect pulse height</u>

The situation under consideration is that of a bright, unblemished surface (high radiance B_1) with darker defects (lower radiance B_2). The contrast between defects and surface is given by

$$C = (B_1 - B_2)/B_1 \qquad B_1 > B_2$$

Contrast varies between 0 and 1 and is dimensionless (7)

Figure 11a represents an oscilloscope trace showing a linescan across a bright surface containing a defect (Figure 5.11b). A bright element produces a negative voltage, the magnitude of which is proportional to the irradiation : thus, zero volts represent a dark element. Providing that the defect completely covers more than one scanned strip, then

$$V_1/V_2 = B_1/B_2$$

and contrast C can be expressed as

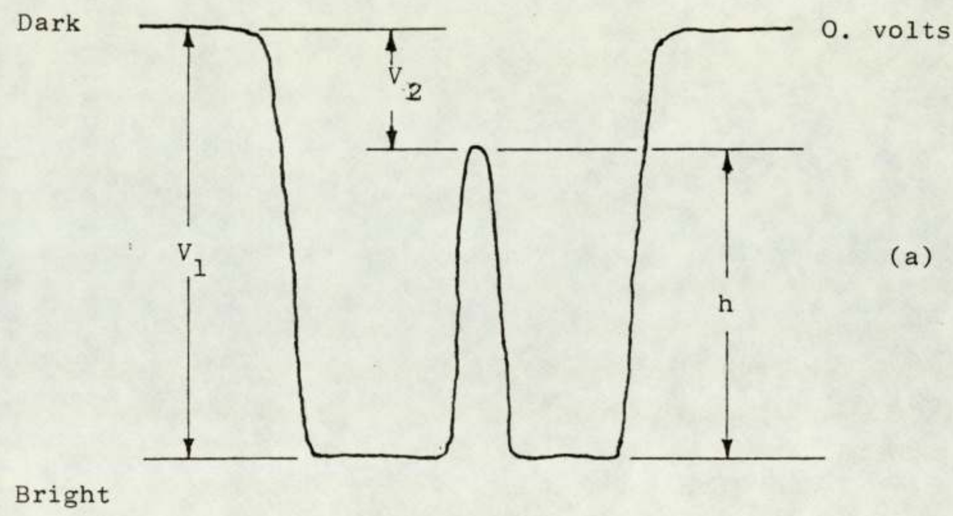
$$C = (V_1 - V_2)V_1 = h/V_1$$

i.e. the ratio of defect pulse height h to bright surface signal V_1. The overall effect of optical imperfections is to "scatter" light onto those elements which would otherwise be dark, and the effect of crosstalk is the overflow of photoelectrons into dark elements. Both of these tend to reduce defect pulse height h and thus the apparent contrast.

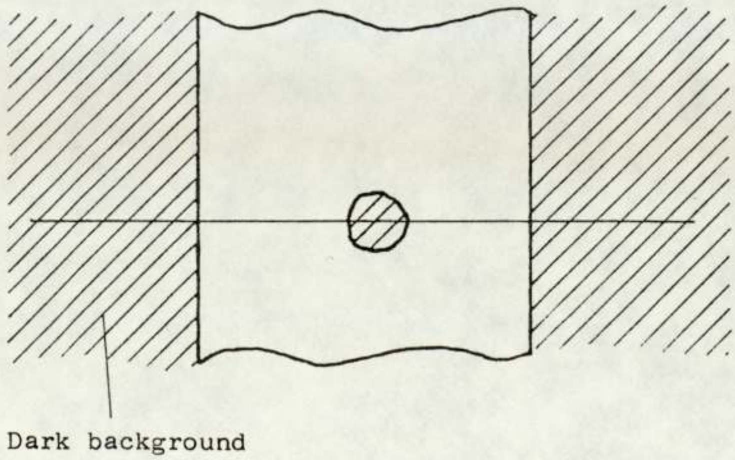
To be useful in detecting defects, a system must produce a defect pulse of a height h large enough to cross a pre-set threshold. Therefore a major objective must be to maximise h for the important defects which are most difficult to detect.

Figure 5.11. Linescan of a Surface Defect

(a) Oscilloscope trace of a linescan of the bright surface and dark defect shown in (b)



(a)



(b)

5. e) iv) Area Index

It is evident from Figure 5.8 that if a defect covers only a proportion of the scanned strip, then the pulse height h will be reduced proportionately if the spatial sensitivity of the strip is uniform.

When considering scan patterns in detail, it is useful to define this proportion as the Area Index. Thus :

$$\text{Area Index AI} = \frac{\text{The area of the intersection of the scanned strip and the defect}}{\text{The area of the scanned strip}}$$

AI is dimensionless and has a value between 0 and 1.

Where defects are large in relation to scanned strip, then AI is unity except for strips at the edge of the defect.

Area Index gives the maximum theoretical value for defect pulse height h_{max} by the expression

$$h_{max} = V_1 \times AI$$

In practice, this maximum value of h is reduced by contrast C, optical imperfection and crosstalk. Other noise will reduce the useful pulse height.

5. e) v) Relative positions of defects and scanning patterns

Consider a high Area Index for at least one element to be "good" as this gives a correspondingly high defect pulse. For any case where the diameter of a defect is less than the combined length of two consecutive scanned strips (d in Figure 5.8), the AI depends upon the position of its centre in relation to the scan pattern. There is a set of "worst" positions and a set of "best" positions for these centres (Figure 5.8 c and d). If the defect is moved in any direction from one of these "worst" positions, then the AI for at least one element will increase above the previous value for any element.

There is a minimum size of defect diameter d_1 which will always give AI = 1, even in a "worst" position (Figure 5.8e). The smallest defect size which can give AI = 1 is d_2 ($d_2 \approx \frac{1}{2}d_1$ Figure 5.8f), and this can only occur if it is in a "best" position. When the defect is displaced from its "best" position, the maximum value of AI falls. More generally, the position of the centre of the defect (x,y) on the projected scan pattern determines the diameter d which will give AI = 1 and the function d = f(xy) can be found as follows for circular defects.

From Figure 5.12a (for a circle) KLMN is a scanned strip. The function of d = f(x,y) in OPQR is repeated by reflections and translations throughout the projected scan pattern because of its symmetry. Thus the function in

OPQR	maps	onto	VWQR
"	"	"	SPQT
"	"	"	UWQT
"	"	"	VWXY etc.

x,y is the centre of a defect diameter d. From Figure 5.12b (for a circle of radius $r = \frac{d}{2}$)

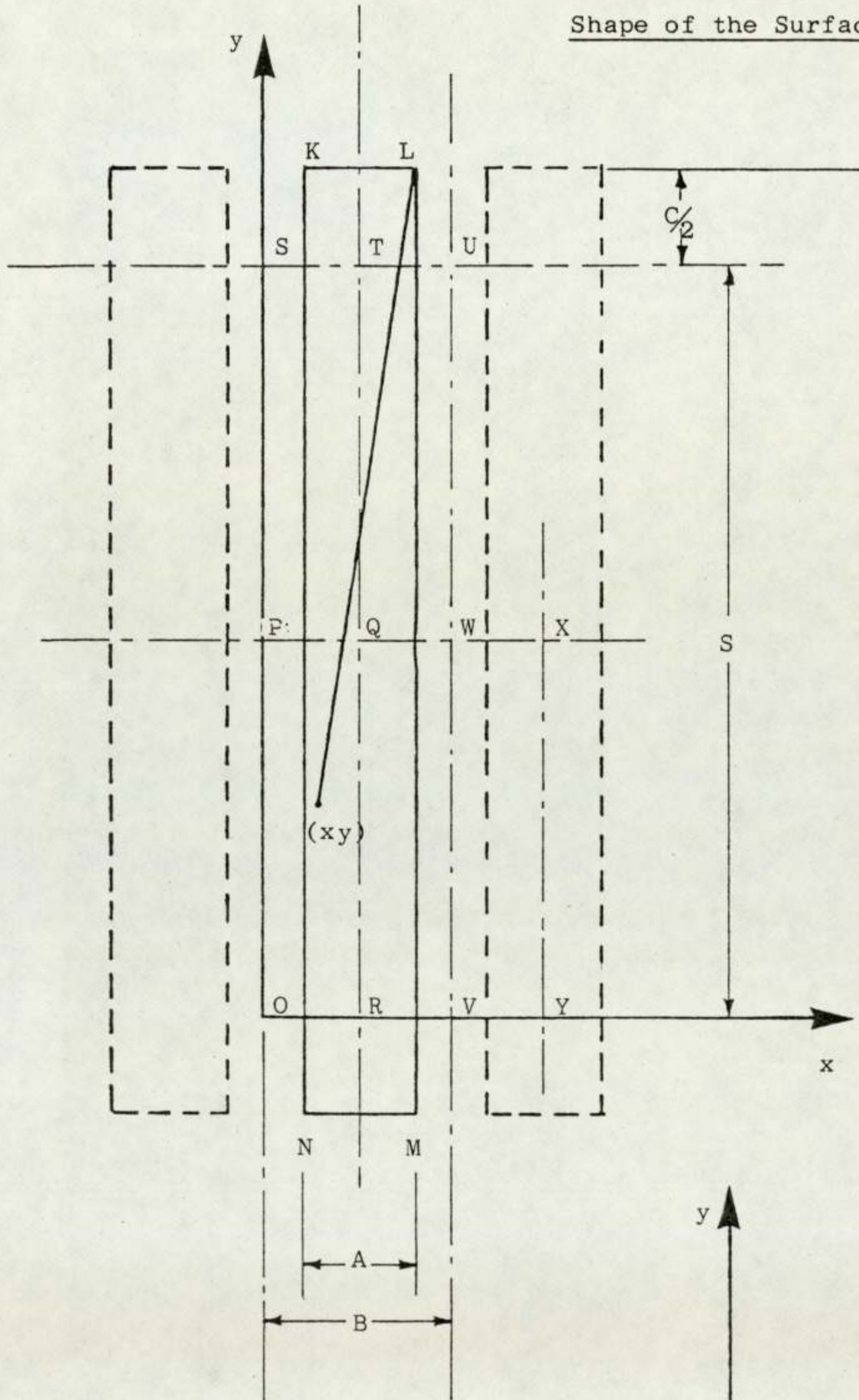
$$r^2 = f^2 + e^2$$

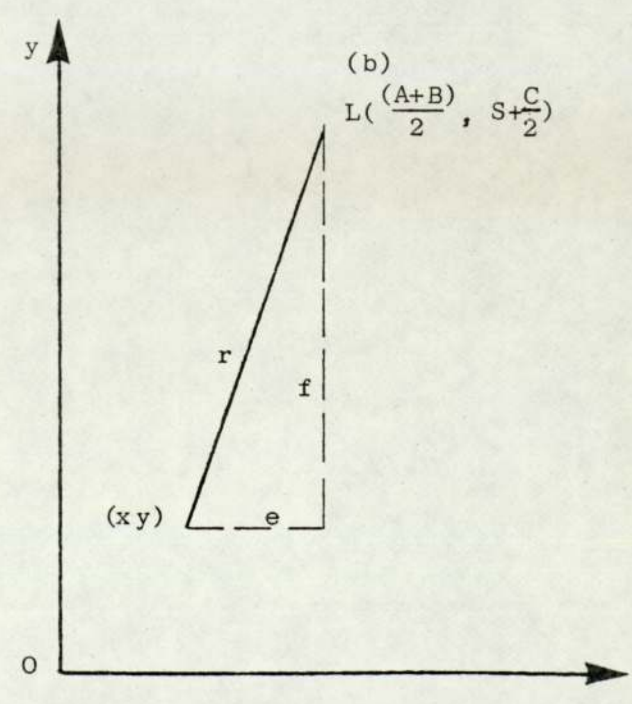
$$f = S + C/2 - y$$

$$e = (A+B)/2 - x$$

$$\therefore \quad r = \sqrt{(S + C/2 - y)^2 + ((A + B)/2 - x)^2}$$

Figure 5.12. Geometry of Scanned Strips, used in calculating the Shape of the Surfaces in Figure 5.13





(a) Three scanned strips
(b) Detail of centre strip showing only those dimensions relevant to deducing r = f(xy)

The value of r is plotted as the Z co-ordinate in a pseudo - three-dimensional graph (Figure 5.13) where it appears as a surface of values of r. The Z co-ordinate of a point (x, y, z) on the surface shows the minimum radius of a defect which could give AI = 1 with its centre at (x,y) on the scan pattern.

Any point in xyr space represents a defect radius r and position xy on the surface. All points above the radii surface give AI = 1. All points below it give AI $<$ 1.

Practical situations are usually concerned with detection of a particular minimum size of defect whose centre position on the scan pattern is random, and all larger defects. A plane in xyr space parallel to the surface (xy) can be used to represent this situation. If the plane is entirely above the radii surface, then the defect will always give AI = 1, and if it is below, AI $<$ 1. If the plane and radii surface intersect, then the ratio of the area when AI $>$ 1 to the whole surface area (xy) is the probability of that radius of defect giving AI = 1.

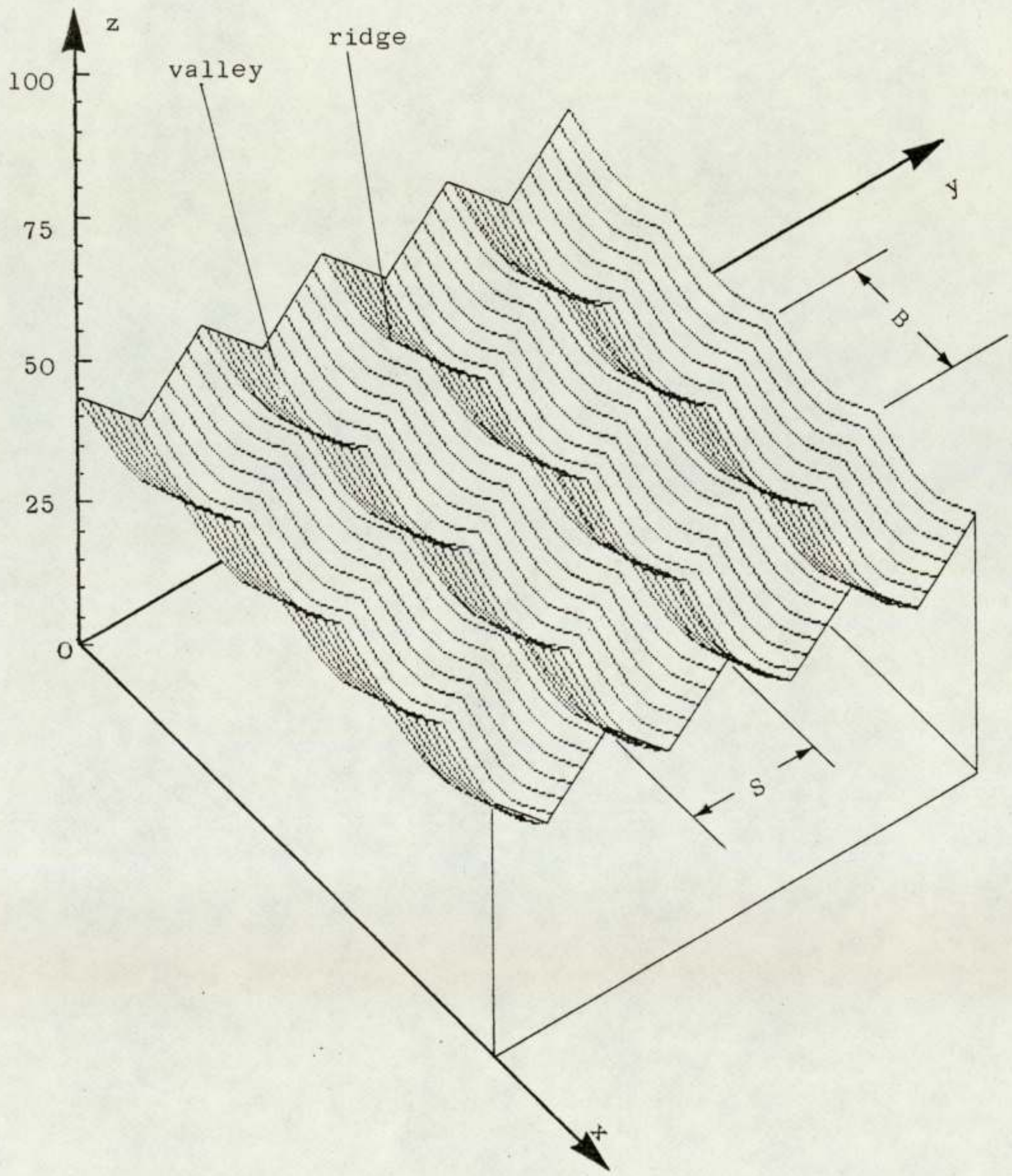
5. e) vi) <u>Probability of unity Area Index for "long" scanned strips</u>

It is evident from Figures 5.13a, b and c, that as S is increased, so the dependence of r on y displacement also increases, and its dependence on x becomes less significant.

Where the scanned strip is "long" (S $>$ 4B) a simplified approach to the function r = f(xy) can be applied, i.e. the x dependence can be ignored and r can be considered simply in terms of the length of the scanned strip which is covered by a defect. Figure 5.14 shows

Figure 5.13. Surfaces Relating to the Minimum Detectable Radius of Defect

The z co-ordinate of a point (x y z) on these three dimensional surfaces represents the minimum radius of a defect which could give Area Index = 1, with its centre at (x y) on a real surface. The The only parameter which has been varied to produce the three surfaces is the Scan displacement S.



a) Scan displacement = Projected diode pitch

S = B = 25 microns

Figure 5.13.b)

Scan displacement = 2 . Projected diode pitch

S = 2.B = 50 microns

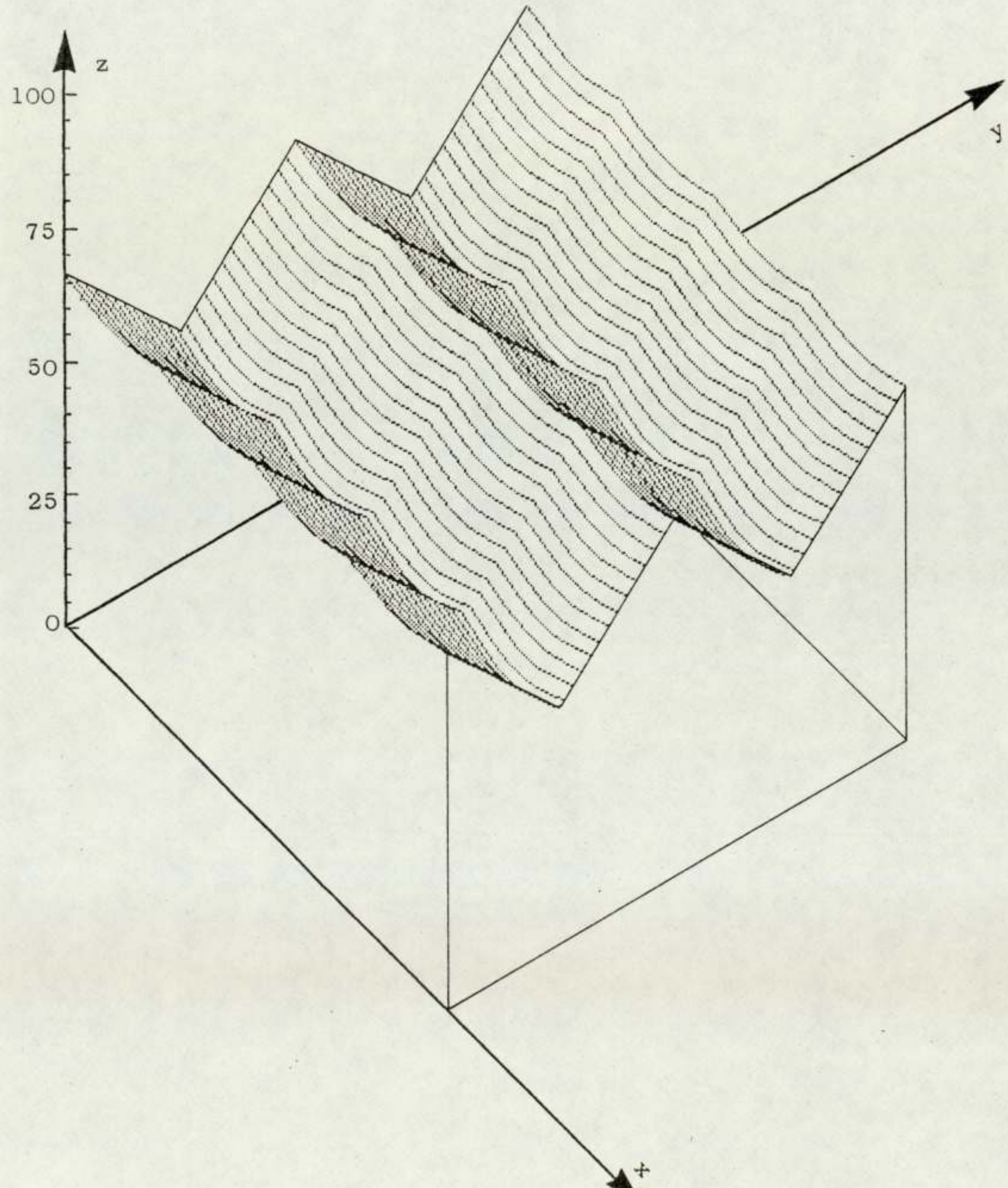


Figure 5.13.c)

Scan displacement = 4 . Projected diode pitch

S = 4.B = 100 microns

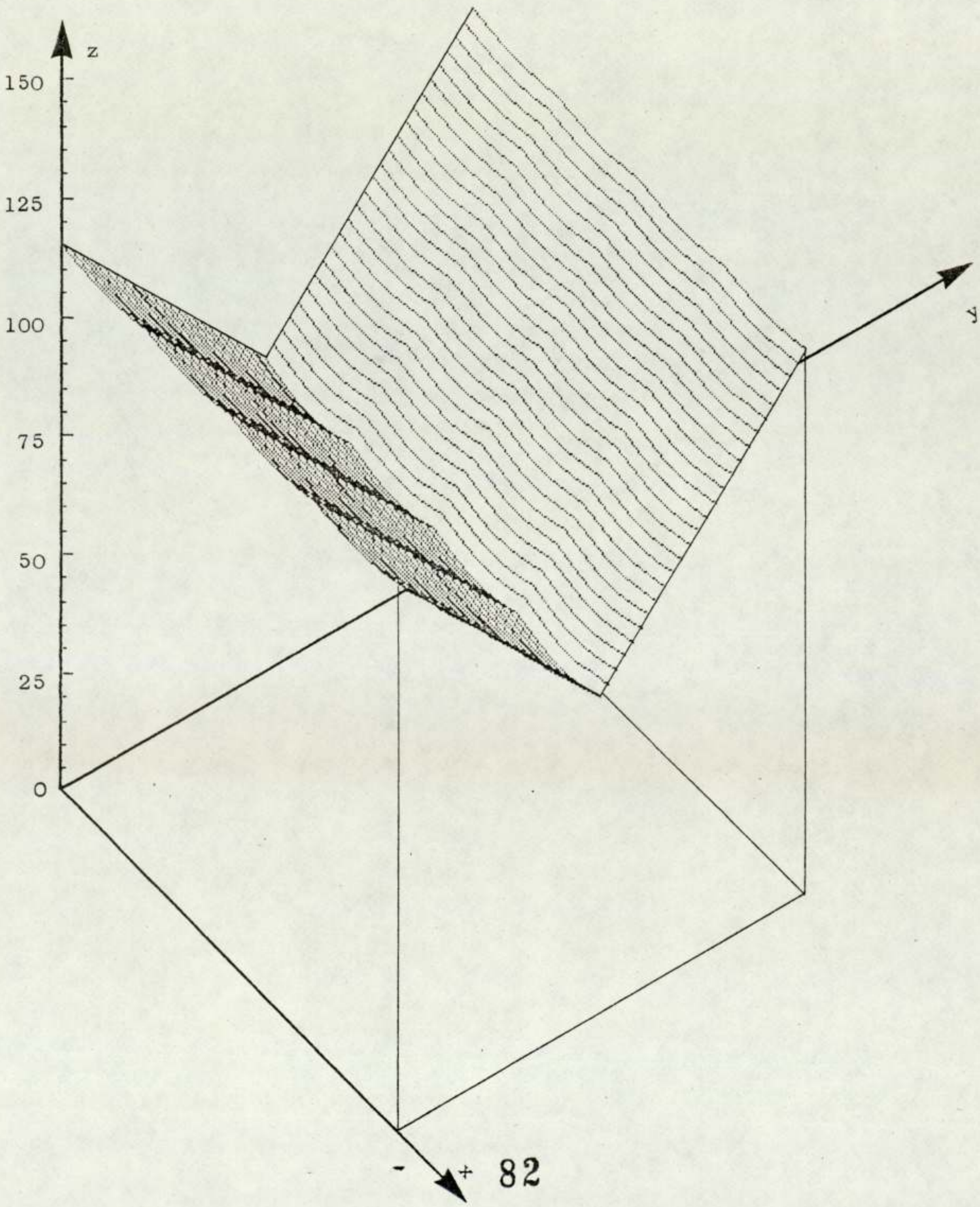


Figure 5.14. Circular Defects on Two Consecutive Scanned Strips, used in deducing the probability of different diameters producing AI = 1

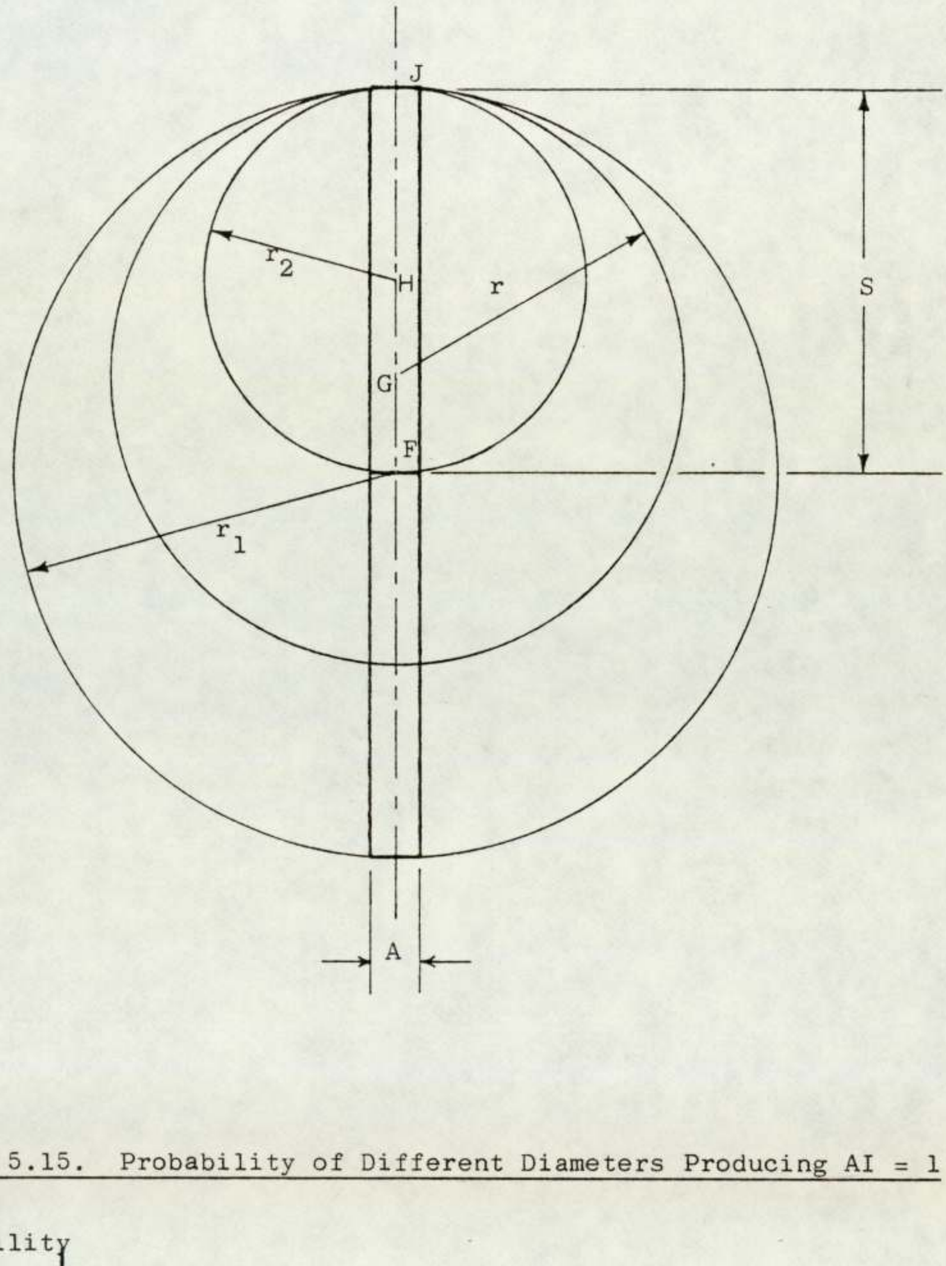
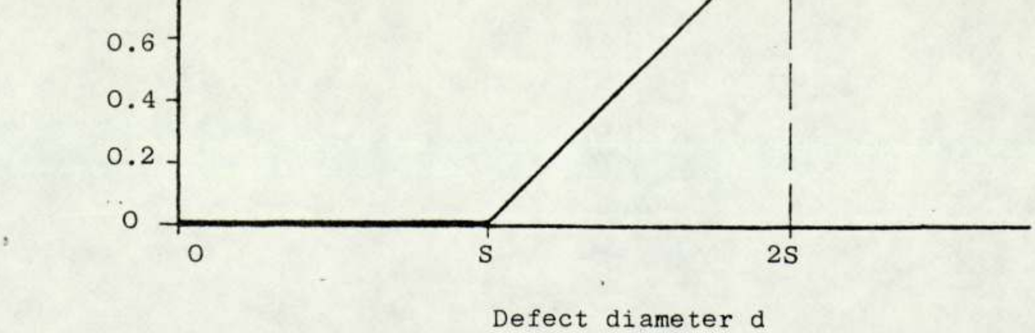


Figure 5.15. Probability of Different Diameters Producing AI = 1



defect circles and two consecutive projected scanned strips. Radius r_2 is the smallest which can give AI = 1 and r_1 is the smallest radius which will always give AI = 1 wherever its centre ($r_1 \approx 2r_2$). The centre line FH is repeated throughout the surface because of the pattern's symmetry in the same way as rectangle OPQR in Figure 5.12a. To give AI = 1, the centre of a circle r_1 must fall at H, and if defect centres fall randomly on the scan pattern, this has a probability P approaching zero. The centre of circle radius r_2 can fall anywhere on FH and still give AI = 1 (P = 1).

For the more general case of a circle of radius r and centre G, the longer r becomes, the more possible points there are on FH which G can occupy in order to give AI = 1, i.e. if the centre G falls on GH, then AI = 1 ; if it falls on FG, then AI < 1. Therefore the ratio GH / FH = P, the probability of a defect radius r giving AI = 1. Because of pattern symmetry, P is also the probability for the whole surface of a defect radius r giving AI = 1.

From Figure 5.14 :

$$FH = S/2$$

$$GJ = r$$

$$HJ = S/2$$

$$GH = GJ - HJ$$

$$= r - S/2$$

$$\therefore \text{ Probability } P = \frac{GH}{FH} = \frac{r-S/2}{S/2}$$

$$= \frac{2r - S}{S}$$

$$= \frac{2r}{S} - 1$$

or Probability P = d/S - 1

Thus, the probability of a defect of diameter d giving an Area Index = 1 is a linear function of d with gradient 1/S between P = 0 and P = 1 (Figure 5.15).

The scanned strip length is taken as S and not S + C, since C is small compared with S and also the sensitivity of the area beyond the limits of S is lower.

5. e) vii) Defect diameters yielding fractional Area indices for "long" scanned strip

In practice it is not always necessary to have an Area Index as high as 1 in order to give a useful defect pulse. Therefore it is useful to find the relationship between Area Index and defect size in order to determine, for example, the defect size which would give AI = 0.75. As AI varies with defect centre position, it is convenient to consider the two extremes of the "best" and "worst" positions.

In this case, a square defect is considered, but there is little difference between the area of intersection of the strip in Figure 5.16 and a circle, as opposed to a square, of the same diameter and on the same centre.

For a "long" scanned strip, and for d $\geq$ A + B, Figure 5.16 shows squares of diameter d centred at the "worst" and "best" positions. The scanned strip length is taken as S and not S + C, since C is small compared to S and also the sensitivity of the region beyond the limit of S is lower. d is taken as $\geq$ A + B so that it always covers at least one strip width, and so d is independent of x displacement.

From Figure 5.16 :

"Best" position $AI = d/S$

"Worst" position $AI = d/2S$

These functions are plotted in Figure 5.17 where the considerable variations between "best" and "worst" cases are clear, e.g. a defect of diameter S could produce an AI having any value between 0.5 and 1. Alternatively, an AI of 0.5 could be produced by a defect having any value of diameter between S/2 and S.

5. e) viii) Volume Index for short scanned strips

For "short" scanned strips, the above model is inaccurate because two factors which were ignored in the simple "long" strip model are important when S is of the same order as C. These factors are the non-uniform sensitivity in the overlap areas, and the x displacement of the "worst" centre position. The case where S = B = C is now considered as this is often used in practice in order to attain equal xy resolution.

The sensitivity of the array in the areas between photodiodes cannot be ignored for this short scan displacement. Consequently, the width of the scanned strip must now be considered as the diode length A plus the interdiode gap G at each side (i.e. $(2 \cdot G) + A$).

The responsivity R of silicon can be stated as :

$$R = \frac{\text{Charge}}{\text{Radiant Energy}}$$

i.e. Charge = (R) . (Radiant Energy)

= (R) . (Radiant flux).(Time)

The charge produced in an area ΔA_k of the photosensor by irradiance I, 5.16. The Geometry of Square Defects on a Scanned Strip, for deducing the AI given by different diameter defects in "best" and "worst" positions. "Long" strips d > A+B

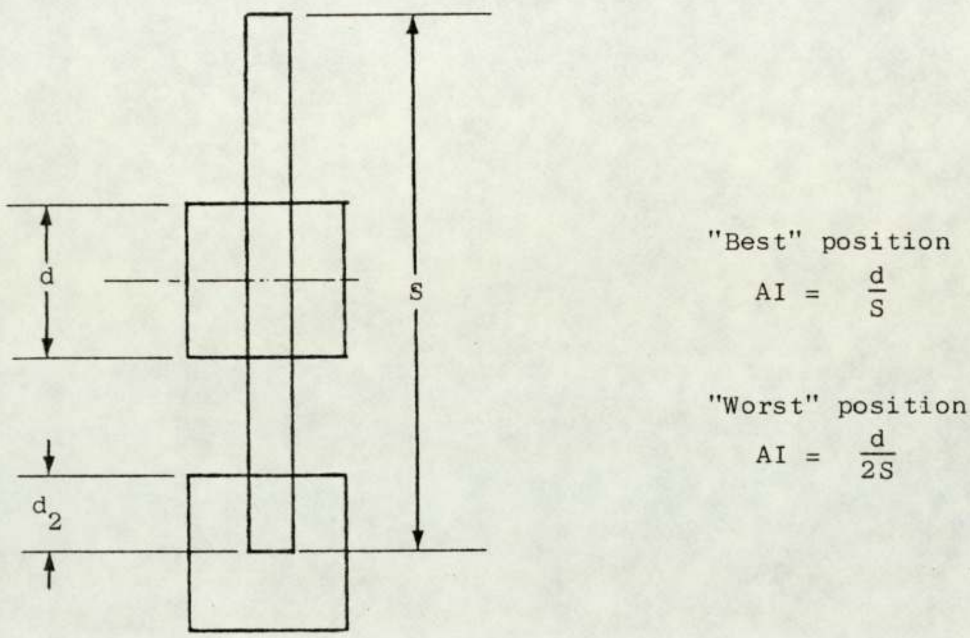
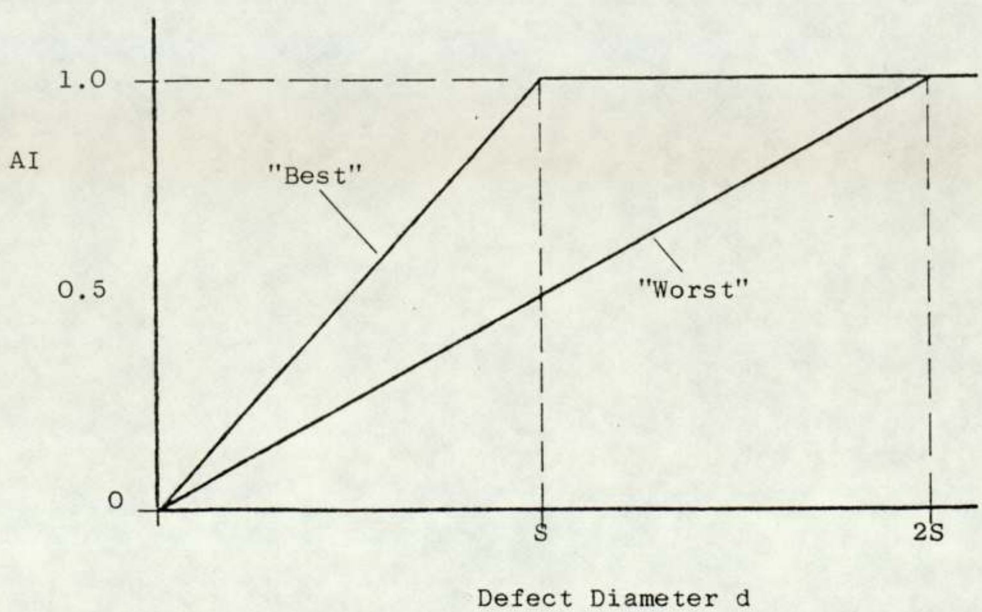


Figure 5.17. AI/Defect Size, for the case shown in Figure 5.16.



(I = flux per unit area), in time t_k is given by :

$$\text{Charge} = R.\ I.\ \Delta A_k.\ t_k$$

The charge produced in an area A under the same conditions is :

$$\text{Charge} = \sum_{k=1}^{n} R.I.t_k.\Delta A_k$$

where there are n areas ΔA_k each with its own time t_k and $t_k = f_t(xy)$. In the limit as $n \rightarrow \infty$ and the areas become infinitesimal:

$$\text{Charge} = \lim_{n \rightarrow +\infty} \sum_{k=1}^{n} R.I.t_k.\Delta A_k = \iint R.I.t_k.dA$$

$$\text{Charge} = R.I. \iint f_t(xy)dA$$

(R and I are constant over the integration).

If R is also a function of xy, $R = f_R(xy)$ then $R_k \cdot t_k = f_{Rt}(xy)$, is a single function which corresponds to dynamic sensitivity over the plane xOy, and

$$\text{Charge} = I \iint f_{Rt}(xy)dA$$

The convolution of $R_k = f_R(xy)$ and $t_k = f_t(xy)$ yields the surface $f_{Rt}(xy)$ (Figures 5.18a, b and c respectively , for the case when S = C = B.)

The double integral above represents the volume of a column beneath the surface with base A on the plane xOy, (e.g. Figure 18d)

If Vol_n is the volume above area A_n, and Q_n is the charge produced in an area A_n by irradiance I, then

$$Q_n = I \cdot Vol_n$$

Q : Coulombs
I : Wm^{-2}
Vol_n : Coulombs $J^{-1}sm^2$

Figure 5.18a. Relative Responsivity/Distance along the Array, shown for One Diode

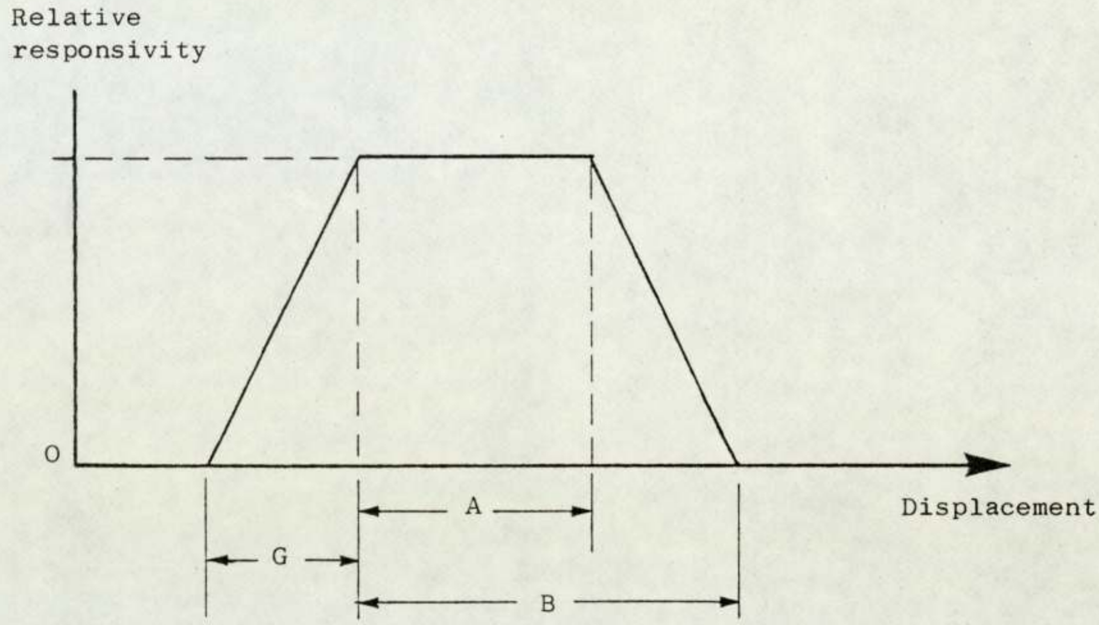


Figure 5.18b. Point Integration Time/Displacement y, for scan displacement S = Array Width C

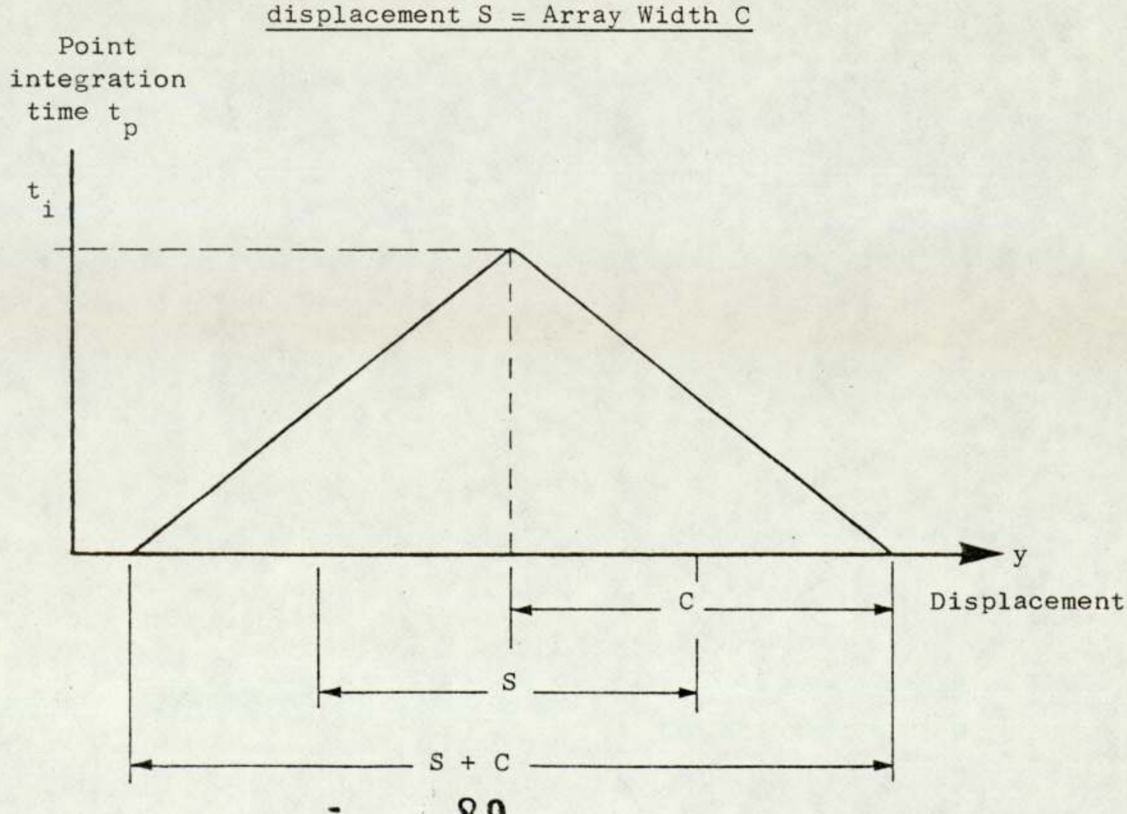


Figure 5.18c. The Sensitivity over a Scanned Strip

$$Z = f_{Rt}(x,y)$$

Scan displacement = Projected diode pitch = projected array width

$S = B = C$

Volume shown = Vol_1

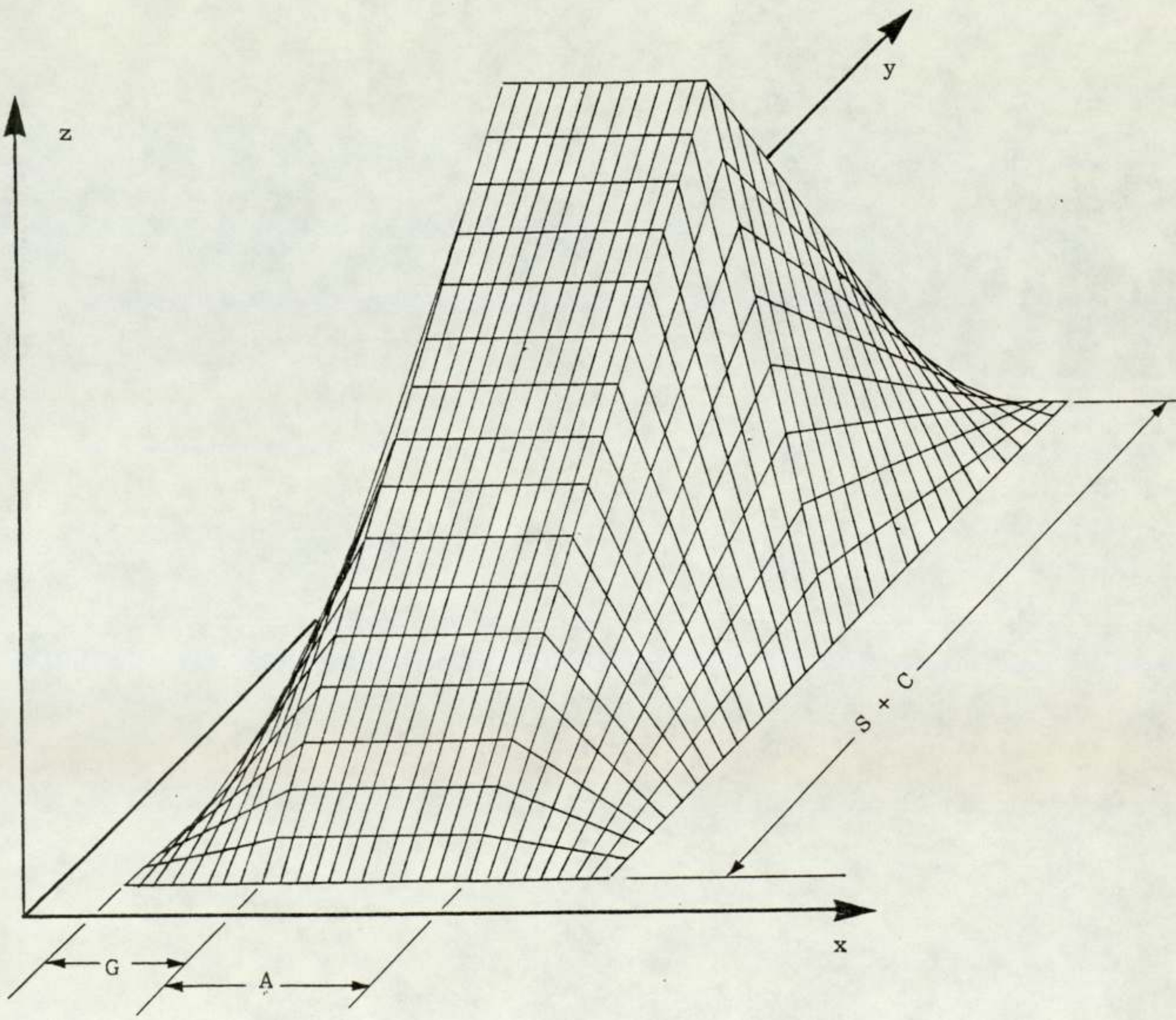
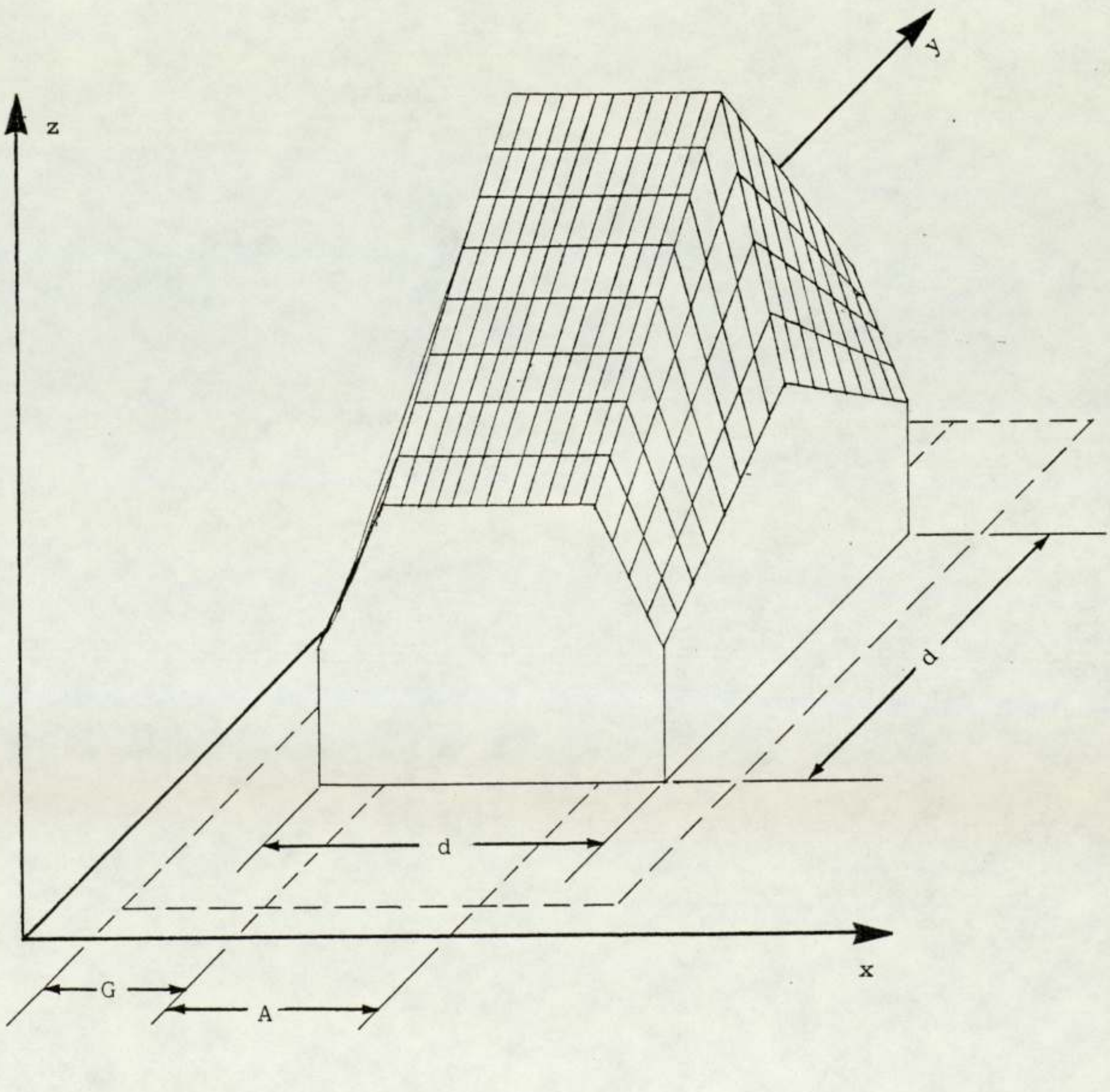


Figure 5.18d. Volume V_3(Sensitivity. Area) for a square defect in a "best" position on a scanned strip. S=B=C



If I is spatially uniform, then

$$Q_n \propto Vol_n$$

and as charge is converted to voltage linearly

$$V_n \propto Vol_n$$

thus the signal level due to shaded area in Figure 5.19 is proportional to the volume shown in Figure 5.18d.

$$V_3 \propto Vol_3$$

where Vol_3 is the volume of a column above area A_3.

Similarly

$$V_1 \propto Vol_1$$

where Vol_1 is the volume over the whole scanned strip (Figure 5.18c.)

and

$$V_2 \propto Vol_2$$

where Vol_2 is the volume over the <u>un</u>shaded area A_3.

$$V_1 = V_2 + V_3 \quad \text{and} \quad Vol_1 = Vol_2 + Vol_3$$

If A_3 has radiance zero then the diode voltage output is V_2. If the adjacent diodes see only bright surface, their output will be V_1 and the defect pulse height will be $V_1 - V_2$ (Figure 5.20)

i.e.

$$h_{max} = V_3 = V_1 - V_2$$

This is h_{max} because it is a maximum theoretical pulse height.

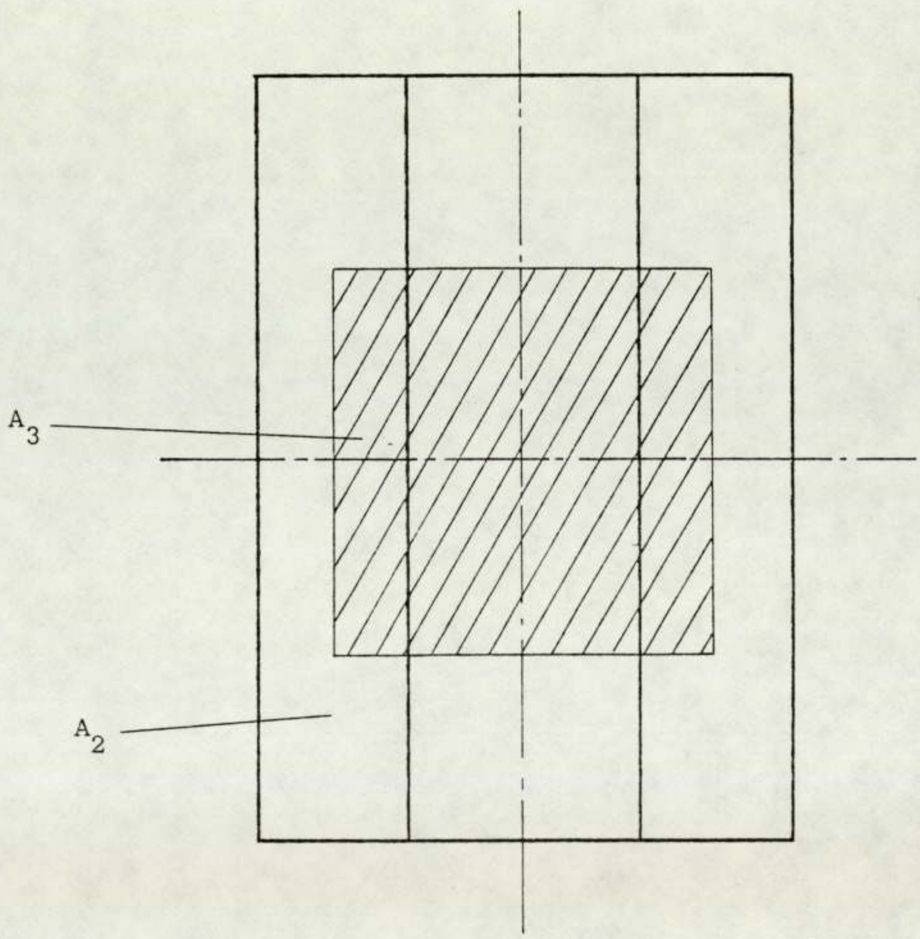
Or

$$h_{max} = \frac{V_3}{V_1} \cdot V_1$$

which is equivalent to

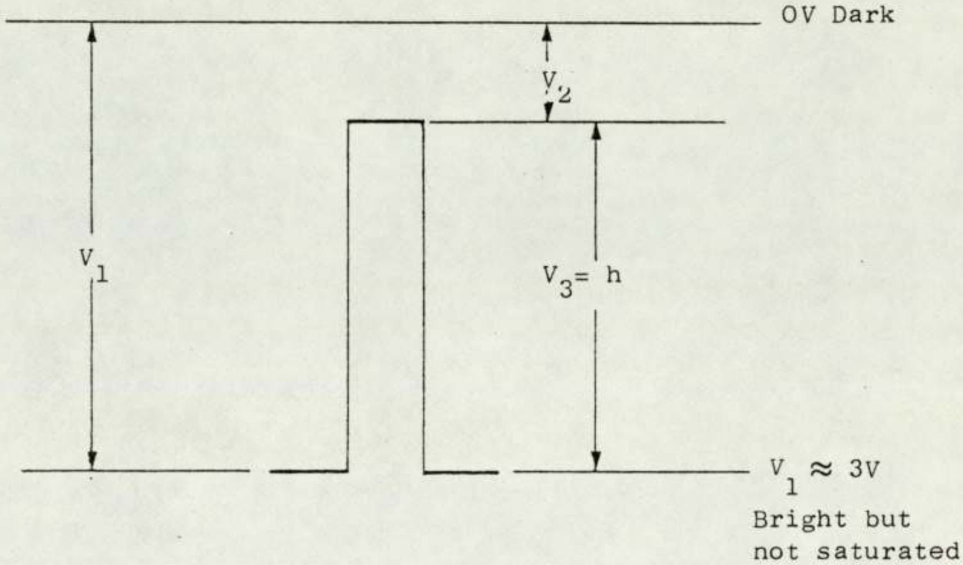
$$h_{max} = \frac{Vol_3}{Vol_1} \cdot V_1$$

Figure 5.19 Square Defect on a Scanned Strip



$$A_1 = A_2 + A_3$$

Figure 5.20. The Theoretical Signal from Three Adjacent Photodiodes : Centre Diode darker



The ratio $\frac{Vol_3}{Vol_1}$ is useful since it can be used to determine the defect pulse height from the scanned strip and defect geometry, and the bright surface signal. This ratio is therefore defined as :

$$\text{Volume Index} = VI = \frac{Vol_3}{Vol_1} = \frac{\text{Volume above defect (Fig.5.18d)}}{\text{Total volume above strip(Fig.5.18c)}}$$

(VI is dimensionless and has a value between 0 and 1) and

$$h_{max} = VI \cdot V_1$$

To calculate VI it is necessary to establish the shape of the surface and the intersection of the defect. The volume can be found by any suitable method, e.g. by integration in each of the regions shown in Figure 5.21 or by a simpler method if all the base areas are rectangular within each region, i.e. the volume above any rectangle is equal to the product of its base area and its height at the centre.

The latter method was used to calculate Volume Indeces for square defects of various diameters at best and worst positions where $S = B = C$. The results are shown graphically in Figure 5.22.

The differences between these two curves are considerable. It is evident from Figure 5.22, and from the relationship between Volume Index and defect pulse height (h) that :

a) A particular defect of diameter d can give a considerable range of defect pulse heights.

b) If a particular threshold is set for h, then the minimum size of defect which will be detected is not constant.

Often the minimum volume index is most important since this yields the minimum defect pulse height which might be encountered with a particular size of defect.

Figure 5.21. A scanned strip showing rectangular regions a to f into which the surface can be divided for volume calculation

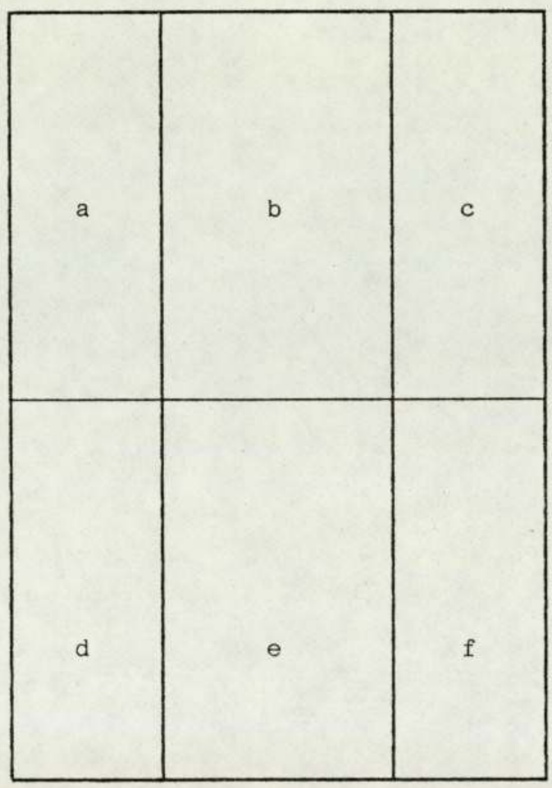


Figure 5.22. Volume Index/Defect Diameter for S = B = C and Square Defects, Volume Index is Related to Defect Pulse Height (Numerical dimensions relate to unity magnification)

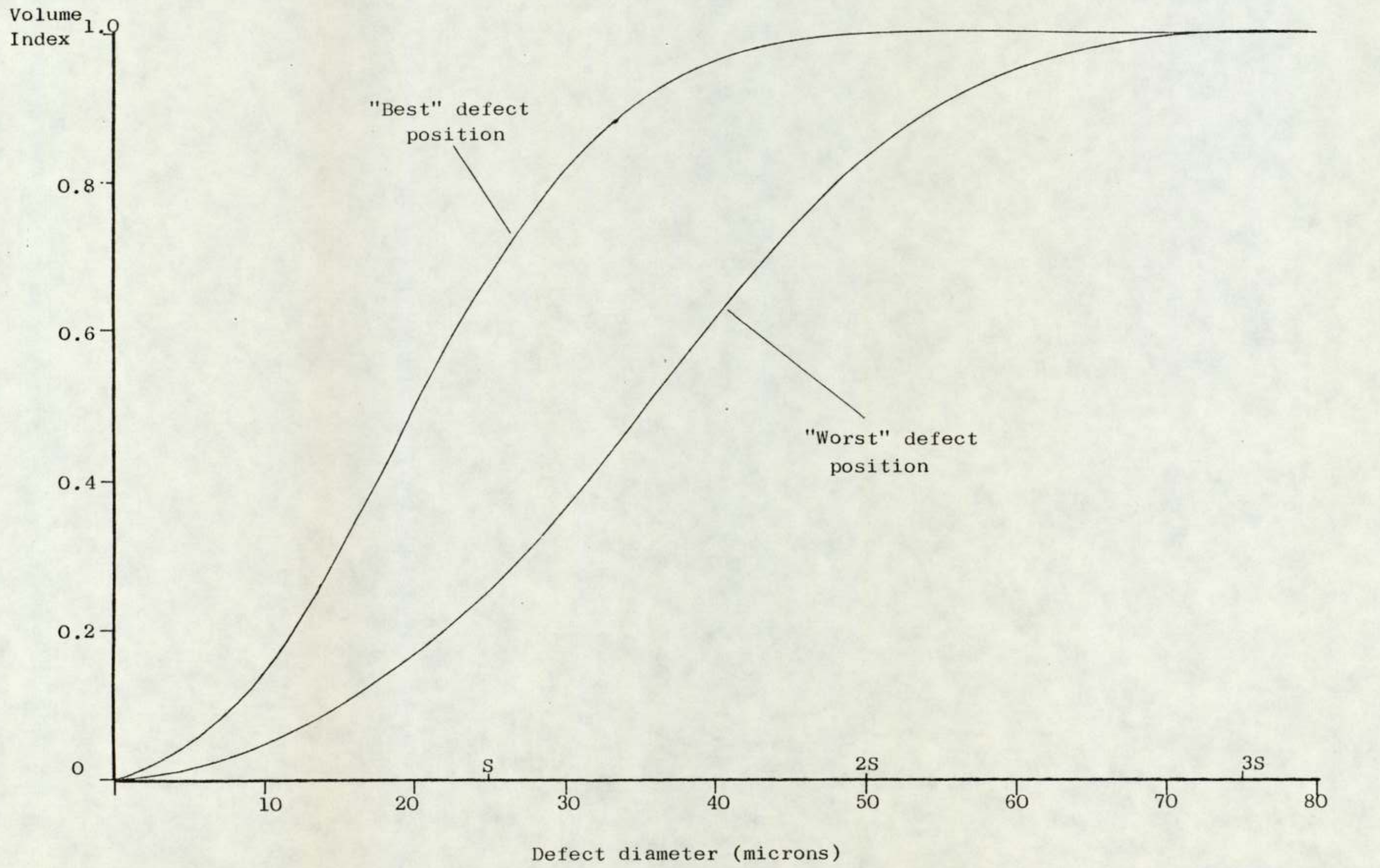


Figure 5.23 shows the minimum Volume Indeces for a variety of scan displacements and for 100 micron diameter square defects at unity magnification. This figure also shows the volume index for a 100micron diameter circular defect with a 50 micron scan displacement. The difference in VI between the square and the circle is clearly small. Figure 5.24 shows this scanned strip (S = 50 micron) and the 100 micron square and circular defects, and Figure 5.25 shows the shape of the area.sensitivity volume.

5.e)ix) The Practical Significance of Volume Index

In a static situation where a defect completely covers one photodiode, i.e. VI = 1, the theoretical defect pulse height is given by :

$$h_{max,static} = 1 \cdot V_1$$

In practice, the defect pulse height is reduced by contrast C, array crosstalk and optical imperfections. The latter two can be represented together by a constant K. K has a value between 0 and 1 and is dimensionless. Thus :

$$h_{static} = V_1 \cdot C \cdot K$$

V_1, C and K are not altered by moving the surface under inspection, but VI may be reduced below unity.

$$\therefore \quad h_{dynamic} = V_1 \cdot C \cdot K \cdot VI$$

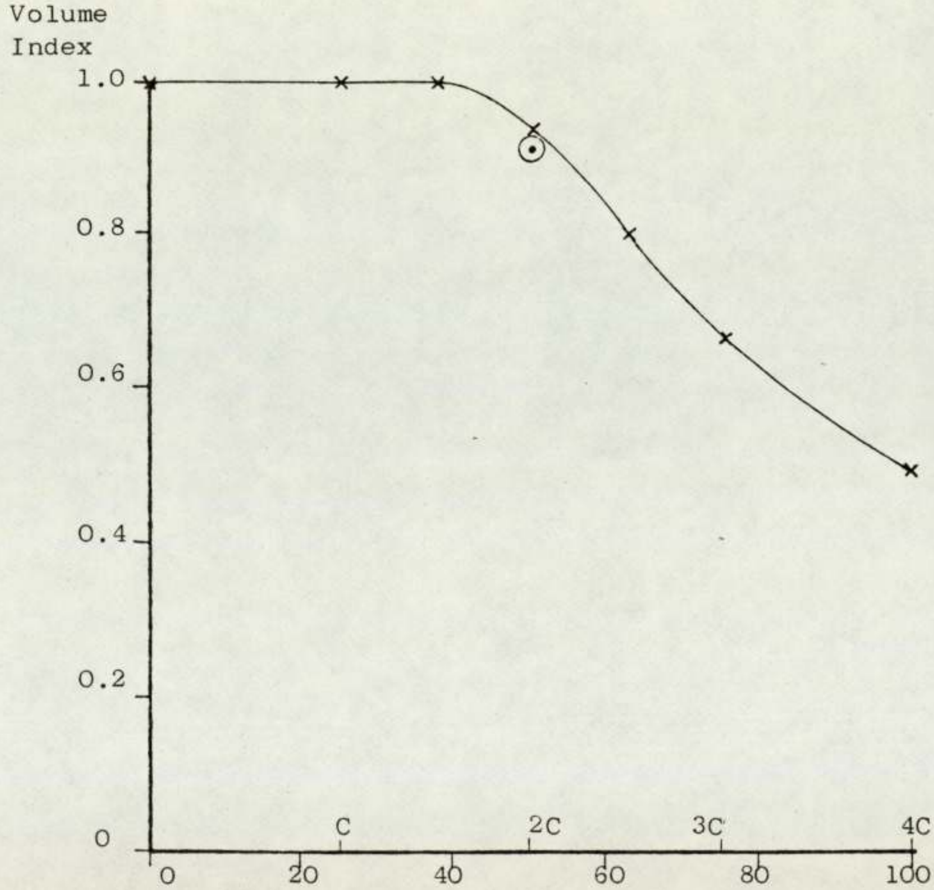
$$\text{or} \quad h_{dynamic} = h_{static} \cdot VI$$

This relationship can be used to determine the expected range of the pulse heights in dynamic situations for a defect, the pulse height of which can be measured in a static case with VI = 1.

Figure 5.23. Minimum Volume Index for Different Scan Displacements at Unity Magnification

X = Calculated points for 100 μm square defects

⊙ = A calculated point for a 100 μm circular defect



C = B

Diode width = Diode pitch

Figure 5.24. A Scanned Strip with Square and Circular Defects

Scan displacement = 2 . Projected diode pitch

= 2 . Projected array width

S = 2.B = 2.C = 50 microns

Defect diameter = 2 . Scan displacement

d = 2.S = 100 microns

(d = 2.r)

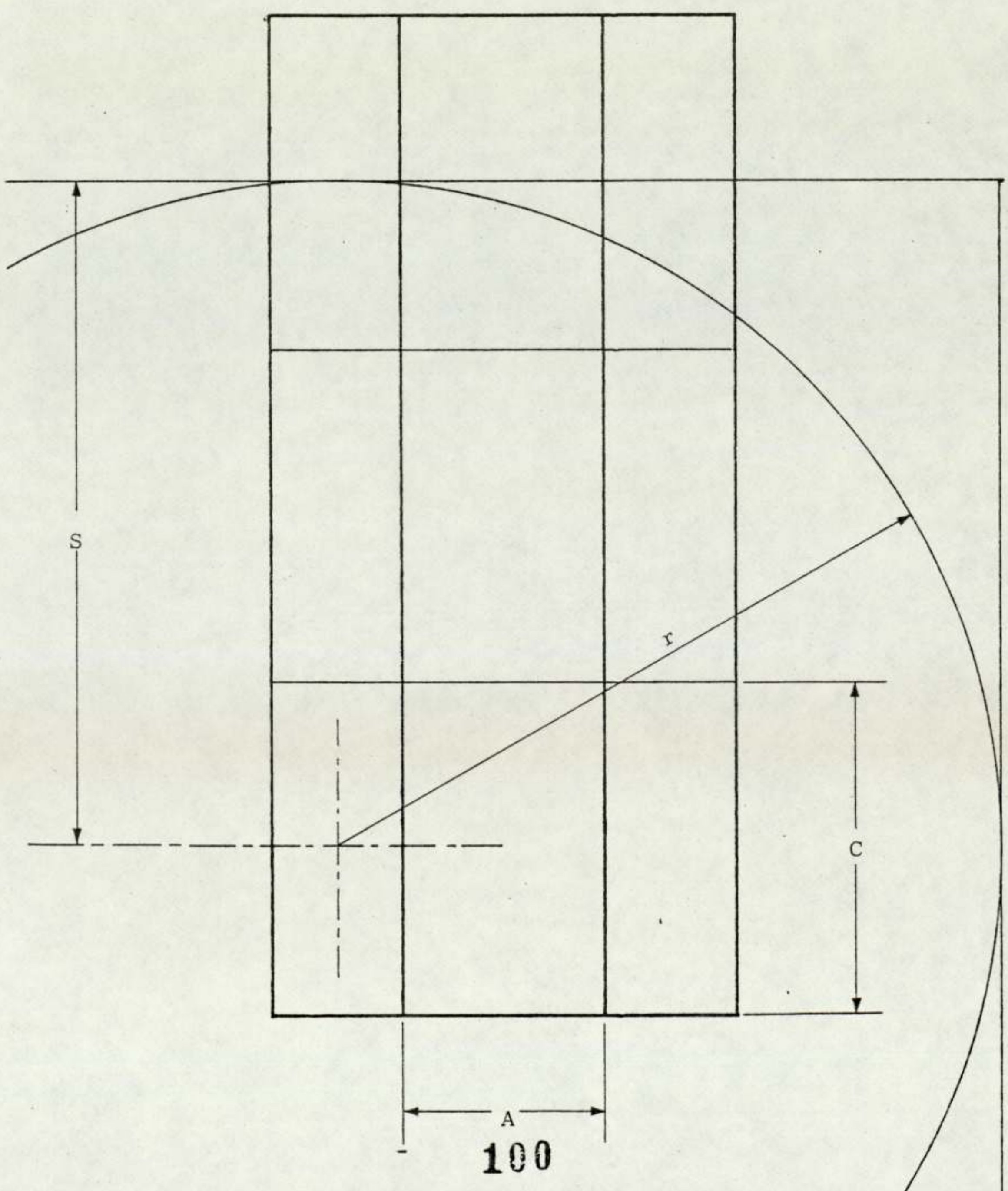


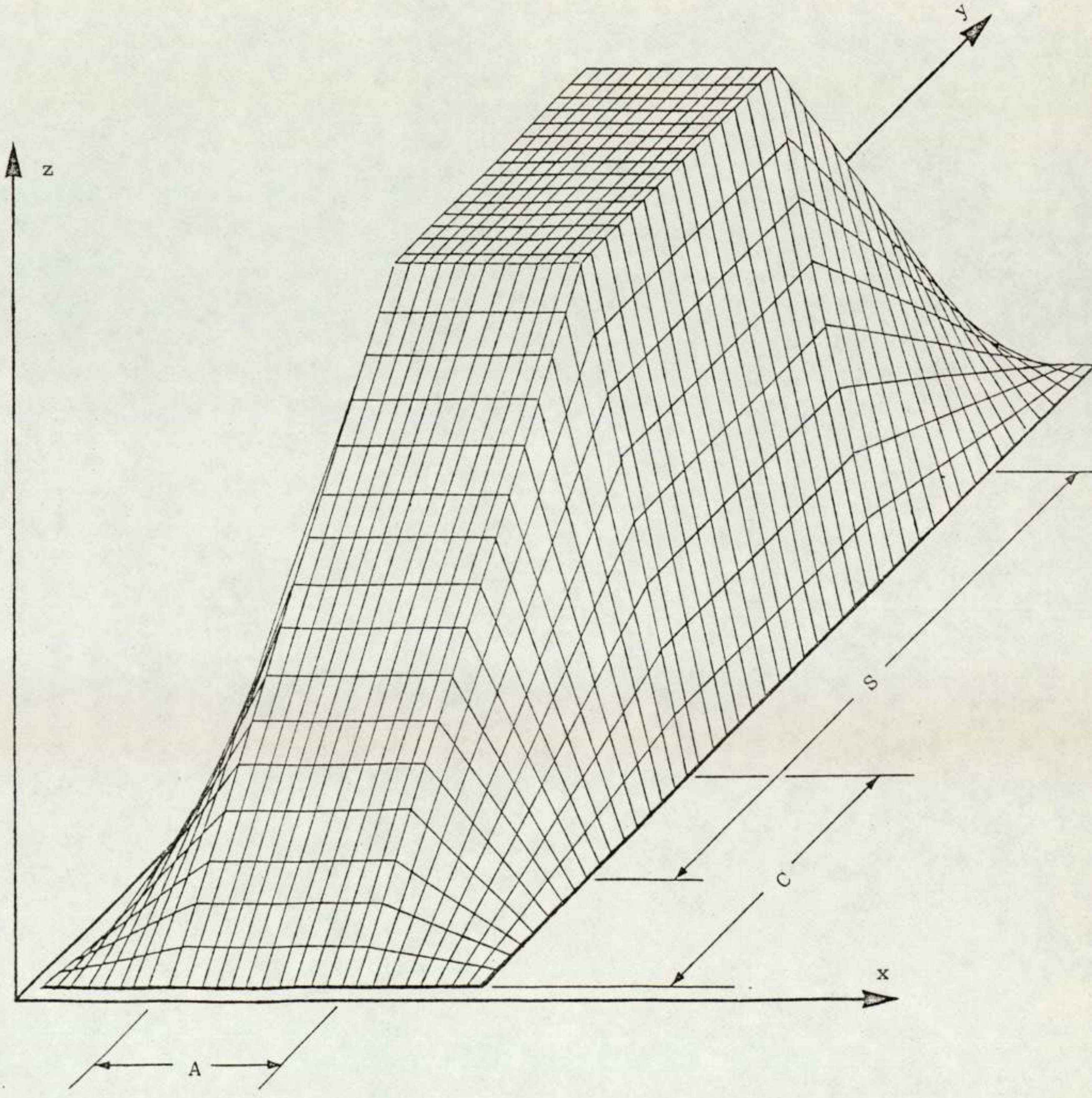
Figure 5.25. The Sensitivity of a Scanned Strip

$z = f_{Rt}(xy)$

Scan displacement = 2 . Projected diode pitch

= 2 . Projected array width

$S = 2.B = 2.C$



CHAPTER 6

The Automatic Surface Inspection

Prototype for VSIs

6. a) Introduction

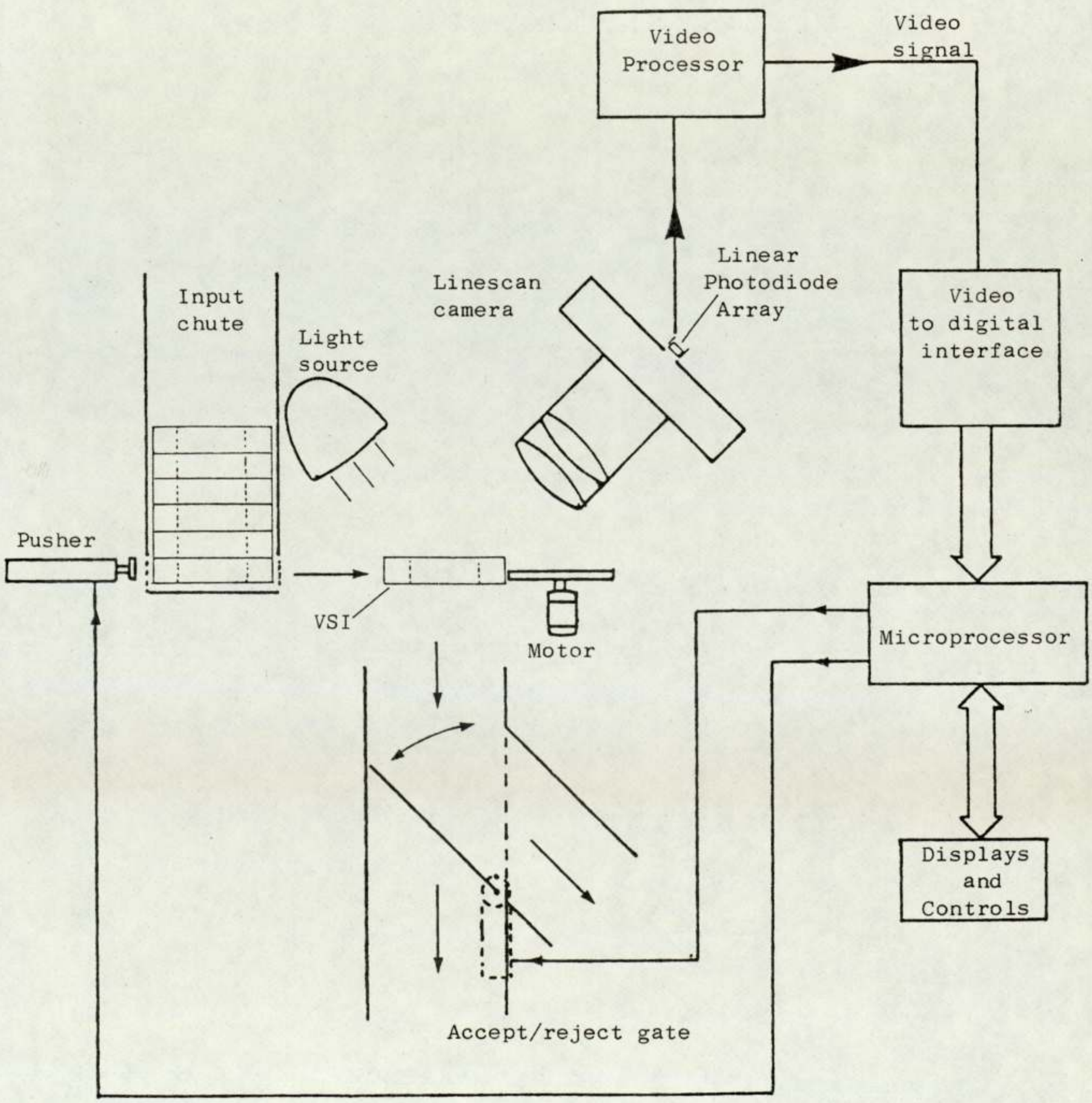
6. a) i) An Overall View of the Prototype

The prototype system consists of the elements shown in Figure 6.1 and Plate 6.1. The camera inspects a radial line on the uppermost horizontal facet of the annular component. The image is focussed into the phtotdiode array utilising the specularly reflected light from the bright source. In scanning the line indicated in Plate 6.2a, the array and video processor produce a waveform, as shown in Plate 6.3a.

The first stage of video to digital processing produces a "squared video", Plate 6.3b ; this is then combined with a clock pulse train giving the trace in Plate 6.3c. The number of pulses corresponds to the number of bright diodes in a scan ; these are counted and this information is passed to the microprocessor. This controls a pneumatic cylinder which feeds components from a stacked chute into the inspection position where they are rotated by means of a small electric motor. After each component is inspected, it is forced out by the next, and so on.

When a component is in position, the microprocessor accepts the data from each scan and makes a decision as to whether or not the inspected face contains a defect. As a result of this decision, a flap is activated by a solenoid, under the control of the microprocessor, to direct the component into either the accept or the reject chute. This whole cycle of operations is started by a simple press-button and can be terminated in the same way, or by a microprocessor decision. The number of rejected and accepted components is shown on a numeric

Figure 6.1. Functional Elements of the Prototype System



LED display from information stored in the microprocessor's memory.

6. a) ii) Design Criteria

Design criteria for this prototype can be classified, in general terms, as follows :

1. Experimental capability in the new technology
2. Safety
3. Cost
4. Feasibility of future requirements which are not in the mainstream of the new technology, or will not be needed for a first production unit.
5. Requirement for an appropriate and convincing demonstration.

The first four of these criteria are implicit in the techniques used for detecting defects, though these techniques might be said to have evolved through necessity rather than to have been part of any overall, pre-planned scheme.

To exemplify this statement, it can be seen that the mechanical configuration of roller bearings and motor drive on a horizontal surface (part of Figure 6.17) are implied, if not dictated by three of the constituent requirements of experimental capability. These three are :

α) Part of the component, say a radial line on the top face, must remain continuously in the field of view of the camera.

β) The component must be rotated.

γ) No movement of the component can be allowed in a direction perpendicular to the face under inspection.

Safety, cost, and experimental versatility were also implicit in the decision to use a low voltage motor with an integral gearbox. (These relationships are shown further in Section 6g, Figure 6.17).

The last design criterion, the requirement for an appropriate and convincing demonstration, was not applied until the feasibility of defect detection had been established. Defect detection can be demonstrated in a variety of ways and these can be divided into three basic levels.

<u>Demonstration Level 1.</u> The presence of a defect is shown on an oscilloscope trace.

<u>Demonstration Level 2.</u> The component is rotated and the presence or absence of a defect is shown by an appropriately coloured lamp.

<u>Demonstration Level 3.</u> The components are automatically fed into the inspection position and then directed into the appropriate chute.

The selection of the correct level is important if the demonstration is to be convincing. It was felt that Level 3 was appropriate in a traditional mechanical engineering environment, and when demonstrating a system involving technology with which those present were not familiar. Since it is considered that the impact of this demonstration is largely dependent upon mechanical handling, and since these design criteria were applied explicitly there, more detail is shown in the appropriate section, 6.g. Mechanical Handling.

6. b) Illuminating the Component

Correct illumination is one of the least tangible and most difficult aspects of this type of project. There are many factors involved, including : all the parameters related to the light source(s); the reflectance and texture of the surface under inspection, and the overall geometry. All of these are related to other areas of the system, particularly the optics.

6. b) i) Specular reflection and scattered light imaging

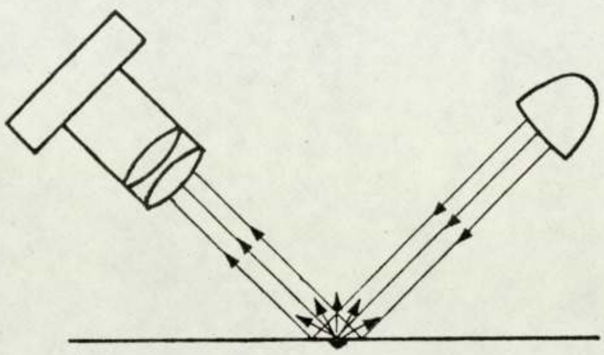
There are two distinct approaches to illuminating a "bright" metal surface in order to observe blemishes, and these are illustrated in Figure 6.2. Blemishes which are dark holes have little or no specular reflection but some light is usually scattered. In Figure 6.2a, the camera "sees" a bright surface with a dark defect (Plates 6.2a and 6.4b). When the non-specular method shown in Figure 6.2b is employed, the camera "sees" a dark surface with a bright blemish (Plates 6.2b and 6.4a). However, with the same source as before, in the latter one, the light intensity which must be detected is much lower since the radiance of the blemish is the same in each case. The non-specular approach was not pursued, since scratches and edge notches on the components reflect light towards the camera, producing spurious defect signals, often of very large magnitude.

6. b) ii) The prototype light source

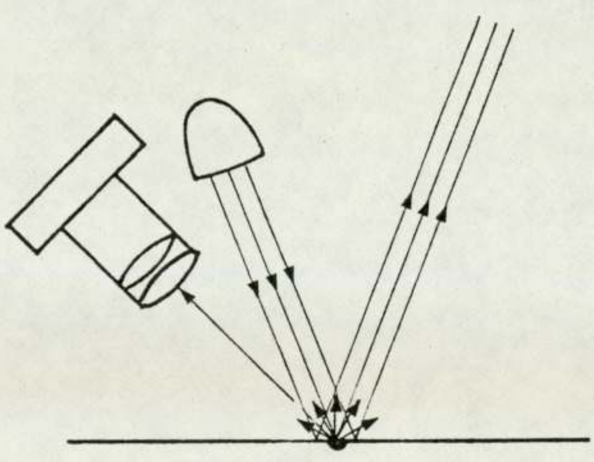
The light source used for the oscillographs shown in this chapter was adapted from a photographic slide projector condenser system, the major modification being the addition of a diffusing screen. The 100W tungsten halogen lamp was focussed at the optical centre of the imaging lens after reflection from the surface (Figure 6.3).

The lamp produced a great deal of heat in this confined housing,

Figure 6.2. Two Methods of Illumination

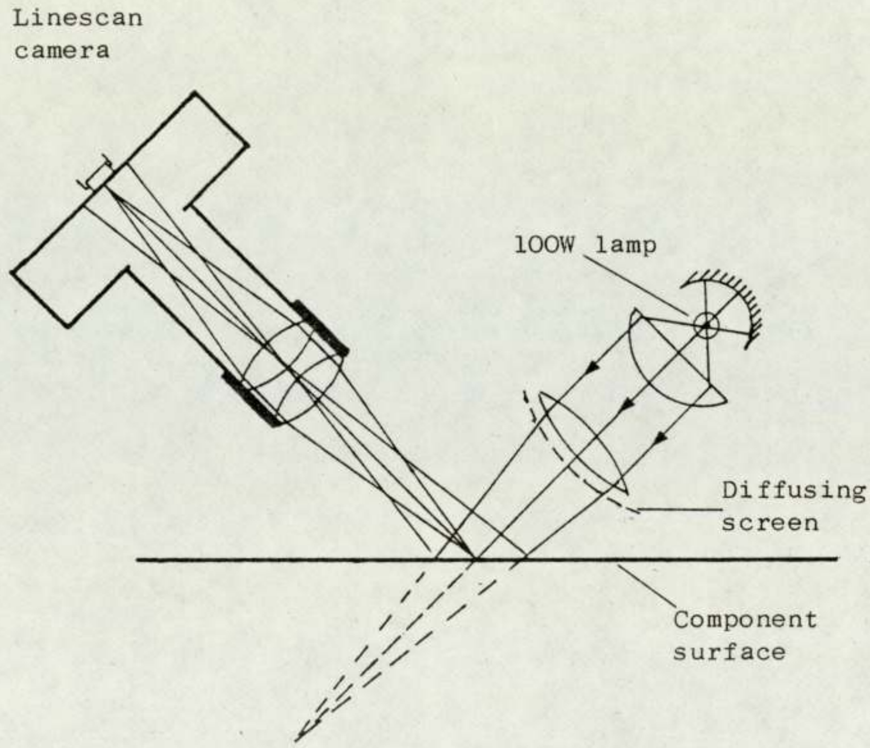


(a) The specular reflection from the bright surface is detected



(b) The scattered light from a non-reflective defect is detected.

Figure 6.3. Light Source and Camera Arrangement used to produce Oscillographs (unless otherwise stated)



and was cooled by a flow of filtered air from a compressed air supply.

The angles of the principal axes of the lens and light with the normal to the surface should be the same. The value in this case was determined by the physical size of the apparatus as the distance between the light source and object was deliberately minimised, and the lens to object distance was also necessarily small.

The 12v lamp was under-run from an adjustabled DC power supply in order to facilitate variations in radiant flux output. Under-running the lamp also prolongs its life considerably. Alternating current sources can be used, but these produce a characteristic 100 Hz. ripple on the video signal. This can be filtered out electronically, but is an unwelcome complication. This AC ripple may be as much as 20 per cent for a household tungsten lamp, but it is much less for lamps with filaments of higher thermal inertia, such as tungsten halogen projector lamps.

The spectral distribution of the radiation from a tungsten lamp is well-suited to the spectral response of silicon photodiodes. Unfortunately, the maxima of both these parameters are in the near infra-red, which produces most crosstalk in the array. This can be reduced by using an infra-red cut-off filter, but at the expense of sacrificing 80 per cent of the radiant flux. This technique was not employed as crosstalk has not been a problem. This is evident from Plate 6.5 which shows two almost identical video signals, one with an infra-red filter and the other without.

The front of the light source was as close as possible to the surface under inspection to ensure that light from surface irregularities such as scratches would always be collected by the lens, and not give dark spikes in the video signal. Figure 6.4 indicates how this can occur, and Plates 6.7a and 6.6 show video traces of the same part of a component with large and small light source apertures respectively. Plate 6.6. also shows the curved "valley floor" due to a vignetting effect caused by the high radiance of the source along its axis. The negative voltage, bright part of the video signal can be regarded for descriptive purposes as a "valley".

The predecessor of the above source, which was used in the prototype, consisted of the same type of lamp at the focus of a paraboloidal reflector, and behind a 4cm diameter circular diffusing screen (see Figure 6.5). This source gave a slightly curved video valley floor but otherwise performed well.

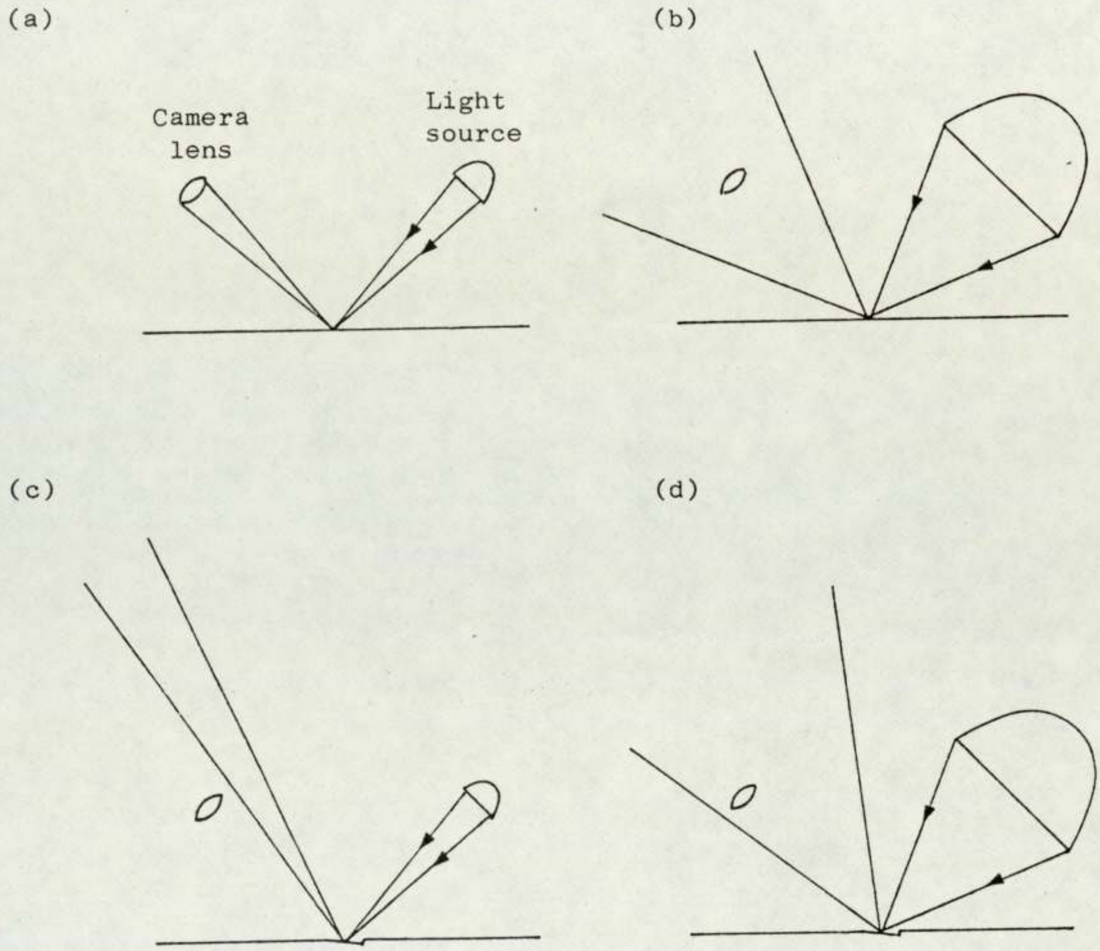
It is also evident from Figure 6.4c that a larger aperture lens would collect more light from surface irregularities when using a small light source. The result of this is that lens apertures cannot be used to control the sensor irradiance in the normal way without modifying the sensitivity to surface texture (39).

6. b) iii) Through-the-Lens Illuminations

An alternative method of illuminating the surface was investigated and this was to project the light through the imaging lens, as in a metallurgical microscope.

Figure 6.6 shows the arrange,emt which produced receptor irrad-

Figure 6.4. Illustration of Lighting Technique; indicates the reason for maximising the solid angle subtended at the surface by the light source



With the small source, the lens does not collect light from surface irregularities which therefore appear dark.

Figure 6.5. Prototype Light Source

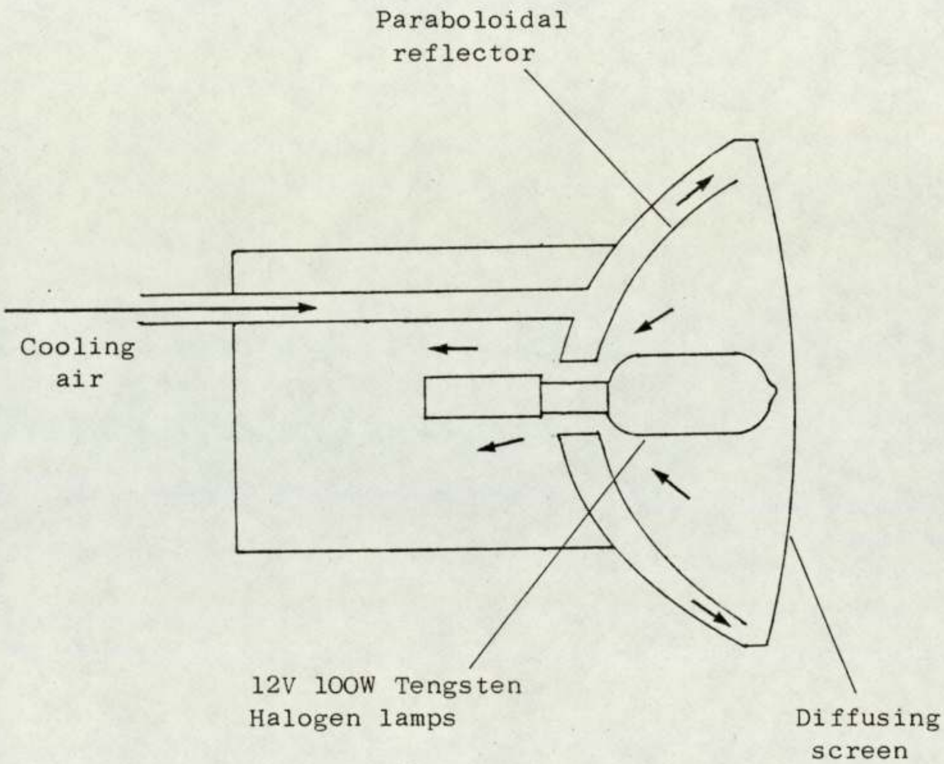
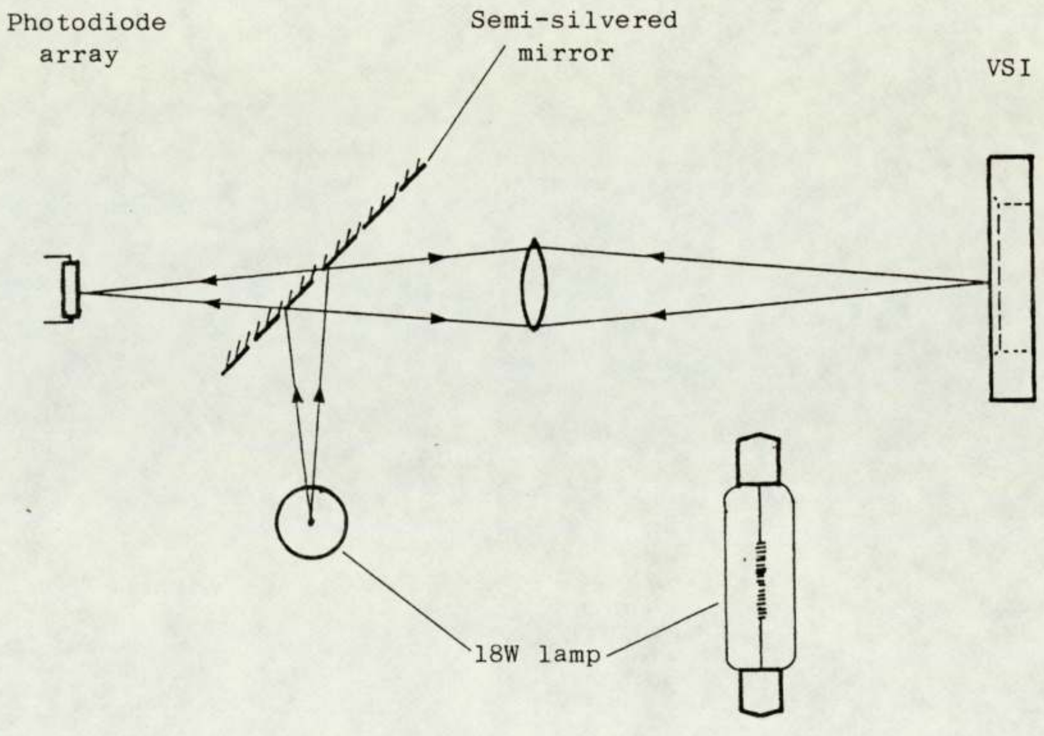


Figure 6.6: Through the Lens Illumination



iance with a small 18w lamp which was experimentally useful though inadequate practically in this application. The image of the lamp was focussed onto the component surface. The lamp must have a sufficiently long filament to illuminate the whole of the projected array. If focus is sharp, the image of the filament can be seen in the video signal. The optimum reflectance of the 45^{o} semi-silvered mirror is 50 per cent, assuming no losses.

Surface texture was more pronounced in the video signal than with the diffuse source, and was highly dependent on aperture. Heat from the lamp within the camera housing was a problem which increased with more powerful lamps. A condenser system would be required, with optics matched in aperture and focal length to those of the imaging lens in order to produce sufficient illumination for this application. In view of the above, this approach was forsaken in favour of the large diffuse source method.

6. b) iv) Factors necessitating High Lamp Power, particularly Magnification

The relationships between the major factors leading to the requirement for a powerful lamp are shown in Figure 6.7.

An important factor is that image irradiance is reduced by increasing magnification. Image irradiance is given by the following expression, which is shown graphically in Figure 6.8.

$$\text{Image Irradiance} = \frac{R\pi T}{4.fNo.^2(1+m)^2} \qquad (W.m^{-2})$$

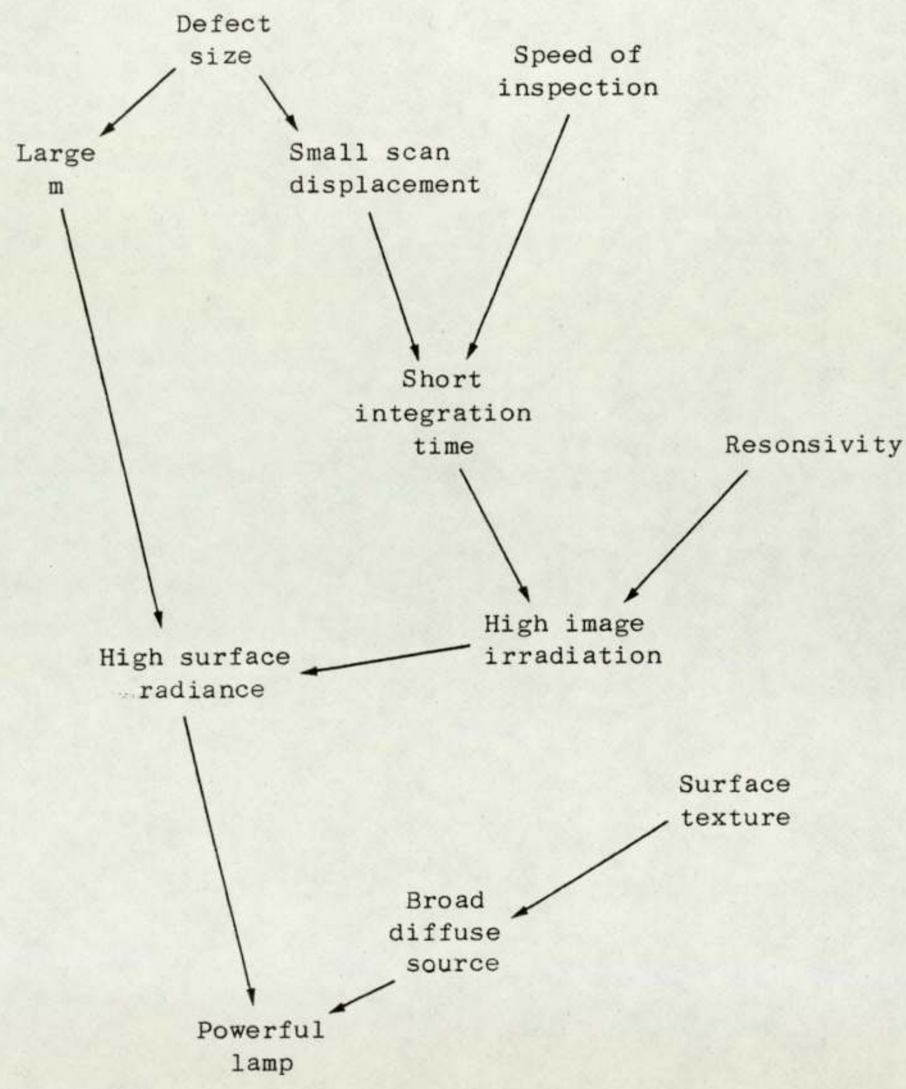
where R = object radiance ($W.m^{-2}Sr^{-1}$)

T = Transmission of lens ≈ 0.9

fNo = Relative Aperture

m = magnification (40)

Figure 6.7. The Relationships of the Major Factors Leading to the Requirement for a Powerful Lamp



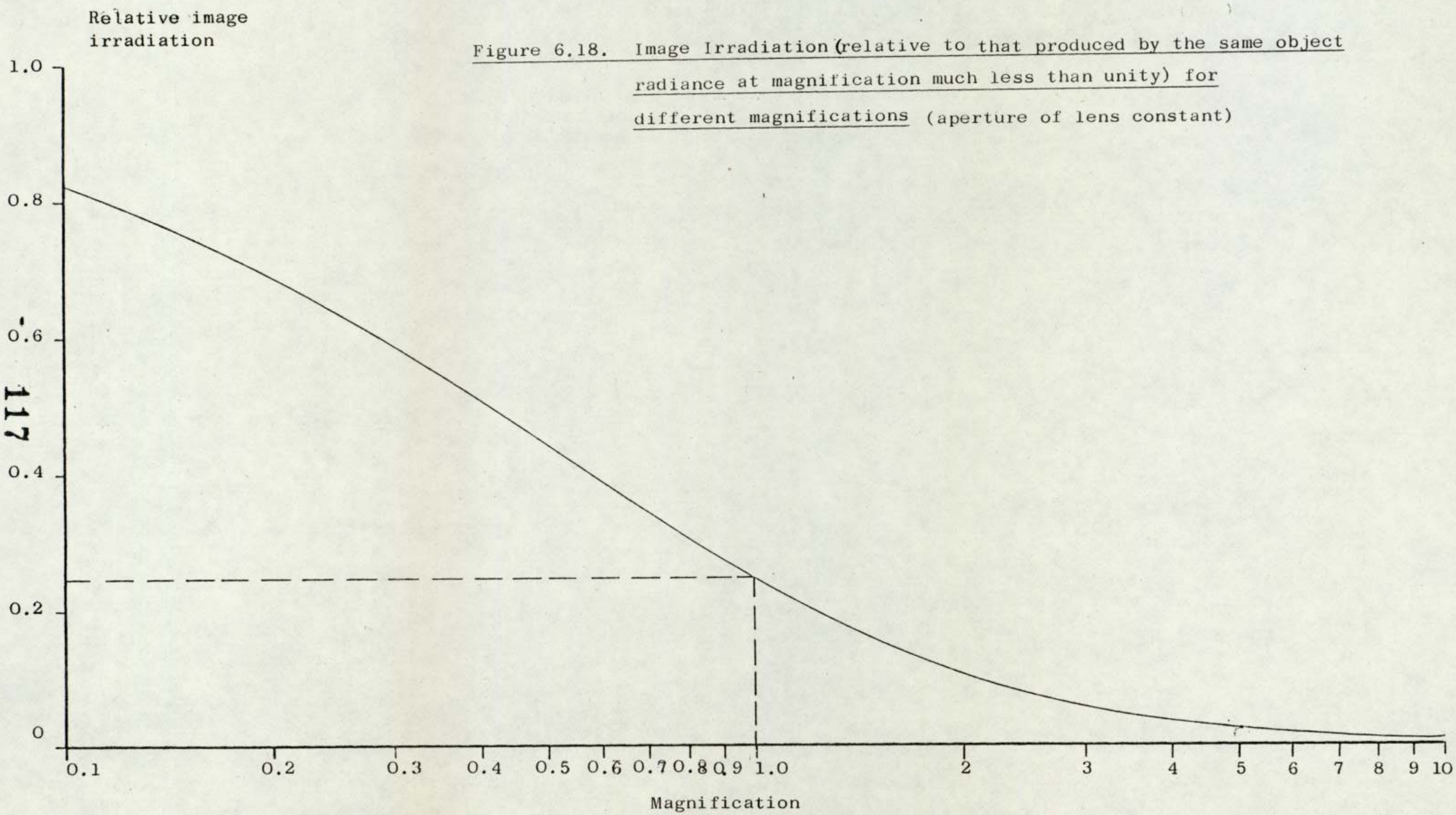


Figure 6.18. Image Irradiation (relative to that produced by the same object radiance at magnification much less than unity) for different magnifications (aperture of lens constant)

It is evident from this equation and from Figure 6.8 that image irradiance at unity magnification has approximately one quarter of its value where magnification is small ($m \ll 1$).

An equivalent statement of this is that the relative aperture (fNo) of a lens is increased at high magnification, e.g. fNo of a nominally f/2.8 lens at magnification of unity is f/5.6. This doubling of relative aperture effects a fourfold reduction in image irradiance.

6. c) The Optical System

Generally speaking, standard types of camera lenses are suitable for use with linear solid state arrays and are widely applied. The simple thin lens formula and magnification ratios are adequate for most calculations (Table 6.1) (41).

When using a high magnification such as 1x, a macro lens is to be preferred, but quite good results are obtainable with a standard lens and extension tube. High magnification also makes focussing critical.

The imaging lens used was a 40mm f/2.8 macro photographic lens with a standard "Pentax" or "Practica" type thread mount (1mm pitch, 42mm diameter). The lens was used largely at full aperture in order to maximise sensor irradiance. This could be increased further, if necessary, by using a larger aperture lens, but this is a costly item and the extra expense was not thought to be justifiable for the prototype.

Table 6.1. Geometrical optics formulae with illustrative ray diagram

$$\frac{1}{f} = \frac{1}{u} + \frac{1}{v} \qquad m = \frac{I}{O}$$

Thin lens formula   Magnification definition

From the above

$$\frac{I}{O} = \frac{v}{u} = m \; ; \quad v = mu$$

$$u = f(1 + \frac{1}{m})$$

where

F = First principal forces

F' = Second " "

f = focal length of lens

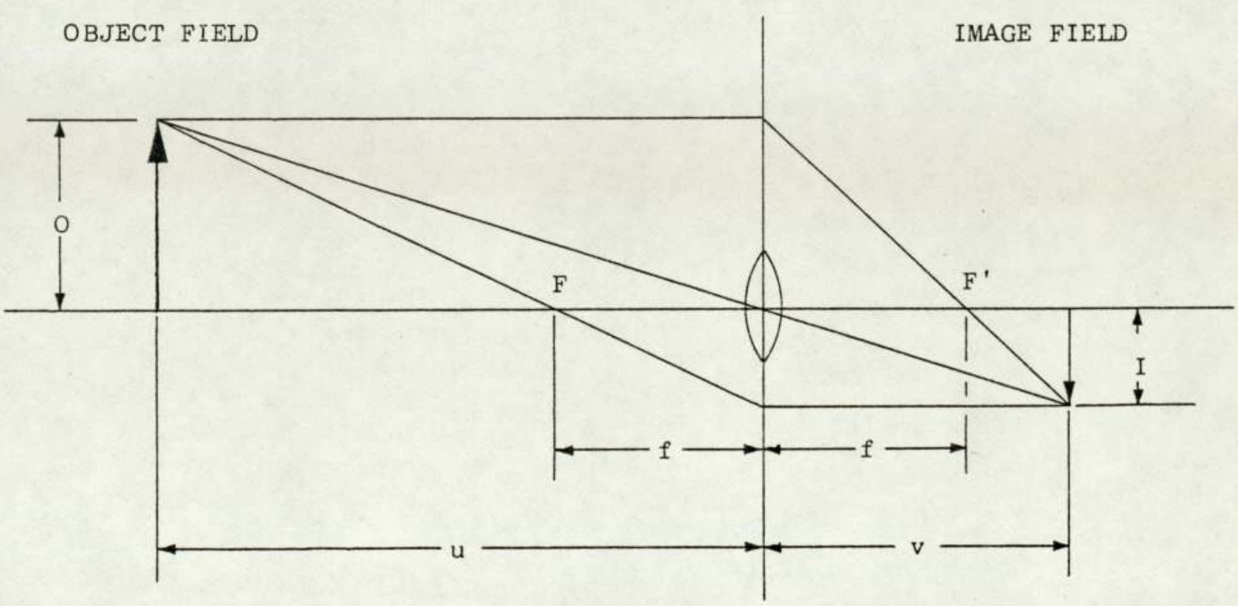
u = object distance

v = image distance

m = magnification

O = height of object

I = height of image



6. c) i) Depth of focal field

For an aberrationless lens, there is only one plane in object space : the focussed plane, from which points can be focussed to points on a plane in image space.

Depth of field refers to the region near the focussed plane from which images appear "acceptably sharp". Any point not in the focussed plane of the lens produces an image which is a circle known as the circle of confusion. If this circle is so small as to be indistinguishable from a point, then the image is "acceptably sharp" and therefore "in focus". The choice of diameter of the circle of confusion is subjective .

Depth of field is given by the formula

$$\text{Depth of field} = \frac{2.C'.fNo.(m+1)}{m^2}$$

where C' = diameter of the circle of confusion in the image

fNo = relative aperture

m = magnification (42)

Thus, for a fixed circle of confusion, depth of field can be varied only by changes in relative aperture and magnification. This yields a depth of field of 560 microns from m = 1, lens = f/5.6 and C' = 25 micron (a liberal value for circle of confusion in this instance).

There are two major implications of this very small depth of field. The first is that the position of the surface of the component under inspection must be controlled precisely. The second implication is that only one facet of the VSI can be inspected by a camera at any one time, since a much greater depth of field (up to 7mm) would be required to focus a top face, seat and base (Figure 4.1).

6. c) ii) Magnification

As a first approximation, magnification is determined by the minimum size of defect which is to be detected, and the dimensions of the elements in the array. Thus, if a defect of 100 micron diameter is to be detected and array element pitch is 25 micron, a magnification of $\frac{1}{4}$ should be used. However, magnification will have to be increased because of factors such as contrast, lens aberrations, crosstalk, and area or volume index described previously (Chapter 5) ; but magnification may be reduced if a smaller defect pulse height can be tolerated.

The method employed to determine the required magnification was to focus the camera on a minimum-sized defect and determine empirically the minimum magnification which would give a useful* defect pulse height with the component stationary ; this was found to be unity (*see Section 6dii).

6. c) iii) Component inspection time

In a dynamic situation, a photodiode may be covered by the defect image for only part of the integration time, thus reducing the defect pulse height h, Providing that at least one element is covered by the defect's image in the static case, giving a Volume Index (VI)=1, then the range of values of h in a dyanmic instance can be found using

$$h_{dynamic} = h_{static} \times VI$$

Volume Index depends on magnification, scan displacement and the position of the defect, which is random, together with other factors dicussed in Chapter 5.

Scan displacement is independent of magnification ; it depends only on the velocity of the component past the projected centre line of the array, and the integration time of the photodiodes. With an annular surface this linear velocity varies with radius. With VSIs this may produce a scan displacement at the outside edge which is 20 per cent greater than at the inside, and so the larger dimension must be used in calculations.

To be useful in a dynamic situation, the unity magnification, 100 micron defect pulse must not be reduced very much by the effects of Volume Index ; a minimum value of VI $\approx$ 0.9 is appropriate. This gives a maximum scan displacement $\approx$ 50 microns for a square or round defect 100 micron diameter, see Figure 5.23.

Table 6.2 shows that the times to inspect components of maximum and minimum diameters are of the order required in practice.

Table 6.2. The Times Required to Scan Components

Diameter	ins.	mm.	Circumference mm.	No. of scans	Time required secs.
Minimum	1.25	31.75	99.75	1995	1.05
Maximum	2.75	69.85	219.44	4389	2.32

where: scan displacement S = 50 microns
integration time t_i = 528 microseconds.

6. d) Video Processing

Video Processing in the context of this project refers to the transformation of the light patterns falling on the array into digital data, which can be used to make a quality decision by either hard wired logic or a microprocessor.

6. d) i) Production of the video signal

The video waveform (Plate 6.3a) is an electrical analogue of the irradiation of the array. This, and other similar waveforms shown, was produced using a Reticon array and video processing boards (Array RL256G, Array Board RC104, Motherboard RC100B).

The only adjustable parameters in these video circuits which it is useful to discuss here are the clock frequency and the time between the start of subsequent scans. A clock frequency of 500kH$_z$ was used which was generated on the motherboard.

The motherboard also periodically generates a pulse to start the array scanning. The interval between these pulses is the light integration time, and is a fixed number of clock periods which can be preset on the motherboard.

As sampling each photodiode takes one clock period (2 μs) the integration time of a 256 element array is $\approx$ 0.5 ms. The photodiodes actually take 256 x 2 = 512 μs, but since there is a blanking pulse at the end of each scan for eight clock periods, the total integration time is 528 μs).

The integration time, and thus scan displacement, could have been halved by operating the array at its maximum frequency of 1MHz, but this would also have involved doubling the radiant power of the light source.

Longer integration times can be obtained either by reducing the clock frequency, or by increasing the number of clock periods between the start of scan pulses. The latter has the effect of lengthening the blank period at the end of each scan.

6. d) ii) Production of the squared video system

The fundamental and widely used technique employed for this operation is to compare the video signal with a pre-set threshold. The polarity adopted yields a logical high for bright diodes (Figure 6.9); this signal is referred to as the "squared video" (Plate 6.3b).

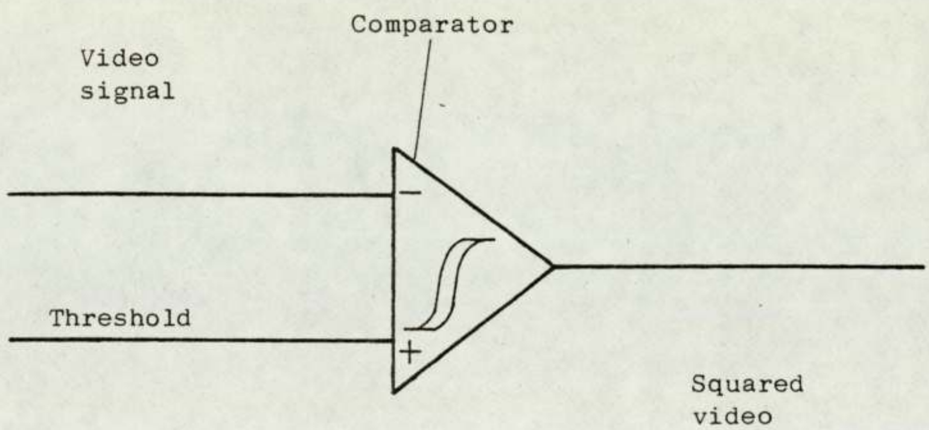
To be useful in this respect, a defect pulse must be higher than the highest expected pulse from surface texture noise. Comparators are so precise that theoretically, the threshold could be set just above the noise, say 1.1 times its value. However, in practice, in order to minimise the frequency of spurious signals from noise peaks, the threshold should be set to at least twice the value of the noise. It is essential to incorporate some hysteresis in the comparator in order to avoid the appearance of spurious pulses in the squared video when the threshold voltage coincides with that of a photodiode's output.

Any logical low pulse between the edges of the component in the squared video indicates a defect. The duration of such a pulse is a measure of the X dimension of the defect where the scan crosses it. Unfortunately, several problems arise which complicate this apparently simple process; these involve ensuring that the defect pulse, and only the defect pulse, crosses the threshold, and in defining the spatial limits of the component.

6. d) iii) Surface Texture

Despite favourable illuminations and a good optical system, the greater part of the noise in the valley of the video trace is due to the

Figure 6.9. The First Stage in Processing the Video Signal



surface texture of the component and not electrical noise or array imperfections. Plate 6.7b shows the video trace given when the VSI is replaced by a mirror and shows only the system noise.

Illuminations should be such that the brightest diodes are just saturated to achieve their full dynamic range, The threshold is set so that a pulse from a defect of the minimum size crosses it and the largest pulse caused by the surface texture does not. This is normally done with the component stationary and an allowance must be made for reduction in defect pulse height due to any difference in Volume Index in the dynamic case (Chapter 5) ; differences in surface texture between components may produce a three-fold variation in the surface texture noise in the video trace (Plate 6.7a and Plate 6.8) and this must be taken into account when setting the threshold.

6. d) iv) Average reflectance variations

The average level of the valley floor in the video signal also varies with the average reflectance of the surface. This may be 20 per cent around the circumference of a single component (Plates 6.8a and b) and the frequency of this variation is usually equal to, or double the frequency of rotation. Further, average reflectance variations of 40 per cent between components in the same batch are common. These large variations cannot be accommodated by a simple D.C. threshold, a threshold which responds sympathetically to these changes is required.

6. d) v) Sympathetic thresholds

a) Peak detector. The threshold can be set to a fixed fraction of the brightest diode voltage through the use of a peak detector. This is employed in some commercial linescan cameras (e.g. IPL camera with ALC Threshold and gating card, PC 212/12).

b) Switched filter. The valley of the video signal is low pass filtered to give an average level and the filter is switched to high pass to follow the sides of the valley (39).

c) Average filter. The whole video signal can be low pass filtered with a time constant of several integration times giving an average level. This is valid only if the valley width remains relatively constant.

The profile of the valley floor may be curved due to the radiance of the light source being higher along its axis; Plate 6.6 shows an extreme example. (This curvature increases with array length). If the curvature is significant, a horizontal threshold is inadequate, and one which follows the video valley profile is necessary. The switched filter threshold (b) described above will fulfill this function, though the switching is complicated by the following.: due to dimensional tolerances, the most significant being concentricity, in the components the width of the video valley varies with a frequency the same as that of the rotation. Consequently, the switching of the filter must follow the valley sides. The variation in valley width is not large (typically 5 per cent), but this is sufficient to make switching at the edges difficult. With the lighting arrangement of the prototype, curvature of the valley bottom was not significant (Plate 6.7b) and so a horizontal threshold could be employed. The averaging filter threshold was used as the 5 per cent variation in this value, due to valley width, could be easily tolerated.

6. d) vi) Counting the bright photodiodes

The next stage of processing used is to count the number of bright diodes on each scan. In order to achieve this, the squared video signal is logically ANDed with a clock pulse train from the video motherboard (Plate 6.3c). The number of pulses in the resultant signal is equal to the number of bright diodes and this is counted at the end of each scan (Figure 6.10). A more complex alternative using similar techniques is to produce a count representing the position of each transition of the squared video ; there is more data produced per scan, which can be used for more complex analysis of defects (43).

6. e) Strategies for Defect Detection

The objective of the processing is to produce a simple "accept" or "reject" signal for each component. There are several strategies which can be employed to extract the relevant information from the digital data in order to produce such a signal. Five of these strategies are outlined in Table 6.3, approximately in order of increasing hardware complexity.

The strategies were developed chronologically in the order in Table 6.3 since it was found that as each was developed, there were particular defects which would not be detected. In order to remedy the difficulties in earlier strategies, more complex ones were needed.

Given the squared video, it is clear that any dark diodes, logical low, in the logical high region, indicate a defect. The first approach to this was to restrict thresholding to the logical high region by strobing the comparator with a gate pulse set to the same width as the logical high regions (Figure 6.11).

The width of the logical high pulse in the squared video represents the width of the component's flat surface where the scan crosses it.

Figure 6.10. The Second Stage in Processing the Video Signal : counting the bright diodes used in Strategies 3, 4 and 5

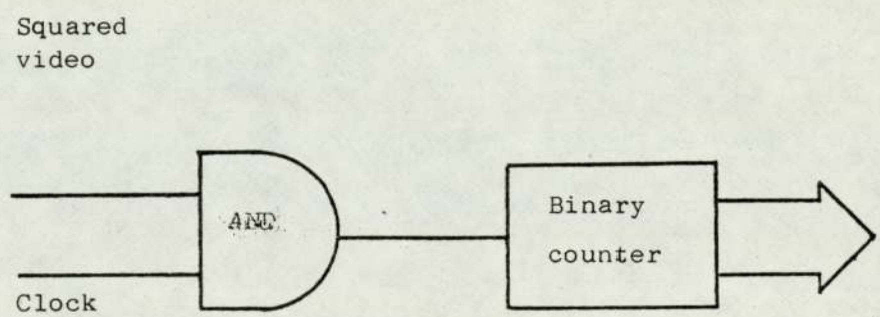


Table 6.3. Defect Detection Strategies

Strategy 1.

A logical low pulse in a fixed region of the squared video is sought, its presence indicates a defect. Figures 6.10 and 6.16b.

Strategy 2.

The number of low to high transitions during each scan in the squared video is counted ; a count greater than 1 indicates the presence of a defect or defects. Figures 6.12 and 6.16c.

Strategy 3.

The number of bright diodes in each scan is counted ; if the number is less than a pre-set minimum, then a defect is indicated.

Figures 6.10 and 6.16d.

Strategy 4.

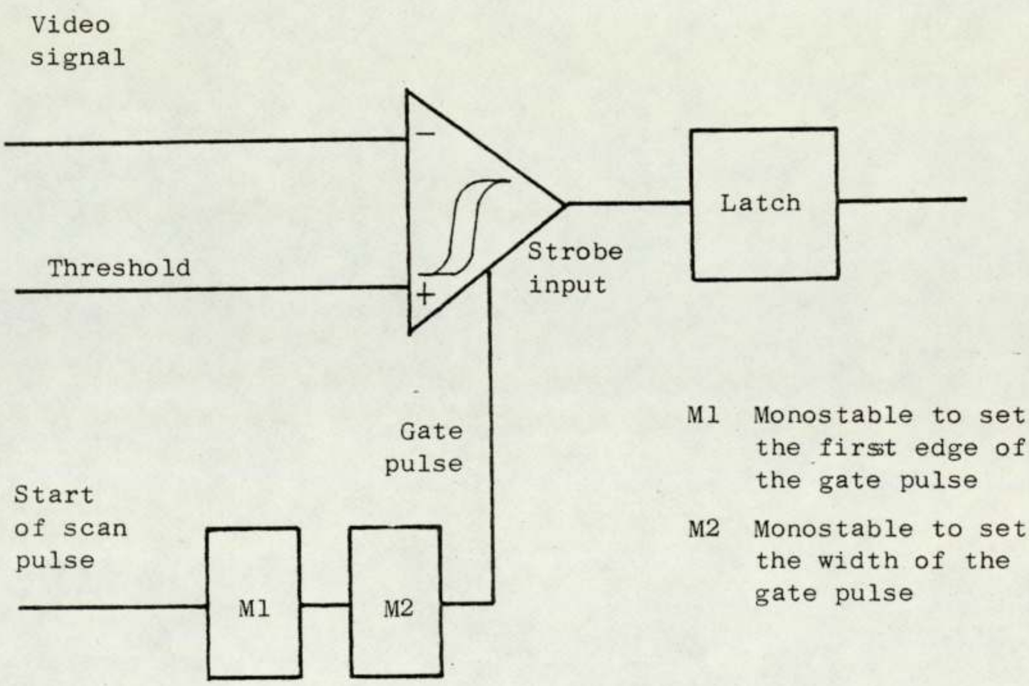
The number of bright diodes in each scan is counted ; if this number changes by more than a pre-set maximum, then a defect is indicated.

Figures 6.10 and 6.16e.

Strategy 5.

The number of bright diodes in each scan is counted and averaged over several scans ; the next number is compared with this average. A difference of more than a pre-set maximum indicates the presence of a defect. Figures 6.10 and 6.16f.

Figure 6.11. Video Signal Processing used in Strategy 1

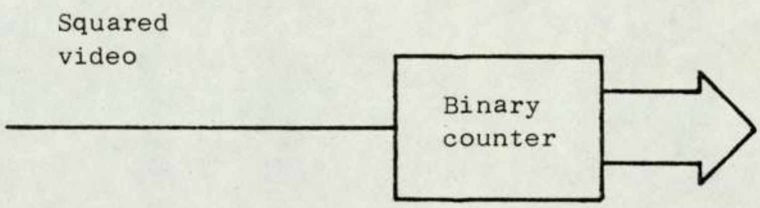


This width may vary by 250 microns round the circumference of a component, and by more than this between components in the same batch. The gate pulse must be "narrower" than the narrowest pulse in the squared video, otherwise the edges of the component will yield defect signals. Therefore, Strategy 1 will not detect small defects up to 250 microns, well above the 100 micron criterion, if they are close to the edges of the component. Defects close to the edge of a facet are considered by customers to be as important as elsewhere, and in some cases more so.

Strategy 2 overcomes this problem partially by searching for any threshold breaking defect providing it is separated from the edge of the component by some bright metal (Figure 6.12). A defect, however, large, on the edge of a facet will result in the squared video pulse becoming narrower, and Strategy 2 cannot detect this. To detect this type of defect, the number of bright diodes in a scan is counted ; this number is reduced when the squared video pulse becomes narrower. Strategies 3, 4 and 5 all utilise this count. Strategy 3 simply indicates a defect if the bright diode count falls below a pre-set number ; this number necessarily represents the minimum width which will be encountered. This strategy will therefore miss any defect up to 250 microns wide. This difficulty is effectively remedied by comparing each bright diode count to a number which varies in sympathy with dimensional variations. Defects change for this bright diode count quickly within a few scans ; whereas acceptable dimensional variations can cause larger changes, but more slowly over thousands of scans.

Strategy 4 subtracts each count from the preceding one ; the difference indicates any rapid change which will be a defect rather than

Figure 6.12. Second Stage of Processing the Video Signal used in Strategy 2



a dimensional variation. Strategy 5 is similar but compares each count to the average over several previous scans. The number of scans over which this average is taken (effectively 1 in Strategy 4), together with the allowed deviation from the average (minimum 2) determine the rate of change in the count which will be detected as defects. A change of at least one diode count from the average must be allowed as there is a continual change of one count due to uncertainty at the edges of the component.

Table 6.4 summarises the characteristics of the five strategies ; it is evident that by employing both strategies 2 and 5, the only defect which would escape detection is one which causes a change of only one diode count and is also joined to the edge of the component. If Strategy 5 alone is used, any defect causing two or more diodes to cross the threshold will be detected.

6. f) Microprocessor

For several reasons a microprocessor was introduced into the system. The prime motivations were to facilitate strategies for isolating defect signals from other variations in the digital data, and to facilitate the storage of data from large numbers of scans in a dynamic situation for subsequent examination at leisure. The microprocessor is also used to control mechanical handling, record numbers of accepted and rejected components, and has potential to cope with future developments.

6. f) i) Hardware

The microprocessor used was an Intel 8085 incorporated on an

	Strategies				
	1	2	3	4	5
No. of diodes required to break the threshold for detection	1 if within gate pulse ($\Rightarrow$ up to 10 at the edge)	1 except if it is wholly connected to an edge, in which case it will not be sensed however large it is	1 or 2 at the minimum radial thickness 10 at the maximum radial thickness	1 greater than the no-defect change between scans which is normally 1. Change must occur between one scan and the next	1 greater than the no-defect change between a scan and the average: normally 1. Change can occur over several scans
Detects excess dimensional errors	yes	no	yes	no	no
Accurate register of component and array	yes	no	no	no	no
Adjustments required for each part no.	Set position and width of gate pulse	None	Minimum no. of bright diodes	Maximum acceptable difference between consecutive scans	No. of scans to average, maximum acceptable difference from average
Fraction of available time used (tine/528μs)	< 0.002 hardware	< 0.002 hardware	< 0.002 hardware	0.17 software	0.60 software
Could be performed with electronic hardware	Very straightforward	Very straightforward	Straightforward	Complex	Very complex

Table 6.4. Characteristics of Defect Detection Strategies

SDK 85 (System Development Kit) (44, 45). The architecture of the SDK 85 as enhanced for use in the prototype is shown in Figure 6.14. Once the idiosyncrasies of the development system have been established it can readily be interfaced to external devices and its memory expanded. Non-volatile memory was added as shown in Figure 6.13 and buffered inputs and outputs, as shown in Figure 6.14.

6. f) ii) Software

The initial programme used to demonstrate the system made a quality decision on one face of a VSI and displayed the numbers of accepted and rejected parts. This was developed on the SDK 85 board using the hexadecimal keyboard, and although a very simple strategy (no. 3) was used, the programme filled the $\frac{1}{2}$K of R.A.M. memory.

To facilitate more practical strategies, programmes were subsequently developed using assembly language on an "Intellec Series II Microcomputer Development System" with "Isis II Operating System". These were used with an Intel "Universal PROM Programmer" to programme the EPROM. (2716 Type UV Erasable Programmable Read Only Memory).

Flowcharts of the programs which operate the prototype, including the defect isolation strategies, are shown in Figure 6.15. A flowchart is also included of a development program which can be used to examine scan count in dynamic situations.

Figure 6.13. Architecture of the Microprocessor System Design Kit as used in the Prototype

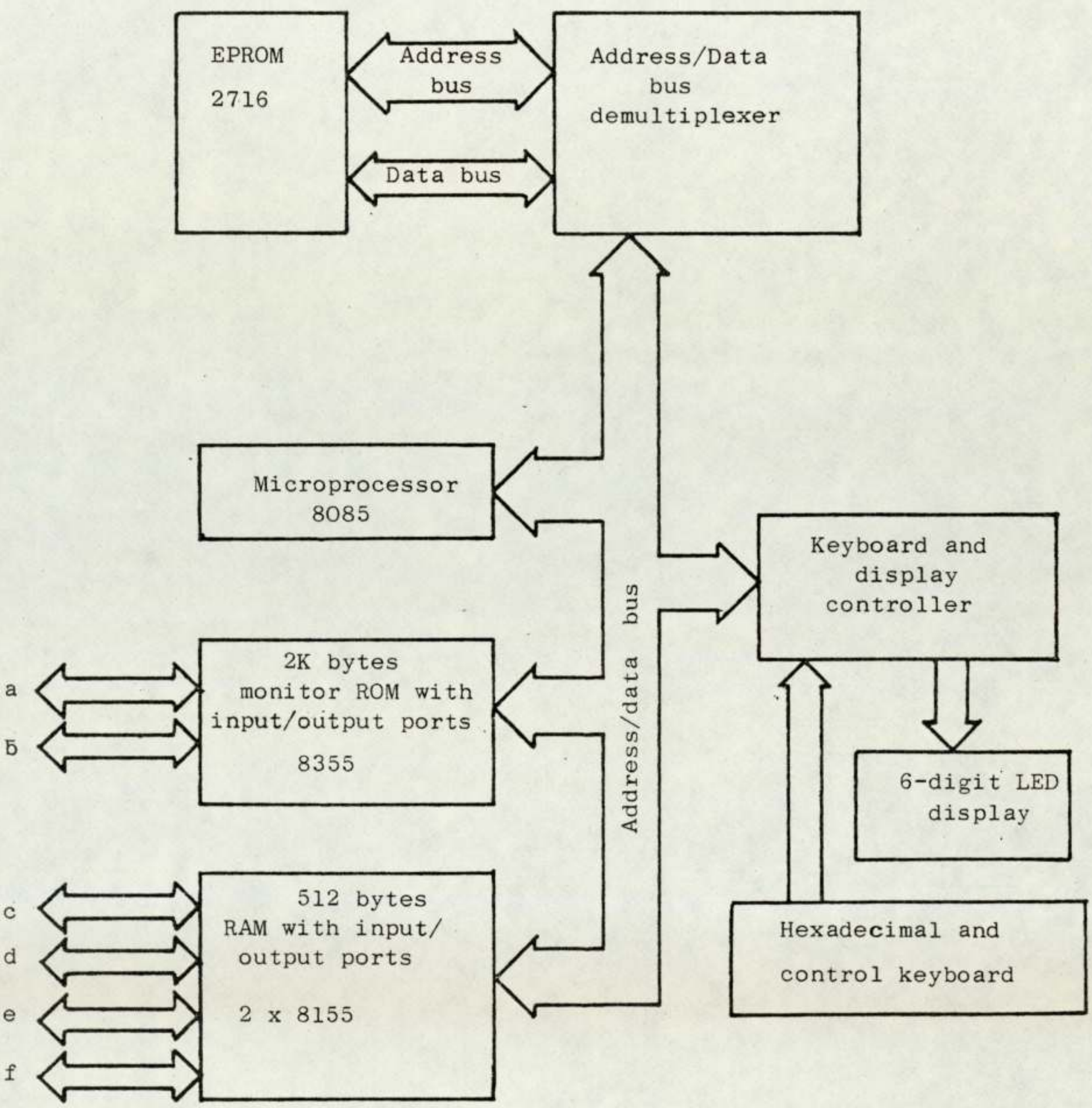


Figure 6.14. Inputs and Outputs to and from the Microcomputer

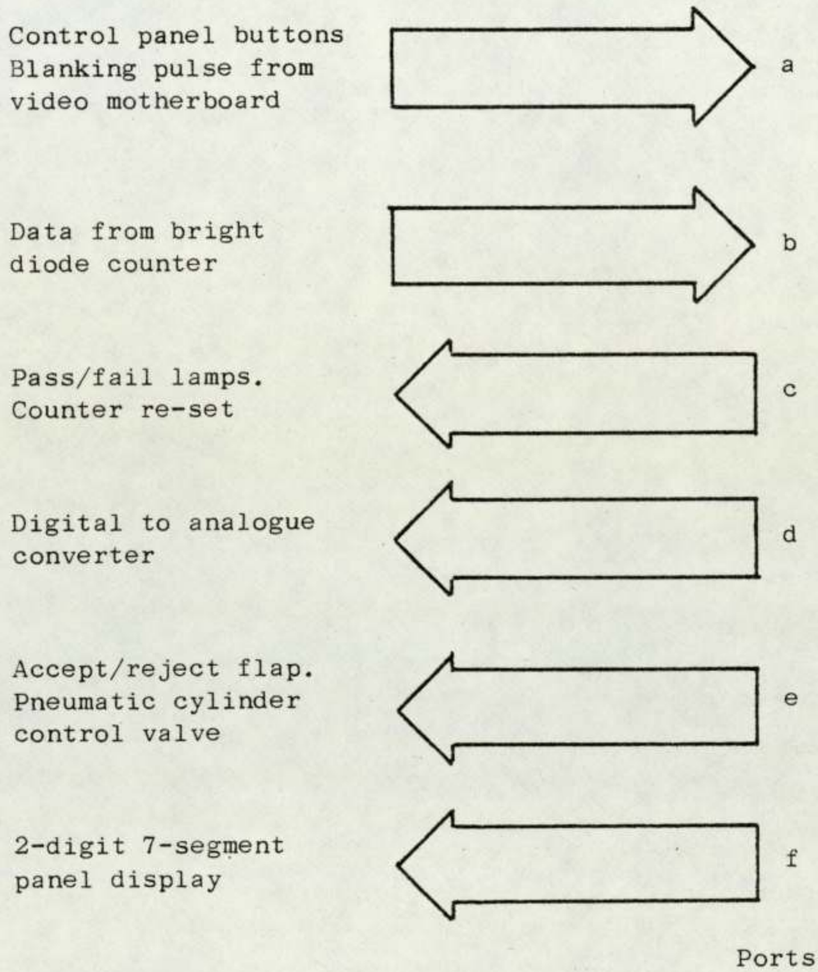


Figure 6.15a. Flow Chart for Operation of the Prototype.
Read in conjunction with flow charts for
Strategies 1 to 5.

x = no. of scans round one circumference + 8 (for Strategy 5) + a margin for mechanical error

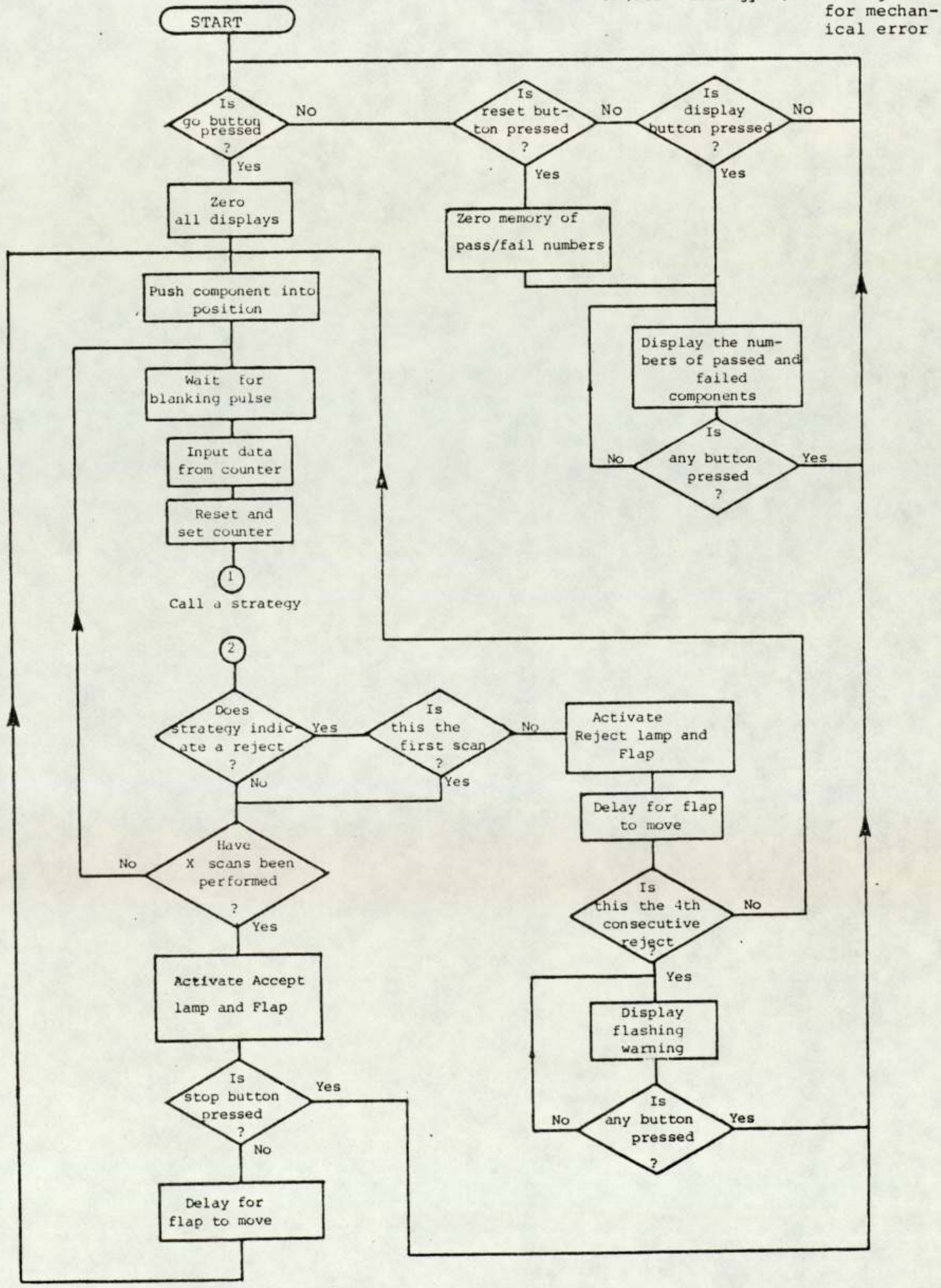


Figure 6.15. Flow Charts for Defect Detection Strategies

STRATEGY 1

STRATEGY 2

STRATEGY 3

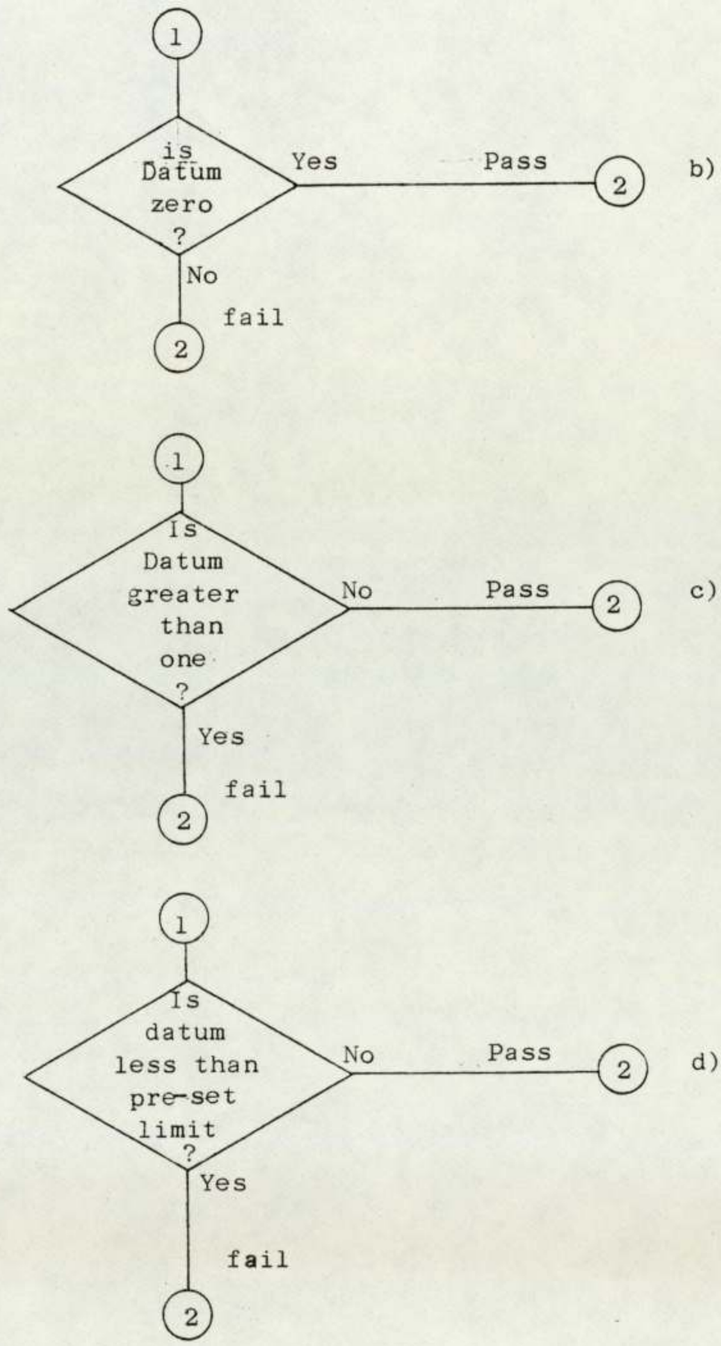


Figure 6.15.e. Flow Chart for Defect Detection Strategy 4

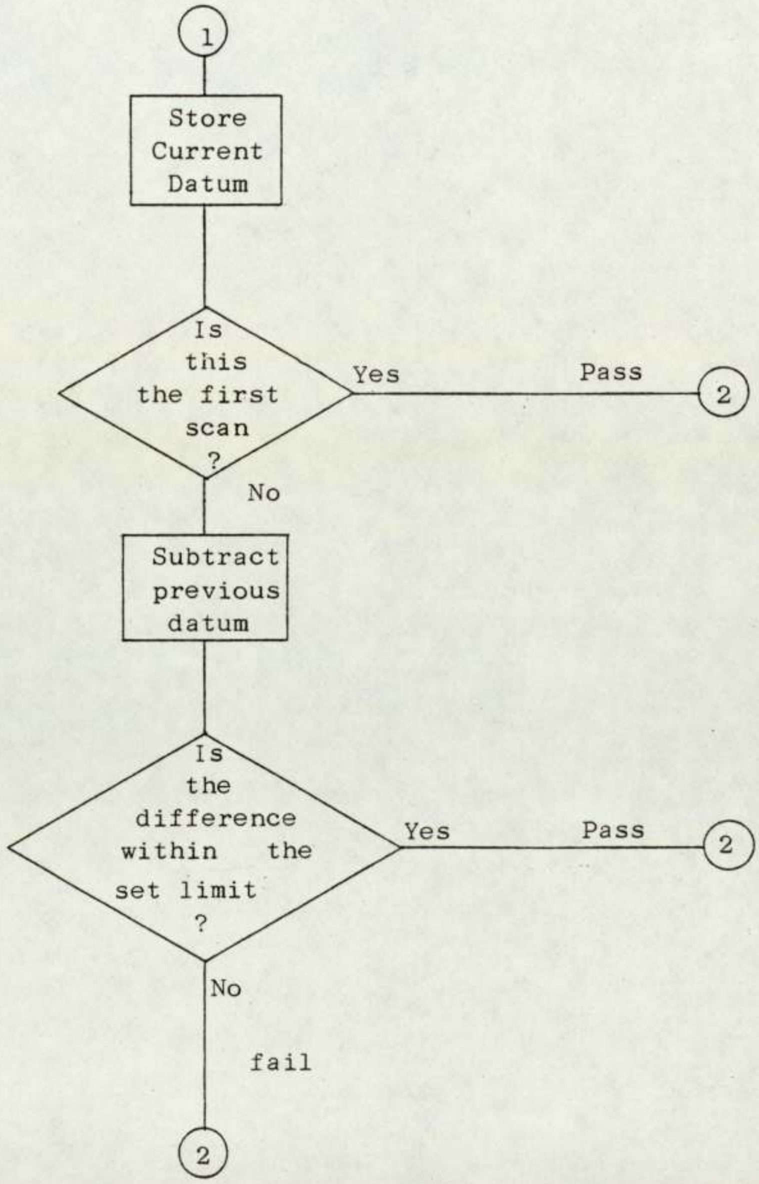


Figure 6.15.f. Flow Chart for Defect Detection Strategy 5

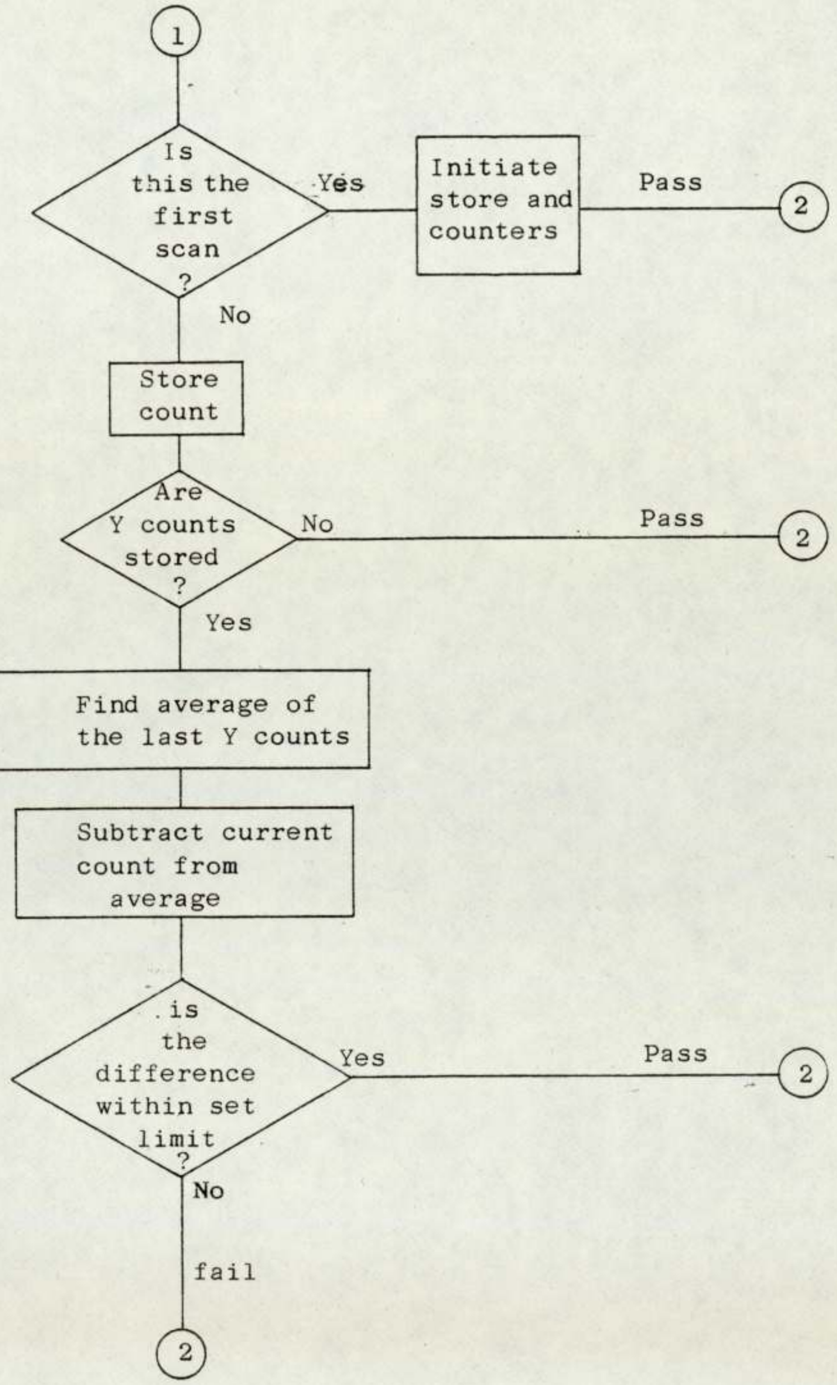
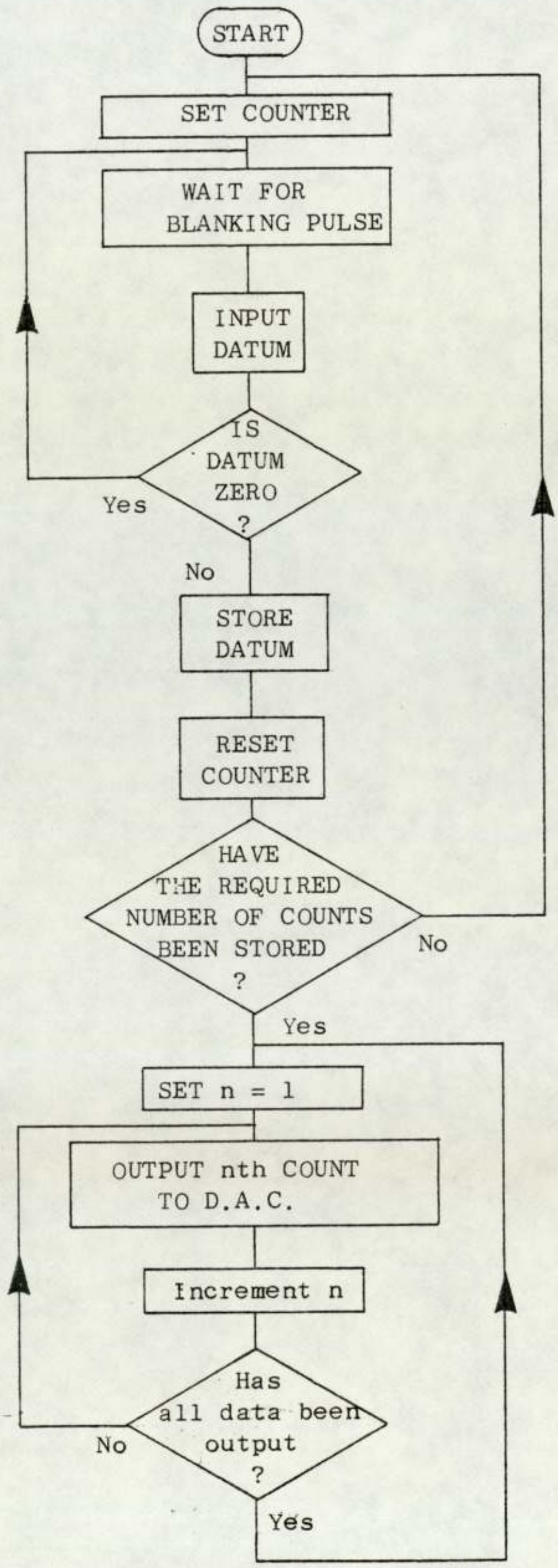


Figure 6.15.g. Flow Chart for Development Program "LOADIS"

This program stores 256 bytes of data and outputs them continuously to a digital analogue converter D.A.C. for display on an oscilloscope.



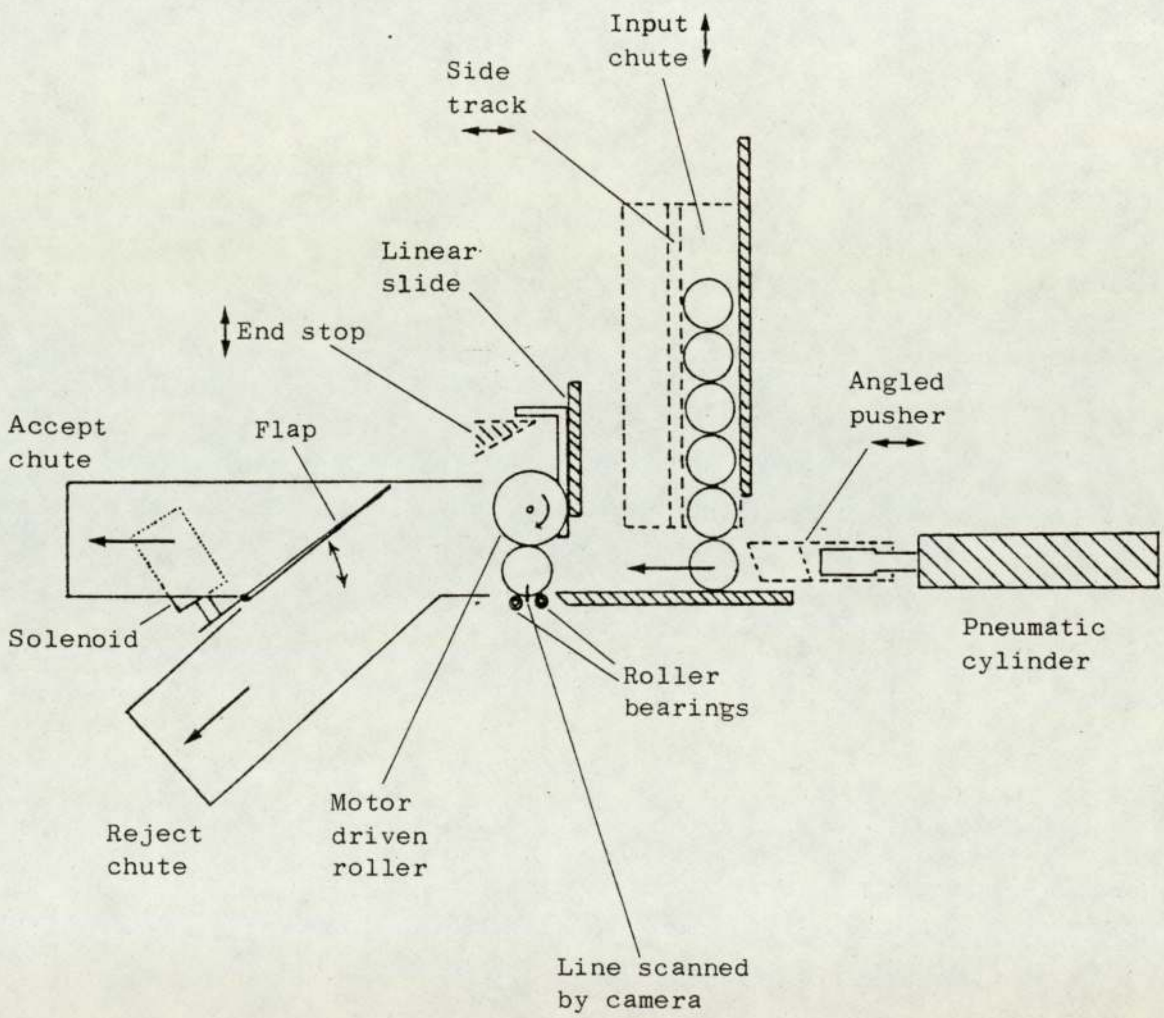
6. g) Mechanical Hardware

The prototype mechanical hardware consists of : the mechanical handling equipment, camera and light mounts, and an enclosure for the electronic circuitry (Plate 6.1). The main features of the mechanical handling system are shown in Figure 6.16.

Since each facet of the mechanical hardware was derived from several of the design criteria (Section 6aii) it is explanatory to show the inter-relationships diagrammatically (Figure 6.17).

The resulting prototype was a functional unit which required very few adjustments for different sized VSIs and has a component change-over time of $\approx$ 0.5 seconds. The electronic control and processing unit had an easily operated control and display panel, but was otherwise completely enclosed.

Figure 6.16. Simplified Plan View of the Prototype Mechanical Handling System



------ Indicates a part which must be adjusted to accommodate different sized components

↔ Indicates direction of adjustment

Figure 6.17. Illustration of the Major Effects of the Design Criteria on the Design of Prototype Mechanical Hardware

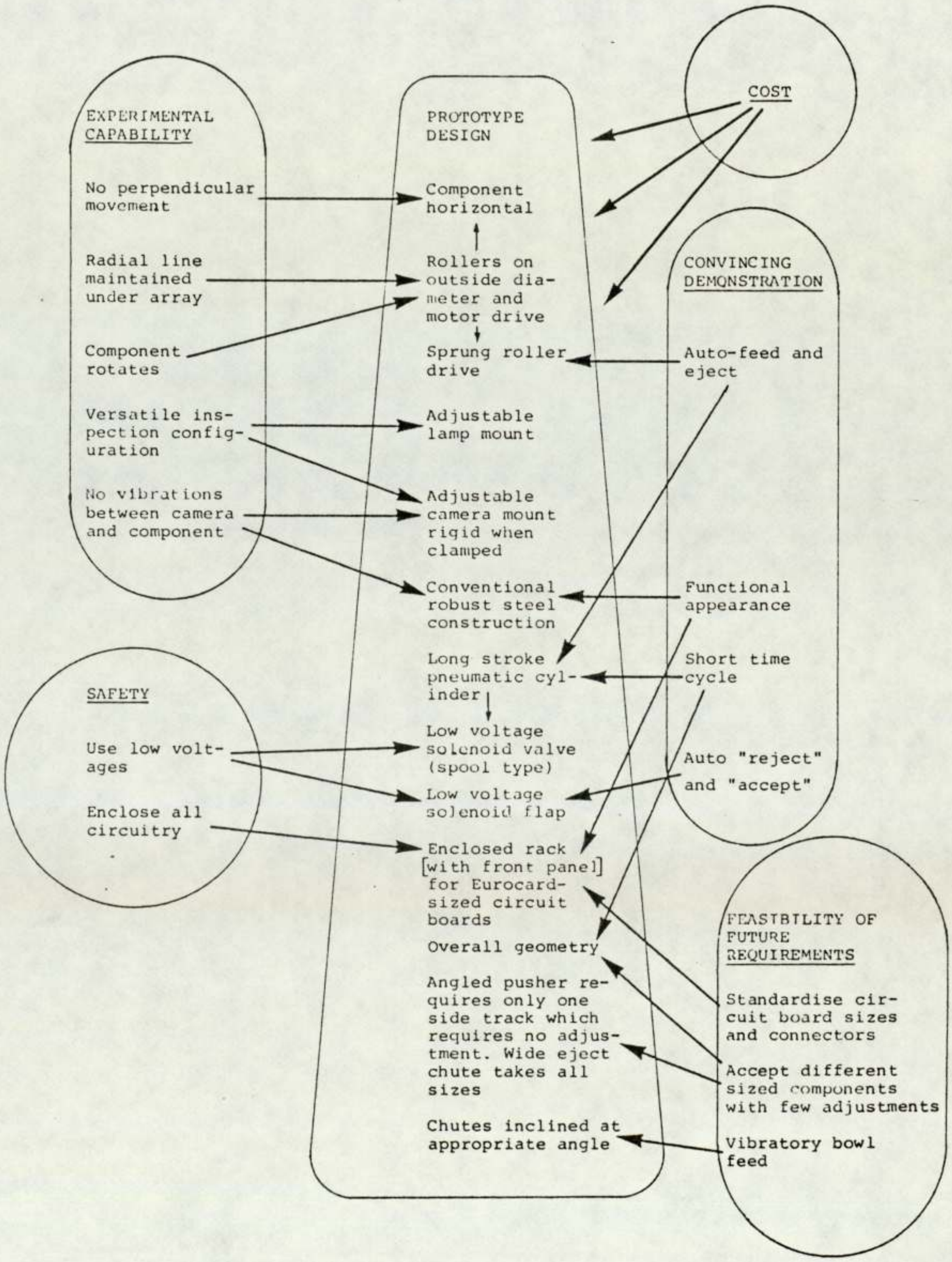
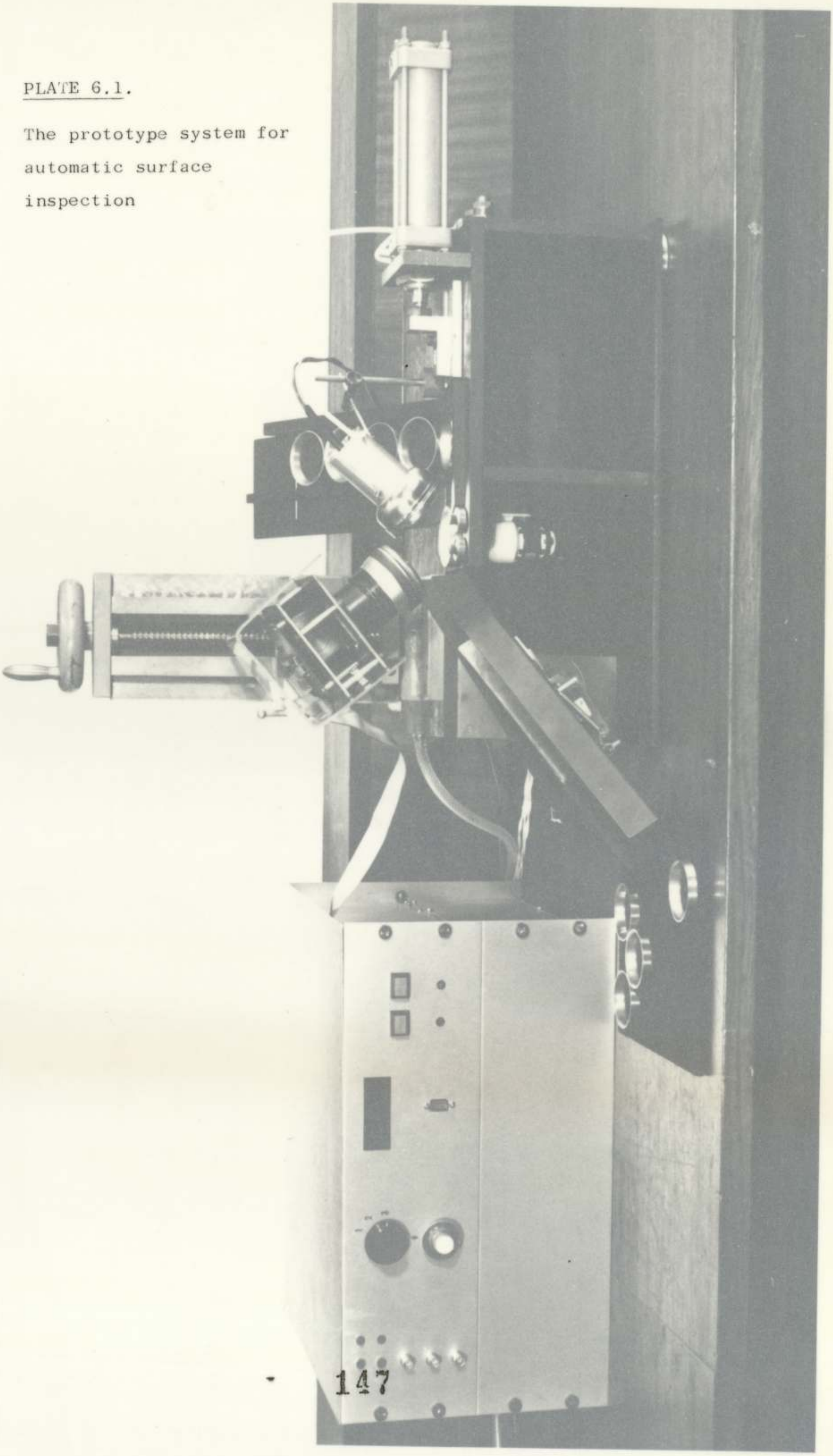


PLATE 6.1.

The prototype system for automatic surface inspection



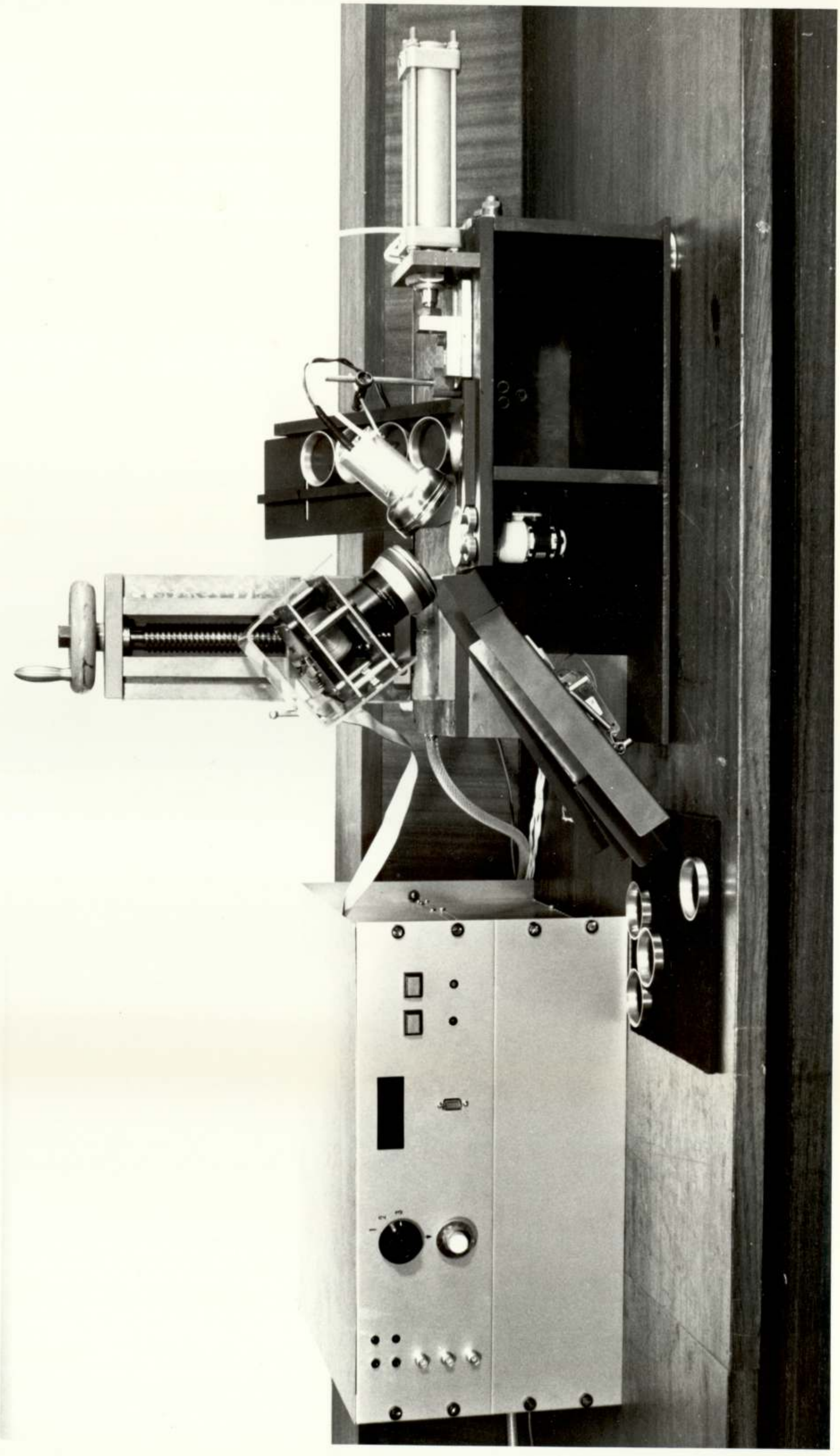
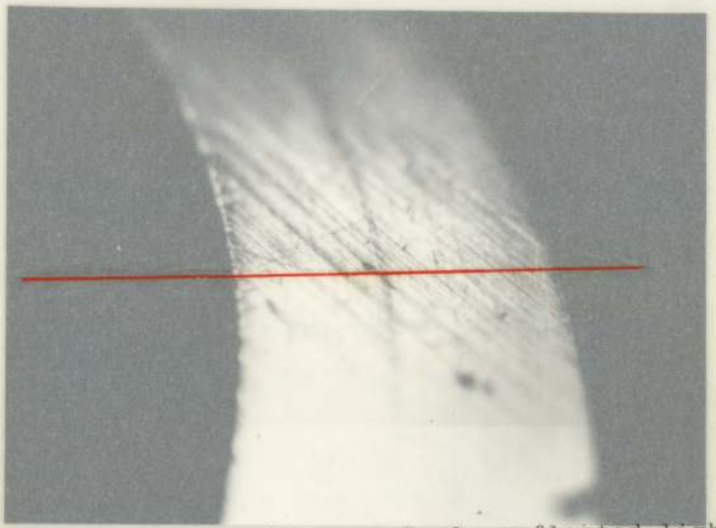
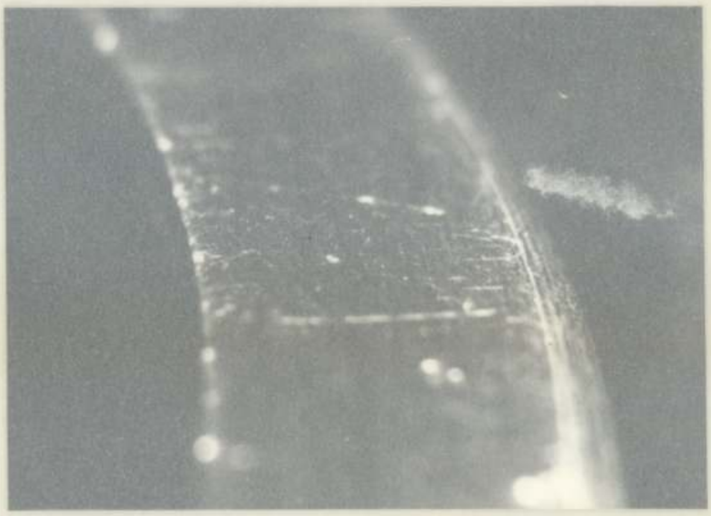


PLATE 6.2. View from the linescan camera position of a defective VSI



a) Produced using specularly reflected light

b) Produced using scattered light



PLATES 6.3., 6.4., and 6.5. Show signals from a 3.5mm wide surface containing a 150 micron casting defect (shown in Plate 6.2). For all oscillographs of video signals x gain = 1Vcm^{-1}, TB = 50μs cm^{-1}

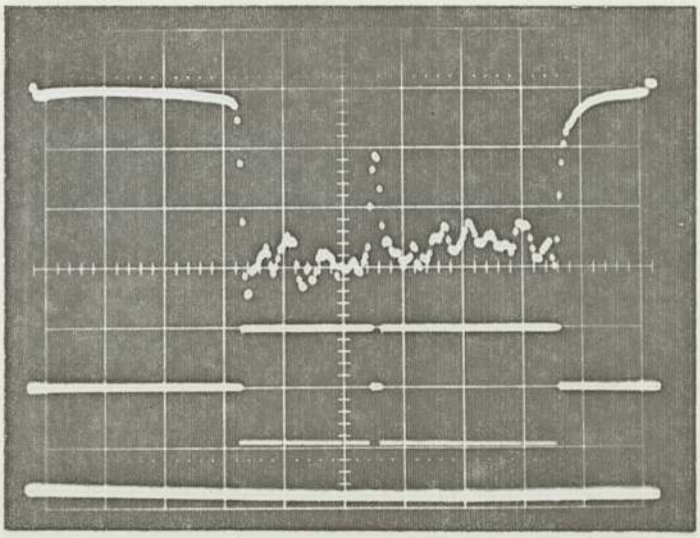


PLATE 6.3.

a) Video

b) Squared video

c) Squared video AND Clock Pulse Train

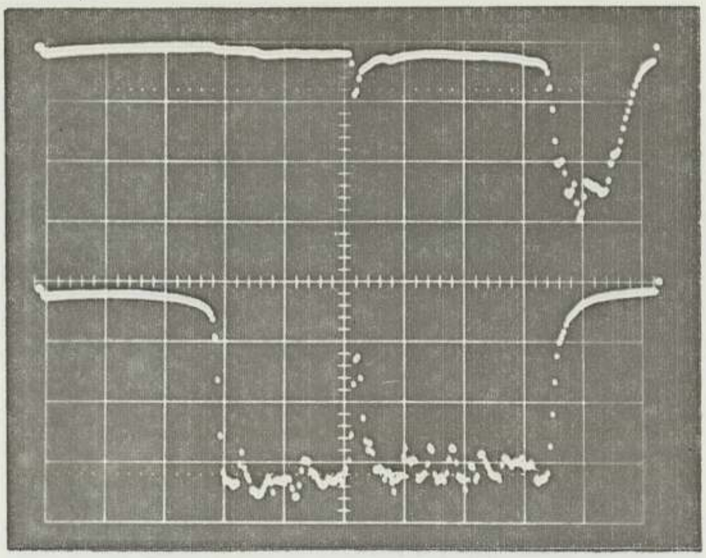


PLATE 6.4.

a) Video produced by light scattered from the defect

b) Video produced by specularly-reflected light

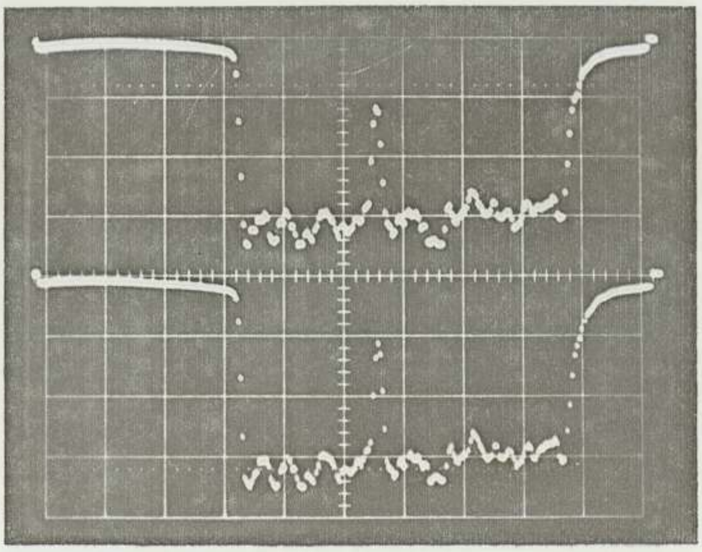


PLATE 6.5

a) Video without IR filter Integration time ≈ 0.5 ms

b) Video with IR filter Integration time ≈ 4.0 ms

PLATES 6.6 and 6.7a Show signals from a 3.5mm wide surface containing a 150 micron casting defect (shown in Plate 6.2.). Material has a high chrome content and its surface is relatively smooth and reflective.

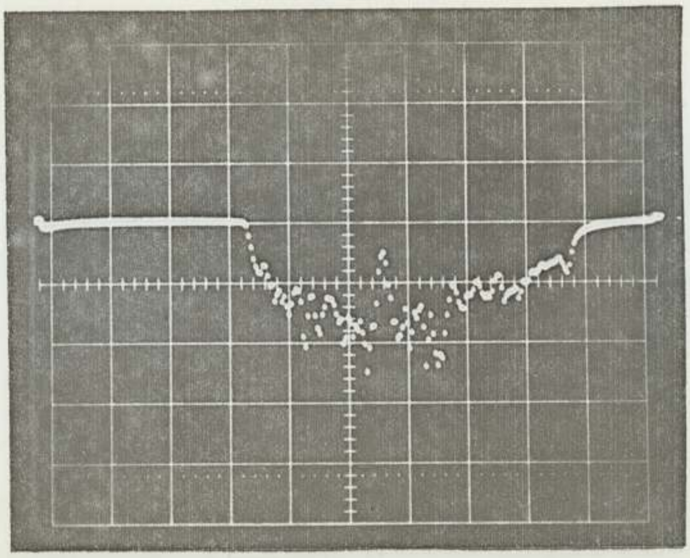


PLATE 6.6.

Video produced using a small aperture light source ; shows pronounced surface texture and vignetting

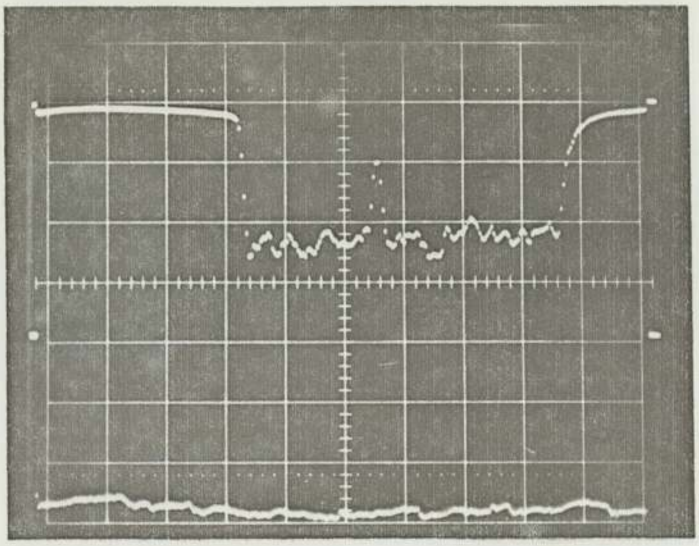


PLATE 6.7.

a) Video: component

b) Video of a plane mirror in place of the component

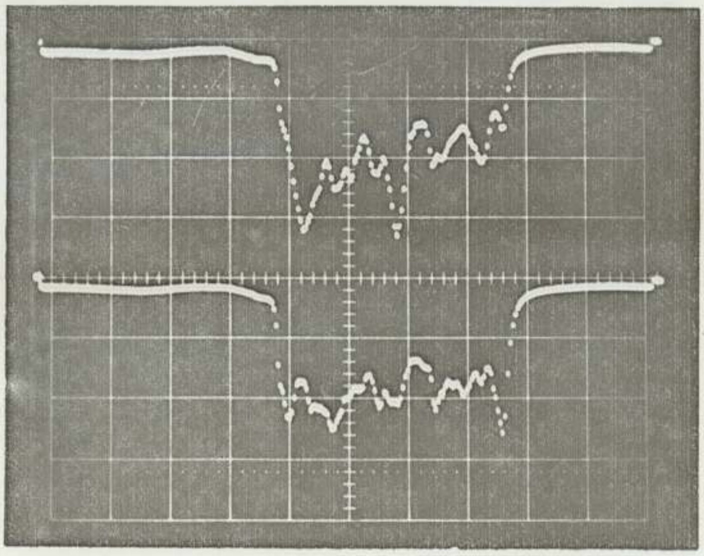


PLATE 6.8.

a) Video of a component with no defect - but coarse surface texture due to the material

b) Video of a different line on the same component as in a ; Lower average reflectance

CHAPTER 7

The Demonstration of the Prototype and Postponement of the Production Unit

7.a. The Demonstration

When demonstrating a system to persons who are not directly involved in the technology, the impression made depends largely on the quality of the demonstration.

Prior to demonstrating the prototype to the company directors responsible for deciding the future of the project, a brief description and costing was distributed (Appendix C). The costing was prepared on the basis of hardware to be purchased, and stated that overheads, contractors fees and salaries were not included.

The prototype was demonstrated as follows at the company's premises in Coventry. The input chute was loaded with a number of VSI's all of the same type, and all with the same face upwards. The components were fed singly into the inspection position, rotated, and removed into either the "accept" or the "reject" chute. The last component, previously marked with black tape, remained in the viewing position since there was no further component to eject it. This component was inspected three times and, on sensing a reject each time, the processor stopped the cycle. The number of accepted and rejected components was displayed ; the components which were rejected had small prosity flaws on the inspected face, the others were not defective. This test was repeated with the same sample and consistently rejected the same components.

It was emphasised that the unit was only a prototype, designed as a development tool and for demonstration purposes, and that developments were incomplete.

The directors were favourably impressed by the performance of the prototype, and were unanimous in agreeing that the system should be developed into a production unit. However, the system, for a variety of reasons related to its cost and benefits, has not been developed to this stage.

7.b. The Costs of Implementing the System

A major problem was lack of personnel in the field of a technology which was completely new to the company, to plan, direct and carry out further developments and design. The undertaking in this context was very much single-handed, which was successful and cost effective up to the stage of demonstrating the prototype, but a substantial team devoted to the project was subsequently necessary ; this was not available.

The problem of lack of technical resources was exacerbated by production trends away from the high chrome alloys in which the majority of components were cast at the start of the project, towards alloys which resemble cast iron. The latter have much lower reflectances and coarser surface textures which give rise to consequent problems.

These technical complications and limited resources necessitated plans to extend the duration of the project ; due to this, prospective costs rose, particularly in the area of salaries.

During the period following the prototype demonstration, an application was prepared for financial assistance from the Department of Industry through the M.A.P. scheme (Appendix C).

This application included all the past and projected costs of the project ; estimates of all foreseeable expenses were included, from telephone calls to contingency consultancy fees in the field of microprocessor programming. Copies of this application were necessarily distributed to senior company executives who viewed the figures as a two- to four-fold escalation in the anticipated cost of the project.

7.c. The Benefits of Implementing the System

The costs of the project must be viewed in the context of falling VSI production and thus, a reduction in the benefits to be gained through automating the inspection.

The causes of falling VSI production are two-fold. The first is the declining importance within the company of this particular category of component, with respect to others, particularly valve guides. The second is the current national and international recession which has had particularly adverse effects on the British automotive industry. The severity of this is evident from the fall in the number of company employees during the three years of the project, from nearly 1000 to approximately 500.

7.d. Postponement of the Production Unit

The initial motivation for developing a system of automatic inspection was to reduce costs through savings in labour. During the course of the project, this was usurped as the primary motive by a need for more consistent quality standards due to problems which had arisen with customers. These problems were solved in the short term by more intensive manual inspection and production controls, and the emphasis reverted to cost saving.

At the time of the completion of the M.A.P. application, expenditure estimate, a decision was necessary as to the future of the project. It was decided, in view of falling benefits and increasing costs that the implementation of the proposed system in the valve seat department should be postponed indefinitely.

CHAPTER 8

Discussion

The project brief stated only that a unit was required to detect surface material defects in Valve Seat Inserts ; however, it was felt that there were other objectives which were not overtly stated, for the sponsorship of the project. The management appeared to have recognised that the future prosperity of the company would involve "new" technology, e.g. solid state electronics and computing. The IHD Scheme offered an ideal means to introduce this technology, with fresh ideas and possibly personnel, without excessive expense, when the exact future needs were undefined.

In order to tackle the project brief as it was stated, surface defect detection requirements were defined and a survey of NDT techniques indicated an opto-electronic approach. A further survey of opto-electronic scanners pointed to a solid state linescan camera as providing a possible and potentially good solution to the inspection problem. A decision was subsequently taken, supported by both the company and the University, to design, develop and build the system (prototype and production units) "in house" wherever possible. Although this may have been more time consuming, and may not have utilised to the full the existing expertise in outside research establishments, it did have the effect of achieving the implied or covert objectives in new technology. There now exists in the company limited expertise in electronics which would have developed considerably had financial constraints not curtailed development. Possibly, more significant is the increase in awareness of electronic and microprocessor technology, and its capabilities, within certain areas of the company.

This increased confidence in hitherto remote technologies is evident from the positive attitude towards the prototype, compared with the very sceptical response to a similar level of technology prior to the project. In house developments allowed the project to be directed towards the specific problems inherent in the brief. It is worth mentioning that had the brief been stated more generally to include all the above objectives, or more flexibly, then the objectives may have been more fully achieved, e.g. at some stage a change of emphasis from VSIs to valve guides, i.e. a more simply shaped component, might have proved fruitful. However, this is a retrospective view and a pre-requisite would be a higher initial level of expertise in a new technology, which was then not defined.

Overall, it is felt that the project represents an effective means of introducing new technology, which was, unfortunately, restricted by commercial consideration, largely due to the current recession.

The company is a member of a group which finances a joint research facility. This was not utilised for a number of reasons, the major ones being : the prospective time scale of projects undertaken by the facility due to existing work loads, and also inadequate communications between it and the company.

Many group research facilities give the impression of being remote and academic to "shop floor" engineers ; to allay this impression , demonstrable solutions to practical problems are required. The appropriateness of a demonstration which has been mentioned in previous chapters, should be stressed. Engineers and managers involved in the day-to-day running of a company are interested in seeing something which "works" rather than a display of laboratory equipment accompanied by an academic treatise.

The effect on management of the presentation of cost should also be stressed. A costing presented prior to the prototype demonstration and the MAP costing both show the same costs (Appendix C). However, the former, exclusive of salaries and other in house expenses was viewed favourably ; the latter all-inclusive costing severely inhibited progress. This was at a time when cost saving was the major motivation for the development, as at the commencement.

A secondary motivation at these times was to improve quality standards through automation ; during one phase of the project, this became the major incentive. In some instances, such changes in project objectives could be detrimental. Fortunately, this was not the case here.

The presence of the quality objective and its emphasis may even prove useful in an industrial relations context. Quality standards may be manipulated in other contexts, though perhaps not overtly. At a time when a customer has accumulated excessive stocks of components, scheduled shipments which are returned as defective, sometimes appear to have been scrutinised with a thoroughness not present at a time of shortage.

Quality control in British industry is often conducted against a background of traditional mechanical engineering practices and attitudes. One particularly prevalent stance is that the most important aspect of engineering is production, and therefore output of finished components is all-important, other things being subsidiary. However, controversy may arise in the fields of production and quality control over when a component is "finished". A component should be regarded as finished only when it has passed a final quality inspection or its quality has been assured by some other means. Unfortunately, quality control is sometimes regarded as a necessary but troublesome extra imposed upon production. To be most effective, quality control procedures must be fully integrated into production from design to final service, and fitness-for-purpose criteria should be applied (2). For material composition and dimensional accuracy, this is generally the case, but it is not so for defect specifications. The notion of a "good", "sound" or "not defective" component is meaningless unless the inspection or NDT method is specified ; often it is implied or left obscure. Efforts have been made, with some success, by some customers and particularly by the quality control manager at the company, to specify criteria for material defects in components. Some of these specifications are open to interpretation by viewers or inspectors, but since discretion is not a characteristic with which a computer can be endowed, even more precise specifications will be needed in order to gain the full benefit of an automated system.

Defect specifications should be drafted during the design and development of a component, together with detection methods, which should then be integrated into the production process. By this approach, those users who normally imply a "no defects" specification may be persuaded to accept fitness-for-purpose based specifications ; otherwise, the introduction of specifications when production is under way is seen as a lowering of standards.

It seems unlikely that a specification based on fitness-for-purpose would yield visual inspection as the best method of detecting material defects. If cavities near the surface are important in use, then their depth is likely to be as important as their area ; visual inspection is not sensitive to the former. An eddy current system, though, is more sensitive to deeper pits and might be employed, providing the "appearance" of defects was regarded with less reverence.

However, defect criteria were not flexible to this extent, and a review of NDT techniques, on the basis of existing criteria, implied the opto-electronic approach which was pursued.

There have been many advances in automatic surface inspection in recent years, particularly associated with laser scanners, solid state cameras, and their interfacing to computers. Applications of this type of system are likely to increase with advances in the technology, and also with increased acceptance by industry of this technology, providing commercial considerations allow this.

In many applications, the inspection has been of the surface of moving strips or belts of material (17, 39) ; some have examined components (47, 48) but few, if any, have attempted the whole surface with the resolution and speed inherent in this project's criteria.

Recent advances in available equipment have come from solid state camera manufacturers. Linescan cameras giving video and squared video were available commercially when this technique was first investigated in the context of this project. However, the additional expense of one of these over that of a camera produced in house was not justifiable for a development tool, particularly as the latter course was likely to elicit a greater understanding and confidence in the device.

One of the major difficulties with any NDT system is to distinguish between defects and acceptable irregularities. The opto-electronic system developed during this project is no exception.

The sensitivity of the system to the various irregularities in VSIs can be effectively reduced by developments in a number of different disciplines. The problems of surface texture, average reflectance and dimensional variations were solved in the fields of optics, electronics and microprocessor software respectively.

Much work has been done in the field of processing video data (46,49,50).However, the more complex varieties are not appropriate in this instance, since the scan time is so short and consequently, the time available for processing is also short. The relatively straightforward strategy used with the prototype for isolating defects from the digital video data occupied 60 per cent of the available time. Prior to processing, the digital information had already been reduced to a minimum by data compression from the very large amount available in the analogue video signal.

During the course of the project, an interface unit has become available for use between a Reticon linescan camera and an Intel single board computer. This produces more scan data than the system utilised here, and though the device has a great deal to recommend it, it is difficult to see how any major increase in data could be processed in the time available in this project without increasing the computing hardware. Indeed, a Reticon system which has become available more recently, incorporating the interface unit, contains an Intel 8085 microprocessor, and this is limited to 250 scans/sec : about one tenth of the rate used here. However, difficulties in digital interfacing should be largely removed in the future by this type of device. Many systems, both in use and under development now utilise linescan cameras interfaced to microprocessors (51, 52, 53, 54).

This concurrent development of microprocessor based systems is an indicator of their versatility and potential.

It is felt that the most difficult part of any system like this, in common with other systems taking information from transducers, comes prior to the digital processing, that is, in producing a valid video signal which can be thresholded to produce digital data. Varying conditions in the component under examination come uppermost here ; this is the area of optics and analogue processing.

At the system/component interface, a new model of the dynamic sensitivity of a photodiode array has been developed in terms of its scanning pattern on an inspected surface. This model describes the situation, particularly for defects of the same order of size as the area interrogated by an array element, i.e. near the limits of resolution of the camera. It is clear from this model that spatial sensitivity over the inspected surface is not uniform (Figure 5.18c) and therefore, the position of a defect (usually random) affects how well it will be detected.

By establishing the height of a defect pulse in the video signal statically, the range of values for pulse height can be found for a dynamic situation. Normally, the minimum pulse height which a defect gives is most important and a threshold is set to detect this. This setting is such that the minimum size of defect which must be detected will always be sensed, but unfortunately, defects down to approximately half this size will also have a probability of being detected.

It is also clear from Figure 5.18c (of dynamic, spatial sensitivity) that equal x y resolution is not given by setting scan displacement equalt to projected array pitch, unless it is because x resolution is reduced by crosstalk in the array. However, this is as close an approximation as one is likely to get with reasonable scan displacements (in terms of inspection time), or with current array geometry.

A consequence of this is that defects with the largest dimensions in the direction of mechanical scan (y) can be preferentially detected. This may be useful in other applications.

CHAPTER 9

Conclusions

A. Attempts should be made to base specifications for defect acceptability on fitness-for-purpose criteria, and to integrate into production suitable NDT methods based on these criteria.

B. A linescan camera or cameras interfaced to a micro-computer can offer an appropriate (and cost effective) solution to component surface inspection problems.

C. Because of the nature of linescan camera systems, (a) smaller defects can be detected on smooth surfaces than on rough, and (b) defects at the limits of resolution will sometimes be detected which are approximately half the size of those for which thresholds are set (Chapter 5).

D. The ratio called Volume Index developed in Chapter 5 is useful in predicting the range of pulse heights given by a small defect in a dynamic situation.

E. The presentation of costs and demonstrations of equipment are important in securing backing for future developments.

F. Economic factors must always be considered, and with automatic equipment, the cost of mechanical handling may easily be greater than that of electronic sensing equipment.

CHAPTER 10

Further Work with Optical Scanners

a) Introduction

The following suggestions for further work represent some of the most promising ideas which have been generated during the course of the project. Most of them were not pursued for reasons of cost or lack of the appropriate resources.

b) Valve Guide Inspection

The automation of Valve Guide inspection using a linescan camera system should prove technically easier and financially more beneficial than the automation of VSI inspection. Experience gained during the current project should assist in facilitating this.

c) Polarised Scattered Light Imaging

Defect contrast in (and thus the performance of) the scattered light illumination method described in Section 6.b)i) might be enhanced to a useful level. This could be achieved by polarising and analysing the incident and reflected/scattered light respectively, since the specularly-reflected light retains more incident polarisation than the scattered light.

d) Through-the-Lens Illumination

A combination of the through-the-lens illumination method of Section 6.b)iii) and the focused light source of Section 6.b)ii) could prove to be useful for some applications. This would be particularly so if a compact light source/camera unit could be produced.

e) Fibre Optic Sensing Head

Optical fibres are available with diameters of the same order of size as photodiode array pitch. If a row of these could be aligned in close proximity with an array, one diode per fibre, a useful lensless sensing head might result. The receiving ends of the fibres could be placed in close proximity to a surface and illumination might be provided by an adjacent row of fibres, or by alternating the sensing and illuminating fibres.

f) Differential Arrays

The production of a valid video signal is critical in surface inspection and this is hindered by variations in parameters, such as reflectance or component size. Many problems could be overcome by differencing the video signals from two linear arrays scanning adjacent parallel lines on a moving surface. A differential technique could be achieved in a number of ways :

1. The image can be split optically by any suitable method onto two arrays.
2. Two parallel lines of a matrix array could be used (Matrix arrays with a small number of defects which are otherwise unserviceable might be utilised).
3. The video signal could be delayed in an analogue shift register and then be compared to the signal from the next scan (or any subsequent scan).

g) Sensitive CCD Matrix for Scanning Strip

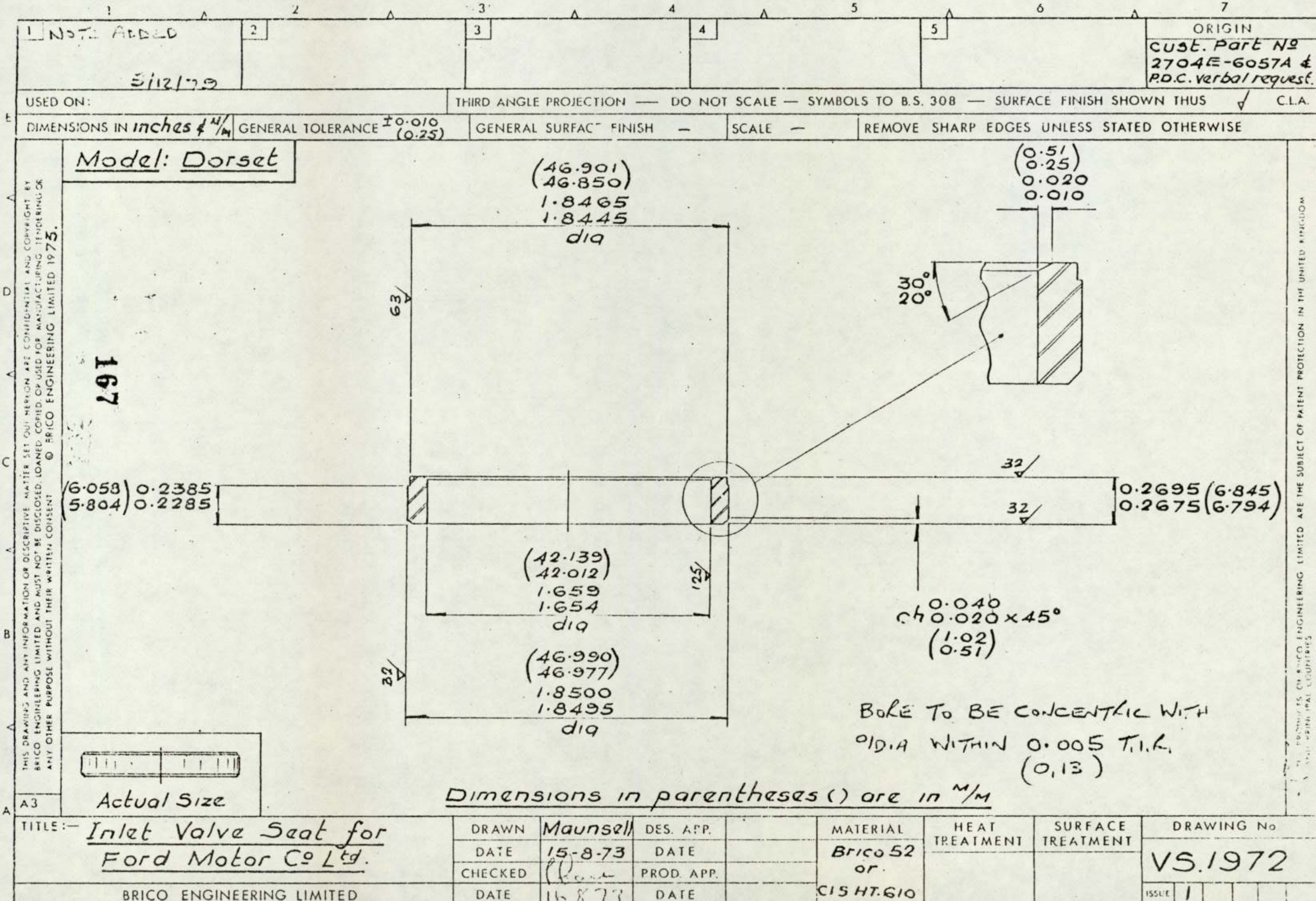
A frame transfer CCD matrix array might be used advantageously for inspecting moving strip if the frame transfer rate could be sunchronised to the mechanical movement. Sensitivity would be greatly increased over that of a linear array if an image point could be spatially synchronised with the charge packet it was producing as it moved across the matrix.

h) Spiral Scan Vidicon

If the electron beam in a vidicon tube could be induced to produce a spiral scan which could be registered with the image of a component, a system might be devised which could inspect annular surfaces very quickly. Other shapes might be investigated by a similar method.

APPENDIX A

Drawing of a Valve Seat Insert
and Material Specifications


(MILLIMETRES)
INCHES
1 NOTE ADDED 5/12/79
ORIGIN
CUST. Part No 2704E-6057A & P.D.C. verbal request.
USED ON:
THIRD ANGLE PROJECTION — DO NOT SCALE — SYMBOLS TO B.S. 308 — SURFACE FINISH SHOWN THUS C.L.A.
DIMENSIONS IN inches & M/M
GENERAL TOLERANCE ±0.010 (0.25)
GENERAL SURFACE FINISH —
SCALE —
REMOVE SHARP EDGES UNLESS STATED OTHERWISE
Model: Dorset
(46.901) (46.850) 1.8465 1.8445 dia
(0.51) (0.25) 0.020 0.010
30° 20°
63
32
(6.058) (5.804) 0.2385 0.2285
0.2695 (6.845) 0.2675 (6.794)
125
(42.139) (42.012) 1.659 1.654 dia
ch 0.040 0.020 × 45° (1.02) (0.51)
(46.990) (46.977) 1.8500 1.8495 dia
BORE TO BE CONCENTRIC WITH O/DIA WITHIN 0.005 T.I.R. (0.13)
Actual Size
Dimensions in parentheses () are in M/M
A3
TITLE:— Inlet Valve Seat for Ford Motor Co Ltd.
DRAWN Maunsell
DATE 15-8-73
CHECKED
DATE
DES. APP.
DATE
PROD. APP.
DATE
MATERIAL Brico 52 or C15 HT.610
HEAT TREATMENT
SURFACE TREATMENT
DRAWING No VS.1972
ISSUE 1
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BRICO

TRADE MARK

Brico Engineering Limited

CAST MATERIAL SPECIFICATION

ALLOY 8

APPLICATIONS ... ... Automotive Piston Rings
Thick Cylinder Liners
Valve Seat Inserts
Centrifugal Castings

CHEMICAL COMPOSITION

	%
Total Carbon	3.0 — 3.25
Silicon	1.8 — 2.5
Sulphur	0.10 max
Phosphorus	0.40 — 0.65
Manganese	0.6 — 1.0
Chromium	0.3 — 0.5
Nickel	0.4 max
Molybdenum	0.4 max
Iron	Remainder

SPECIFIED PROPERTIES

PROPERTY	PISTON RINGS UP TO 100 mm (4")	PISTON RINGS 100 - 150 mm (4" - 6") & CYLINDER LINERS	VALVE SEAT INSERTS	UNITS
HARDNESS	230 min	230 min	200 - 260	HB
MINIMUM RING TENSILE STRENGTH BS4K6	310 (20)	280 (18)	———	MPa (t.s.i.)
MINIMUM ELASTICITY NUMERAL BS5341	100 (14.5)	96 (14.0)	———	GPa (x 10^6 p.s.i.)
MICROSTRUCTURE	Graphite. uniformly distributed size 4 — 6 ASTM 427 Type A and B with D kept to a minimum. Matrix: pearlite, 5% max. free ferrite, no free carbide Phosphoride Eutectic: Evenly distributed as a discontinuous network.			

Brico Engineering Limited

Holbrook Lane, Coventry CV6 4BG England
Telephone: 0203 89014/8

Telegrams: Brico Coventry
Telex 31685

BRICO
TRADE MARK

Form 408

Æ AN ASSOCIATED ENGINEERING LIMITED COMPANY

1st Issue

Brico Engineering Limited

CAST MATERIAL SPECIFICATION

ALLOY 42

BRIMOCROME 42

APPLICATIONS: .. .. Valve Seat Inserts (sand and centrifugally cast)

Chemical Composition

	%
Total Carbon	2.8 — 3.1
Silicon	2.2 — 3.0
Sulphur	0.12 max.
Phosphorus	0.35 max.
Manganese	0.6 — 1.0
Chromium	1.6 — 2.4
Molybdenum	1.8 — 2.5
Iron	Remainder

Specified Properties

Hardness .. .. 38 - 44 HRc

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Brico Engineering Limited

TRADE MARK

CAST MATERIAL SPECIFICATION

ALLOY 52

APPLICATIONS: .. .. High Duty Valve Seat Inserts

CHEMICAL COMPOSITION

	%
Total Carbon	1.5—2.0
Silicon	1.5—2.0
Sulphur	0.10 max.
Phosphorus	0.10 max.
Manganese	0.6—1.2
Chromium	13.5—15.0
Molybdenum	0.35—0.50
Iron	Remainder

SPECIFIED PROPERTIES

Condition	Hardness HRc
Annealed	28 — 35
S.A.	35 — 41
HT 580	43 — 49
HT 610	40 — 47
HT 640	38 — 44

EQUIVALENT MATERIAL Alloy C15 "Valmet" (Wellworthy)

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APPENDIX B

A Report on the Possible
Use of an Eddy Current
Method of Inspecting
Valve Seat Inserts

QUALITY CONTROL IN THE

MANUFACTURE OF

VALVE SEATS

EDDY CURRENT METHOD OF INSPECTION

CONTENTS

INTRODUCTION

THE DEFECTS TO BE DETECTED

The smallest defect which can be seen on a bright metal surface, by the naked eye in good light, is a BLACK HOLE .004" dia. Approx (assumed to be a round pinhole)

The depth of this type of casting defect can vary from about .002" and deeper.

CRACK DETECTION

Eddy current devices are designed primarily for the detection of cracks rather than holes or porosity type surface defects. However if the latter types of defect are big enough it may be possible to detect them using an eddy current crack detecter.

THE TEST MACHINE

Two eddy current systems were investigated, these were the Teledictor and Wells Krautkramer systems. The Teledictor general purpose low cost system did not compare in sensitivity with the more expensive Wells Krautkramer which is described here.

TESTS

STANDARD DEFECT SAMPLES

In order to evaluate any non destructive testing (N.D.T.) system, in this case eddy current, it has been necessary to produce a range of Valve Seat samples each containing a known defect. To do this finished Valve Seats with no natural defects were machined to produce a defect of known dimensions on each one. These samples were used in the test.

THEORY (Ref. 1)

Eddy currents are electrical currents in a conducting material which have been induced by a changing external magnetic field. The eddy currents oppose the changes producing them.

If a changing external magnetic field is produced by an alternating current in a coil, and this is put near a metal surface, then eddy currents are induced in the metal which oppose the changes producing them, and thus oppose the alternating current.

If the metal material is solid the eddy currents have complete paths (loops), if the material is cracked the eddy current loops are interupted. These differences in the material change the amount of opposition to the alternating current in the coil and can therefore be measured electrically in the coil.

These electrical changes are processed electronically and displayed as a signal on an oscilloscope screen.

The frequency of the alternating current is an important parameter.

For high frequency a small coil is used giving sensitivity to small defects over a small area of a surface with little depth of penetration.

For a low frequency a large coil is used which is not so sensitive to small defects but covers a larger area and gives better depth penetration.

The instrument used in this test has two tiny coils in the probe which are operated differentially to remove the effects due to the edge of a surface.

The ratio of crack (or defect) depth/width is also important and should ideally be greater than 3:1 for detection (i.e. depth should be more than 3x the width, as for a crack.)(Ref 2)

TEST METHOD

The Valve Seat is rotated, on a non conducting support, by a lathe, and the eddy current probe is placed close to the surface (typically a .010" clearance) as shown in fig 1.

The electrical signal from the probe is displayed on the oscilloscope screen, as shown in figs 2,3, and 4.

The instrument has a threshold level which can be pre-set to give an automatic reject output.

A high frequency of 1 MHz was used to give best sensitivity to small surface defects. This signal was supplied to a small 2mm diameter probe which is most sensitive at its centre.

RESULTS

Acceptable surface irregularities such as grinding marks give rise to a background noise signal as shown in Fig 2 and a crack or large defect may appear as in fig 3.

For smaller defects the height of the signal of fig 3 gets less, the noise remains the same and so the signal is eventually swamped by the noise.

The signal must be at least twice the noise level to be able to set the reject threshold level and get automatic rejection reliably. i.e. a signal to noise ration better than 2:1 is needed.

Fig 2 and fig 3 show approximately the noise level in the centre of the face with fig 3 also showing a signal from a defect .015" dia. X .011" deep.

However when the probe was moved near to the outside diameter of the face of the Valve Seat, the noise level increased by about 10 times, fig 4.

This edge noise appears to come from the small dents and scratches present at the edge. If these were not present on the Valve Seats the edge noise level would probably be lower.

The presence of two different noise levels from different areas of the Valve Seat is a complication but it should be noted that in order to examine the whole surface, the probe must move right accross it from edge to edge Therefore the greater noise level must be considered as the most relevant.

The table page 3shows the dimensions of a range of defects and whether they were detectable above the noise at the centre and whether they produced a signal which could be detected above the edge noise (eg. if the probe was tracking from the side to side.)

The defects were approximately circular.

DIMENSIONS OF THE DEFECT		DEFECT SIGNALS	
DIAMETER INCHES	DEPTH INCHES	DETECTABLE ABOVE EDGE NOISE	DETECTABLE ABOVE CENTRE NOISE
.015"	.011"	✓	✓
.012"	.008"	✗	✓
.012"	.005"	✗	✓
.011"	.009"	✗	✓
.010"	.009"	✗	✓
.010"	.005"	✗	✓
.009"	.010"	✗	✗
.009"	.006"	✗	✗
.007"	.004"	✗	✗

It should be noted that although the .011" dia and .010" dia holes were detected the signal to noise ratio, even at the centre, was only about 2:1. Also, the .015" dia hole which was detected above edge noise only had a signal to edge noise ratio of about 1.1:1 (i,e, the signal was only 10% greater than edge noise.) (Though it had a s/n ratio at the centre of about 10:1)

Setting the lower limit of sensitivity at a hole 015" dia is still a little optimistic as the signal to noise ratio is poor. The size of the smallest hole which could be reliably and repeatedly detected must be greater than this.

FACTORS AFFECTING THE SUITABILITY OF AN EDDY CURRENT INSPECTION SYSTEM

EXISTING TECHNOLOGY

The basic eddy current technology is tried and tested (at least in the crack detection field) and instruments can be bought " off the shelf". However, from 4 to 6 seperate probes would be needed, each mechanically moving accross a surface, in order to inspect all the surfaces. These probes would have to be multiplexed (i.e. switched into circuit sequentially at the correct instant in time, with the switching signals and noise suppressed). This is not part of the tried and tested technology and is certainly not obtainable "off the shelf".

COST

The costs quoted here are at 20/3/79 and are for the basic detecting equipment only with no consideration for mechanical handling.

The cost of a Defectomat C with 5 point probes and connecting cables is as follows.

1.	Defectomat C, 2.820	@	£8163	=	8163
5.	Cables and adaptor	@	£439	=	2195
5.	Point probes, 6223.71	@	£292	=	1460
	TOTAL				£11818 Plus the cost of multiplexing equipment.

If mulitplexing could not be acheived then a system which operates on the same principles as the Defectomat, but can use up to 4 probes could be used. This is the circograph system, also sold by Wells Krautkramer, the cost of which would be in the region of £28,000.

OPERATION

The sensitivity on a particular surface could be reduced by increasing the probe clearance. This clearance between the probe and surface under test is critical and must remain constant to within .002" during a run. Each probe's clearance must be set before each run, (possbly manually with a feeler gauge) (A run here being several hundred Valve Seats of the same type) a fairly sophisticated mechanical system would be needed to 'RE-PRESENT' the probes to each new Valve Seat at the correct clearance. Also it must be remembered that the probes will also have to track accross the surfaces.

A considerable level of skill is needed to make all the numerous adjustments necessary to obtain optimum performance from the defectomat C itself.

SENSITIVITY

Provided that surface texture does not vary greatly the colour of a surface under test should not affect eddy current performance eg on black heat treated surfaces. The surface texture however is important, grinding marks and more importantly the small edge dents caused during production (eg when barrel drying) produce noise signals which can swamp any real defect signal.

The smallest detectable defect, the lower limit of the Defectomat sensitivity, is a round hole .015" dia and .011" deep. This is considerably larger than the smallest hole detectable by the naked eye in good light.

CONCLUSIONS

1. An eddy current system for detecting defects in Valve Seats would cost (for detecting equipment alone) between £12000 plus multiplexing equipment and £28,000 such a system would also require complicated automatic probe manipulation
2. The system would not be sufficiently sensitive to reject parts with some small defects which can be seen with the naked eye.
3. The system offers little versatility of application to other jobs where the surfaces are not so regular or which are not round and therefore rotatable.

REFERANCES

1. Introduction to electromagnetic non destructive test methods. Hugo L Libby 1971 (14)
2. Personal communication with Mr Flynn; Wells Krautkramer. (55)

H. Fortescue

30th March 1979

Fig. 1

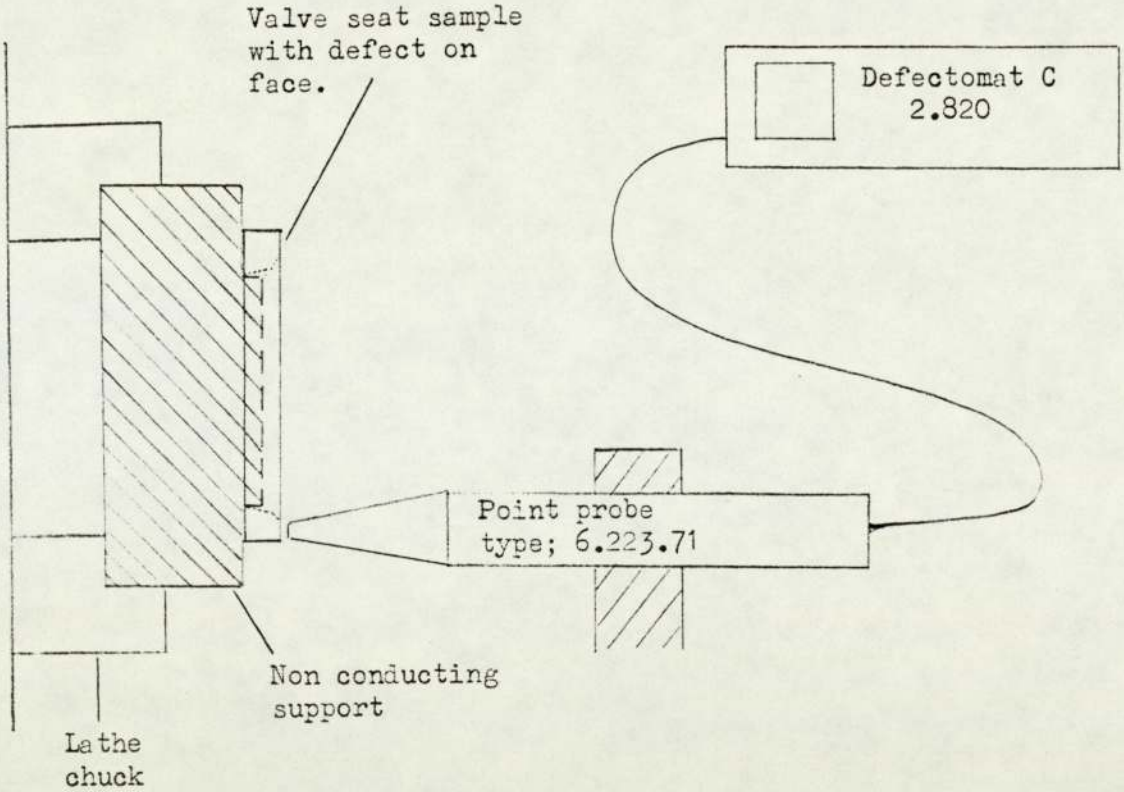
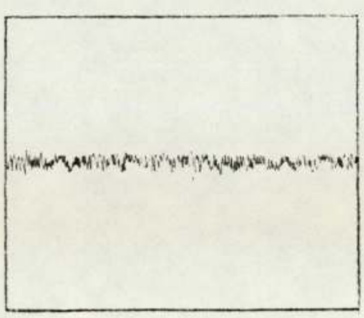
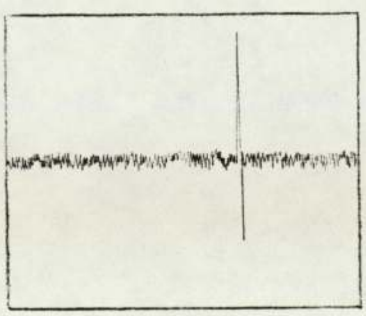


Fig. 2



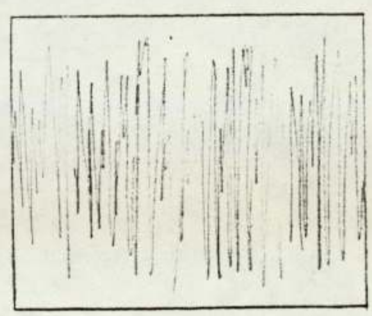
Noise at valve seat centre

Fig. 3



Noise and defect signal (.015") at valve seat centre

Fig. 4



Noise at valve seat edge (outside diameter)

APPENDIX C

Two Presentations of the
Estimated Costs of
Automating Visual Inspection
of Valve Seat Inserts

The two documents included in this appendix are estimates of the cost of developing an automatic inspection facility. The following points are pertinent.

1. The first estimate states that it excludes "in-house time and space (i.e. clerical assistance, software production, design, drawing, machinery, assembly construction and test of electronics)", and is based on performing the great majority of the development in house. However, the second estimate includes all possible contingencies and their costs, together with many already spent on the project, all labour and overheads and subcontracting of the mechanical handling. Extra costs included in the second estimate surplus to those in the first are as follows.:

Costs (£)	Year 1	Year 2	Totals
Labour	9785	6330	16115
Overheads	3230	2090	
	500	200	6020
Consulting fees	1270	530	
	8950		10750
Sub-contracts			
15000 less 4680 for mechanical hardware in the exclusive estimate	10320		10320
Consumables	260	100	360
Development system aids	1500		
	700		2200
Other capital expenditure :			
14500 less 9880 for lighting, electrical hardware and test equipment in the exclusive estimate	4620		4620
Trials and testing		250	
		180	430
Other costs	200	340	
	400		
		250	1190
	TOTAL		52005

Exclusive Estimate + Extra Costs = Inclusive Estimate

14500 + 52000 = 66500

2. Mechanical handling costs account for a significant proportion of the cost of this type of development.; although it is not possible to allocate costs precisely, in this case, the mechanical handling is thought to account for approximately one third of the total.

From the exclusive estimate :

Mechanical handling cost = £4680

Total cost of development = £14560

Mechanical handling proportion ≈ 32%

From the inclusive estimate

Mechanical handling cost (£)

Half of overheads	=	3010
Half of IHD fees	=	4480
Sub-contracts	=	15000
Half of consumables	=	180
One third of prototype	=	500
Half trials and testing	=	210
Part of other costs costs	=	450
TOTAL	=	23830

TOTAL COST OF DEVELOPMENT = £66500

Mechanical handling proportion ≈ 36%

3. The Microprocessor Application Project M.A.P. is a scheme whereby government support is made available to encourage UK industry to apply microprocessor technology. Financial support is available in the areas of training, feasibility studies and applications, and is administered by the Department of Industry (56).

Interdisciplinary Higher Degrees Scheme Office
The University of Aston in Birmingham, B4 7ET.

AUTOMATIC "VISUAL INSPECTION" OF VALVE SEAT INSERTS

Performance

The proposed automatic inspection machine will inspect approximately 72,000 Valve Seat Inserts per week. (i.e. one every two seconds assuming 40 hours working). The unit will detect any dark defect on a bright metal surface which can normally be seen by the unaided eye in good light. It may be fed from a vibratory bowl and inspected parts will be delivered into accept or reject bins.

Setting up

To set up the unit for a new batch the operator should only be required to set threshold dials, focus some of the cameras and adjust the track width.

Prototype

The prototype demonstrates all of the important features of the proposed machine, though a considerable amount of development and design work still needs to be done to incorporate and coordinate all of these features into a production unit.

COST

The cost of producing a first production unit will be between £13,000 and £18,000.

This estimate includes £1,300 capital expenditure for essential test equipment.

No allowance is made for in house time or space, (.i.e. clerical assistance, software production, design, drawing, machinery, assembly, construction and test of electronics.). It would be of considerable benefit to Brico to develop expertise in electronics, but if this is not possible, then contracting out some of the electronics work could add another £2,500 to the cost.

BENEFITS

Customer relations should improve with the introduction of more reliable quality control, with associated long term benefits.

This project could pave the way for future in house automation of inspection tasks, using up-to-date electronics and microprocessors.

Approximately half of the time of four female operators is spent on visual inspectio of valve seat inserts (approximately £12,300 p.a.).

Reinspection costs to Brico, of customer returns due to material defects was £1,200 last year.

A fully automatic machine doing a reliable inspection would save the majority of thes costs, approximately £13,500 p.a., and bearing in mind the capital outlay of £13,000 to £18,000 this gives a payback period of between 11 and 16 months.

Telephone 021-359 3611.
Extension Nos. 6178, 6183, 6338. (IHD Switchboard)
Telex 336997.

AUTOMATIC "VISUAL INSPECTION" MACHINE FOR VALVE SEAT INSERTS

ESTIMATE OF COSTS FOR BUILDING ONE MACHINE

Lighting	£
Power supplies, controllers and lamps	720
Mechanical Hardware	
Vibratory bowl, frame, boxes, pneumatics, motors and tracks	4,680
Electrical Hardware	
Video cameras	3,600
Microprocessors, interfacing and power supplies	3,540
racks and cabinets	720
Test Equipment	
Oscilloscope, meters and spares	1,300
	14,560

ANALYSIS OF COSTS

AUTOMATIC VISUAL INSPECTION OF VALVE SEAT INSERTS

PREPARED BY:
J. Kipping

ANALYSIS OF COST OF PROPOSED PROJECT TO FULLY DEVELOP AN AUTOMATIC VISUAL INSPECTION MACHINE TO DETECT POROSITY OF MACHINED CAST VALVE SEAT INSERTS.

It is proposed that this project will run from 5th January 1981 to 21st May 1982 - a total of 66 working weeks. Development of the basic ideas will run for 26 weeks, up to 11th July 81 and manufacture and testing will last the remaining 40 weeks.

Table 1

This shows the cost of all aspects of the proposed project. These add up to £66,500 at today's prices.

Table 2

These are explanatory notes of table 1.

Table 3

These show the cost broken down three ways i.e.

a) Cost to Brico of developing project fully
b) Costs incurred to date
c) Costs to Brico even if the project is not developed

In general terms, if the government accepted the cost figures at their full value, then Brico would have to pay £27,140 (allowing for contingency/ inflation) in order to fully develop the project.

TABLE 1

otes		1981 Year 1	1982 (5 months) Year 2
1.	LABOUR		
2.	Graham Mitchell		
	Peter Bend		
3.	Howard Fortescue		
2.	Gordon Steel		
2.	Reginald Rollins		
2.	Grade 8 Operator		
		£9,785	£6,330
	OVERHEADS		
4.	Cost of employing people (33% of wages)	£3,230	£2,090
4.	Office Space	£500	£200
	CONSULTANCY FEES		
5.	Aston University 15 days @ £120	£1,270	£530
6.	IHD fees: 78 - 79 £2,829		
	79 - 80 £2,867		
	80 - 81 £3,251		
	£8950	£8,950	
7.	SUB CONTRACTS		
	Including: mechanical drawings, mechanical parts machining, mechanical parts assy., vibratory bowl, motors etc.	£15,000	
8.	CONSUMABLE MATERIALS		
	£1 per day for 360 days	£260	£100
9.	DEVELOPMENT SYSTEMS AND AIDS		
	Principles and prototype building	£1,500	
	Aston university, 20 days @ £35	£700	
10.	OTHER CAPITAL EQUIPMENT		
	Including: electrical hardware, test equipment	£14,500	

TRIALS AND TESTING

	50 master V.S.I. @ £5.00		£250
11.	300 V.S.I. @ .60p		£180

OTHER COSTS

12.	Travel for H.F. 100 miles per week for 17 weeks	£200	£340
13.	Cost of extending development area	£400	
14.	Machine installation cost		£250
		£56,295	£10,270

TOTAL = £66,500

TABLE 2

NOTES

1. Year 1 - 46 week working year, development up to 11th July, 26 weeks
Year 2 - Up to 21st May, 20 weeks.

2. These wages would be paid, regardless of the project.

3. Estimated salary paid from 1st October 1981.

4. Money cannot be saved by abandoning project.

5. This figure will only arise if expert advice is required.

6. ~~Always~~ Already paid.

7. In a more detailed form, this figure includes:

   Outside contract of mechanical drawings
   Outside contract of machining of parts
   Assembly of parts
   Vibratory bowl
   Frame
   Boxes
   Pneumatics
   Motors, sliders and tracks

8. Such things as paper, pens, solder, light bulbs, wire etc.

9. This money has already been spent.

10. This figure is made up as follows:

Lighting power supplies, controllers and lamps	£720
Electrical Hardware video cameras, microprocessors interfacing and power supplies, racks and cabinets	£7,860
Test Equipment Oscilloscope, meters and spares D.V.M. signal generator	£3,000
Prom programmer	£3,000

11. V.S.I. only need to be taken out of production, tested and put back again - no real cost.

12. Cost of travel for H.F. from 1st October 1981.

13. Estimate from Mr. A. Rouse includes a figure for overheads (employment)

14. Estimate for moving machine and providing compressed air and electricity.

NOTE:
* No allowance has been made for contingency/inflation - see Tables 3 & 4

TABLE 3

COST TO BRICO OF DEVELOPING PROJECT

Wages	£8,960
Aston university fees	£1,800
Sub contracts	£15,000
Consumables	£360
Capital equipment	£14,500
50 Master V.S.I.	£250
Travel for H. F	£540
	£41,410
+ 10% contingency/inflation	£45,550

COSTS INCURRED TO DATE

I.H.D. fees	£8,950
Development systems and aids	£2,200
	£11,150

COST TO BRICO EVEN IF PROJECT NOT DEVELOPED

Wages	£7,155	
Overheads	£5,420	
Office Space	£200	
Office extension	£400	
Machine Inst. cost	£250	
	£13,905	
	TOTAL	£66,500
	Total with contingency/inflation taken	£73,635

If Brico can claim 25% of £73,635 (i.e. £18,410) from government as a grant, then the true extra cost of developing the project will be

£41,410 + 10% - £18,410 = £27,140

APPENDIX D

Symbols Used

APPENDIX D

SYMBOLS USED

a	Photodiode length
b	Array pitch
c	Array width = photodiode width
d	Defect diameter
f	Focal length
h	Defect pulse height in the video signal
m	Magnification
t_i	Light integration time of photodiodes in an array
t_p	Point integration time 5.e)i)
u	Object distance
$\dot{v}$	Image distance
v	Velocity of surface
A	Projected photodiode length = a/m
B	Projected array pitch = b/m
B	Radiance
$\breve{C}$	Projected array width = projected photodiode width = c/m
C	Contrast
G	Projected gap between diodes
I	Image size
I	Irradiance
N	Number of elements in an array
O	Object size
R	Responsivity
S	Scan Displacement
T	Clock period
T	Optical transmittance
X	Number of scans during one rotation of a VSI
Y	Number of scans over which the average is taken in Strategy 5
η	Quantum efficiency
fNo.	Relative aperture
Ra	Roughness average
CLA	Centre line average
C'	Circle of Confusion in image space

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