# THE CONSTRUCTION, DEVELOPMENT AND EVALUATION OF A PORTABLE FERRO-PRECIPITATOR

by

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I, IVAN SUNJKA, declare that this dissertation represents my own work, both in conception and execution.

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## DEDICATION

This study is dedicated to our Saviour

the LORD JESUS CHRIST

# ABSTRACT

This dissertation is concerned with the construction of the locally developed Ferro-precipitator which can be utilised outside a laboratory environment. The American developed Ferrograph machine, besides being expensive (R42 000 + GST in 1984), can only be used inside a dust free, temperature controlled room.

As lubricants in machinery moving parts play an important role in their performance and durability many methods of evaluating the health of machines have been devised, but none by themselves can give a complete picture of what is happening inside the machine.

Various methods of oil analysis have been studied in this dissertation for comparison and/or complementary purposes, so as to establish the role of the Ferro-precipitator in the context mentioned. Spectrometric, Debris and Radio Tracer methods are based on quantitative aspects of wear particle analysis, whereas the Magnetic Plug method shows visibly large wear particles in the very high wear pattern range.

A further aspect to consider is the fact that the Spectrometric analysis method, which is the most common and comprehensive method available in South Africa, is laboratory orientated. This means that an oil sample has to be taken from a machine and then sent to a laboatory for analysis. Besides being time consuming from the time the samples are taken to the time when the results are known, the Spectrometric analysis method is also very expensive.

The Ferro-precipitator that has been developed, is sensitive to particle size and to the rate at which these particles are generated. This is due to the phenomenon that a varying magnetic field strength will attract different size ferrous particles accordingly. This concept was validated by manufacturing ferrous particles of various sizes, firstly by grinding and secondly by sieving. These particles, in both cases, were passed through the Ferro-precipitator in a medium of oil, and graphs of density versus distance along the slide were plotted. The graphs showed distinct variations between particle sizes.

The manufactured particles were also statistically evaluated by establishing the correlation between the machined and/or the sieved particles to the optically measured particles.

The sensitivity of the Ferro-precipitator was further demonstrated by comparing results obtained from an engine test carried out under controlled conditions using the Spectrometric method. If developed further, the Ferro-precipitator could be used in the field, which would eliminate the time lost due to samples being sent ot a laboratory. Also the cost of the machine would be a fraction of the price of the Ferrograph and/or the Spectrometer.

An in-depth study of particle morphology can be carried out on the wear particles deposited on the slide, with the aid of a Scanning Electron microscope using its X-Ray attachment. The potential for such a study was demonstrated on the engine test performed for this dissertation.

# OPSOMMING

Hierdie verhandeling het te doen met die konstruksie van 'n plaaslik onwikkelde Ferro-presipiteerder wat buite 'n laboratoriumomgewing benut kan word. Die Ferrograaf-masjien wat in Amerika ontwikkel is, is nie net duur nie (R42 000 + AVB in 1984), maar kan slegs binne 'n stofvrye, temperatuur-gekontroleerde kamer gebruik word.

Aangesien smeermiddels in die bewegende dele van masjinerie 'n belangrike rol in die werkverrigting en duursaamheid daarvan speel, is baie metodes ontwikkel om die welstand van masjiene te evalueer, maar geeneen van hulle kan 'n volledige prentjie gee van wat binne-in die masjien gebeur nie.

Verskeie metodes van olie-ontleding is tydens hierdie studie vir vergelykende en/of aanvullende doeleindes bestudeer ten einde die rol van die Ferro-presipiteerder in die genoemde konteks te bepaal. Die Spektrometriese, Oorblyfsel- en Radio-opspoormetodes word op kwantitatiewe aspekte van die ontleding van slytasiepartikels gebaseer, terwyl die Magnetiese propmetode slytasiepartikels van sigbare grootte in die hoë bestek van die slytasiepatroon opwys.

'n Verdere aspek wat oorweeg moet word, is die feit dat die Spektrometriese ontledingsmetode, die mees algemene en omvattende metode beskikbaar in Suid-Afrika, laboratoriumgeoriënteerd is. Dit beteken dat 'n oliemonster van 'n masjien geneem en dan na 'n laboratorium gestuur moet word vir ontleding. Benewens die vermorsing van tyd tussen die neem van die monster en die bekendmaking van die uitslag, is 'n Spektrometer ook baie duur.

Die ontwikkelde Ferro-presipiteerder is sensitief vir partikelgrootte en die tempo waarteen hierdie partikels voortgebring word. Dit is vanweë die verskynsel dat 'n wisselende magnetiese veldsterkte ysterpartikels van ooreenkomstig verskillende groottes aantrek. Hierdie verskynsel is bevestig deur ysterpartikels van verskillende groottes eerstens deur middel van afslyping en tweedens deur middel van sifting te vervaardig. Die afgeslypde en gesifte partikels is in 'n oliemedium deur die Ferro-presipiteerder gevoer en grafieke van digtheid teenoor afstand oor die skyfie is getrek.
Die grafieke toon duidelike variasies tussen partikelgroottes.

Die vervaardigde partikels is ook statisties geëvalueer deur die korrelasie tussen onderskeidelik die afgeslypte en gesifte partikels en die opties gemete partikels te bepaal.

Die sensitiwitiet van die Ferro-presipiteerder is verder gedemonstreer deur die resultate verkry an van 'n enjintoets uitgevoer onder beheerde toestande met dié van die Spektrometriese metode te vergelyk. Die Ferro-presipiteerder, indien verder ontwikkel, sou ter plaatse gebruik kon word en sodoende die tydsverlies betrokke by die stuur van monsters na 'n laboratorium uitskakel. Die koste van die masjien sou ook 'n breukdeel van die prys van 'n Ferrograaf-masjien of Spektrometer wees.

'n Diepgaande studie van partikelmorfologie kan met behulp van 'n Aftas-elektronmikroskoop met X-straal toebehore op die slytasiepartikels wat op die skyfie neerslaan gedoen word. Die potensiaal vir so 'n studie is gedemostreer tydens 'n enjintoets wat vir hierdie verhandeling uitgevoer is.

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# CHAPTER ONE

# THE PROBLEM AND ITS SETTING

## 1.0 *INTRODUCTION*

Wear of materials and component parts in machinery and engines is the cause of expenditure on maintenance repairs, and consequently production time is lost. Yet modern industry still demands more strenuous conditions of operation and therefore the reliability of machinery and engines can only be improved by better design information, improved mechanical properties of materials and parts, and accurate monitoring systems.

Since lubricants are imperative for all moving parts of machines, methods of analysing and techniques for examining lubricant debris have been devised during the past thirty years. Many techniques for analysing lubricants are available, but none by itself gives a complete picture of the condition of the machine. The analysis method chosen for a specific application will depend on the sensitivity of the monitoring instrument, the specific information required and the cost of obtaining the information.

According to Scott and Mills (1978) techniques such as spectrographic oil analysis and magnetic plug analysis have been found to be useful for the monitoring of lubricant-washed components by lubricants and lubricant contaminant analysis. For machine condition monitoring, specific information is required on the concentration and size of the wear particles to determine the operative wear regime. Given the morphology of the particles it is possible to establish the mechanisms of wear. Once the composition is known it is possible to define the origin of the particles.

For oil-washed components, information on for example, the morphology and composition of particles can be obtained by ferrography. Since the Foxboro ferrograph (Foxboro/Trans-Sonic, Inc., Burlingham, Mass. USA) is expensive (± R42 000 + GST in 1984), and can only be used in a laboratory environment, it was decided to develop and construct locally, a ferro-machine which can be used outside a laboratory environment at a much lower cost.

The construction and the development of the locally built machine, the Ferro-precipitator, was done in two stages. During stage one the operation of the locally developed Ferro-precipitator was validated by producing ferrous particles of sizes between 10 and 75 microns to demonstrate the accuracy and repeatability of the machine.

The second stage of development was to evaluate the Ferro-precipitator within a practical working environment. Motor vehicle engines were used to illustrate the performance of the instrument. Initially the sensitivity of the spread of larger to smaller wear particles was demonstrated and thereafter a comparison was made with a currently used programme (Spectrometric Oil Analysis Programme, Wearcheck, Durban).

## 1.2 *THE PROBLEM STATEMENT*

The aim of this study was to construct, develop and evaluate a portable Ferro-precipitator with reference to its sensitivity to ferrous particles and its requirements to detect engine wear for the purpose of providing an alternative method of establishing engine health outside the laboratory environment.

## 1.3 *THE SUBPROBLEMS*

### 1.3.1 *The First Subproblem*

The first subproblem was to construct and develop the Ferro-precipitator with reference to its sensitivity to ferrous particles for the purpose of producing an alternative method of monitoring engine lubricants outside the laboratory environment.

### 1.3.2 *The Second Subproblem*

The second subproblem was to evaluate the performance of the Ferro-precipitator with reference to its effectiveness to detect engine wear in order to demonstrate its practical application as an alternative method of monitoring engine health.

## 1.4 *HYPOTHESES.*

### 1.4.1 *The First Hypothesis*

The first hypothesis was that the Ferro-precipitator would be sensitive to ferrous particle sizes down to 1 - 75 microns and that the level of sensitivity could be demonstrated.

### 1.4.2 *The Second Hypothesis*

The second hypothesis was that the Ferro-precipitator would demonstrate the status of engine health and that results obtained would be compatible with current research.

## 1.5 *ASSUMPTIONS*

### 1.5.1 *The First Assumption*

The first assumption was that the Noran "Voyager 2100" EDX-microimaging system available at the University of Durban-Westville, Natal for particle size measuring method would be acceptable.

### 1.5.2 *The Second Assumption*

The second assumption was that the densitometer design/calibration and method of utilisation would be acceptable as far as accuracy and repeatability are concerned.

## 1.6 *DELIMITATIONS*

1.6.1 The densitometer would only be developed to a stage where it would be complementary to the test methods used.

1.6.2 A motorcar engine would be used for demonstrating the Ferro-precipitator's ability to proclaim engine health. Cost was a limiting factor and therefore only one 96-hour engine test was carried out to validate the sensitivity of the Ferro-precipitator.

## 1.7 *DEFINITIONS*

### 1. Tesla or Weber

Tesla/Weber is a unit of magnetic flux which, linking a circuit of one turn, produces in it an electromotive force of one volt as it is reduced to zero at a uniform rate in one second (Basic Guide to the metric system in S.A. 2nd Ed. Sept., 1969), and equal to $10^4$ Gauss.

### 2. Ferro-precipitator

Ferro-precipitator is the name allocated to the locally developed ferrograph machine which can be used outside the laboratory environment.

### 3. Ferrograph machine

A Ferrograph machine refers to an instrument developed overseas by Foxboro/ Trans-Sonic, Inc. Burlingham, Mass. USA, and is used only in a laboratory controlled environment.

### 4. Ferrogram

A Ferrogram is a substrate (glass slide) containing the precipitated ferrous particles.

### 5. Laboratory environment

Laboratory environment is understood as being a dust free, temperature controlled space where sophisticated equipment is housed for the analysis of oil samples.

## 6. Density

For the purpose of this investigation density refers to the percentage area covered by wear particles deposited on the ferrogram and/or concentration of the particles within a sample of oil, measured with a densitometer.

# CHAPTER TWO

# REVIEW OF THE RELATED LITERATURE

## 2.1 *INTRODUCTION*

The ferrograph is an instrument used in research on lubricants, the study of wear mechanisms and as a device for the detection of the onset of abnormal wear in machinery and engines.

Wear of materials and component parts in machinery and engines is the major cause of expenditure on maintenance repairs, and also contributes to production time lost. Since lubricants are imperative for all moving parts of machinery, methods of analysing wear and techniques of examining lubricant debris have been devised during the past thirty years (Pinotti, Hull and McLaughlin, 1943; Westcott and Seifert, 1972; Aoki; 1989).

Many techniques are available for lubricant analysis but none by itself gives a complete picture of the condition of the machine (Westcott and Seifert, 1972; Jones, Sastry and Youdan, 1977; Eyre, 1984a; Dalley, 1990). The following are some modern known monitoring methods already in use:

1. Spectrometric methods - Atomic Absorption and Atomic Emission (Butler and de Villiers, 1972: Stauber and Weismann, 1980);

2. Ferrographic method (Seifert and Westcott; 1972; Aoki, 1989);

3. Magnetic Plug method (Eyre, 1984; Leng, 1984);

4. Radio Tracer method (Pinotti *et al.*, 1949);

5. Debris Analysis (Moreton and Yardley, 1981).

All of the abovementioned methods employ engine particle wear as a basis for determining machine health.

When the sensitivity spectra of the first three methods are compared (Leng, 1984), it can be shown that most monitoring methods have a region which can be associated with their ability to detect wear particles associated with engine health (Hampson, 1981). Figure 2.1 illustrates the efficiency (sensitivity) of the three monitoring methods commonly used for the analysis of oil lubricants. It shows that the spectrometric oil analysis technique is most sensitive to particles in the range 0-10 microns, as compared with the ferrographic technique where the sensitivity occurs in the 5-90 micron range, and the magnetic plug technique, where it occurs in the 90 micron and above range. The importance of this observation must be seen against the background of normal engine wear and its relation to engine health. Eyre (1984) in his paper delivered at the University of the Witwatersrand, illustrated how the magnetic plug technique, spectroscopy and ferrography complement each other in terms of their relative sensitivity ranges.

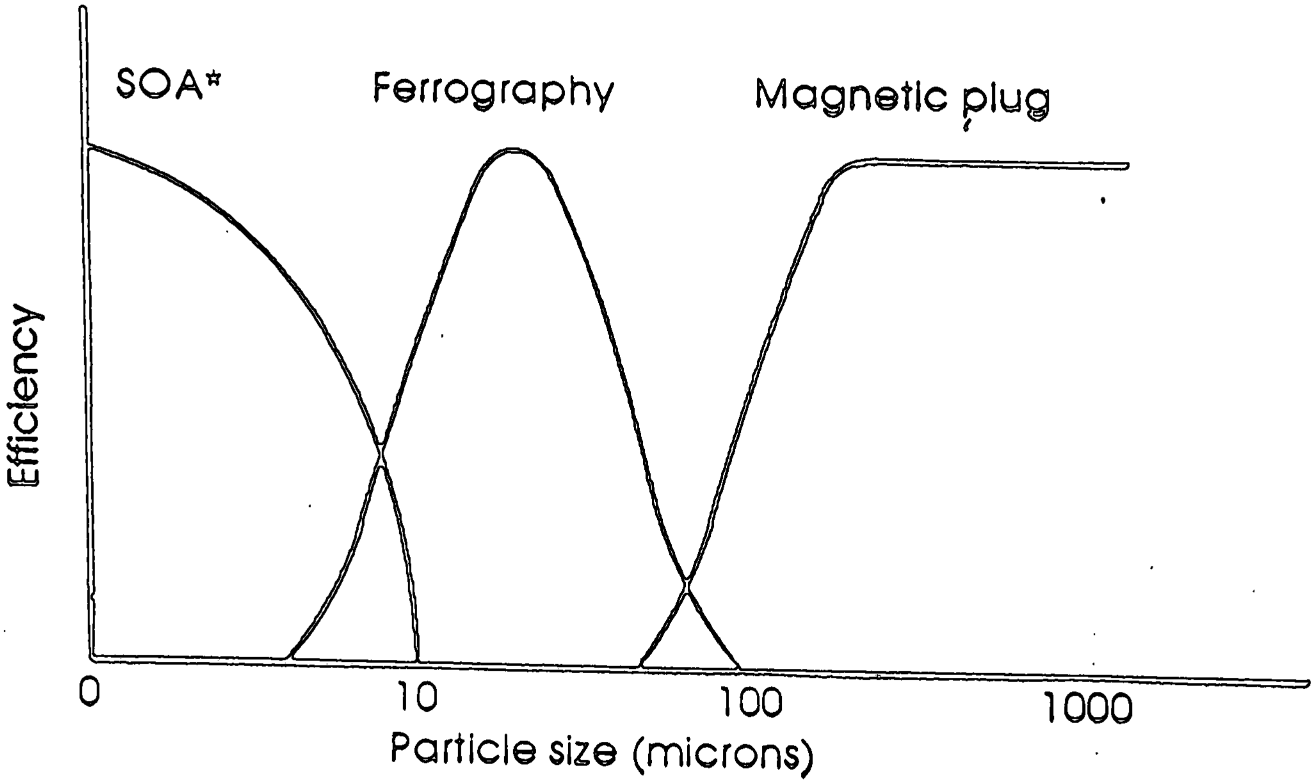


**FIGURE 2.1:** **Comparison of Sensitivity of Three Analysis Methods to Determine Degree of Wear** (Source: Leng, 1984)
*SOA = Spectrometric Oil Analysis

The specific characteristic features of the five lubricant analysis techniques are discussed in the following sections.

## 2.2 *OVERVIEW OF OIL PARTICLE ANALYSIS TECHNIQUES*

### 2.2.1 *Spectroscopy*

By determining the energy level and intensity of spectral lines emitted by an energised oil sample, the constituent elements can be analysed both quantitatively and qualitatively. Some useful information that can be obtained by spectrographic means are as follows:

1. high elemental content, indicating that some constituent parts have a higher than normal wear pattern; or
2. abnormal silicon content, which may indicate that re-evaluation of the filtering system is required; or
3. chemical elements related to cooling water additives can be traced indicating leakage of water into oil; or
4. an indication of the amount of additives remaining in the oil. Low values would indicate a need for maintenance (Jackson, 1972; Butler and de Villiers, 1972).

Two types of spectroscopy are employed for the analysis of element content in oils:

1. Atomic Emission

The Atomic Emission method is based on the fact that every element when excited in a flame, arc or spark, emits light at characteristic wavelengths. By passing the light emitted from a burning sample, it is possible to estimate the concentration of the element by measuring the intensity of that wavelength of light which will be characteristic of the element under consideration (Butler and de Villiers, 1973; Gilmore, 1977).

The Atomic Emission analysis is a well-known technique in South Africa and is used extensively in lubricant analysis for the routine monitoring of aircraft and railway locomotive diesel engines under the so-called Spectrometric Oil Analysis Programme (SOAP). The reason for its general usage is that the analysis monitors the presence of up to thirty elements during a single test ( Martin, Wearcheck, Durban, personal communication, 1994)

However, besides being sophisticated and time consuming between sample taking and resulting feedback, the method does not give an idea of what type of wear takes place in a working machine (Barwell, 1978). Comparative tests carried out by Westcott and Seifert (1973) revealed that, for well atomised samples, an Emission Spectrometer responds accurately to particles in the fractional micrometer size, but that it is essentially insensitive to particles larger than a few microns.

### 2. Atomic Absorption

The relationship between Emission and Absorption spectra was formulated by Kirchoff in 1859, and according to his law, all matter absorbs light at the wavelength at which it emits. In practice the absorption principle is usually only applied in the analysis of gaseous matter (Stauber and Wiesmann, 1980).

In the Atomic Absorption method, the radiation from a light source, i.e. a hollow cathode lamp, is passed through the absorbing medium (Rubenska and Moldan, 1969). A dispersion unit isolates the measured resonance line from the other lines emitted by the light source and the resulting radiation flux is measured by some detection system.

This technique is less extensively used in South Africa for the analysis of lubricating oils because a maximum of one element (light source through hollow cathode tube) can be analysed per run (Martin, Wearcheck, Durban, personal communication, 23 March 1994).

### 2.2.2 *The Ferrographic Method*

A Ferrograph machine which is capable of precipitating magnetic particles ranging from a few microns down to approximately twenty nanometres from liquids such as lubricants, was developed by Seifert and Westcott (1972). With this instrument ferrous (wear) particles are arranged according to size on a transparent slide. Seifert and Westcott (1972) found that particles recovered from lubricant oils exhibited an amazing complexity and range of size and types.

The developed ferrographic analyser consists of a pump to deliver the lubricant sample at a rate of approximately 0,25 ml per minute, a magnet that develops a high gradient magnetic field near its poles, and a treated transparent (glass slide) on which the particles are deposited. The lubricant sample, diluted with a special solvent to promote the precipitation of wear particles, is pumped over the slide which is mounted at a slight angle to the permanent magnet. **None of the literature studied indicated the angle of the slide to the magnet nor the strength of the magnetic field. It appears that this information is not given because of its proprietary nature.**

The ferrous particles adhere to the slide due to the influence of the varying magnet field and are distributed according to size. A washing and fixing cycle removes the residual oil and causes the wear particles to adhere permanently to the slide.

Investigations by various authors (Hofman and Johnson, 1977; Scott and Westcott, 1977; Barwell, 1978) have shown that the health or condition of a machine can be determined by the study of the sizes, shapes and relative quantities of these wear particles on the slide. An indication of the severity of the system can be evaluated by an empirical function, the ***Severity Index*** (Is) (Discussed in Section 3.3.4). This function is based on the relationship between large particles - greater than five microns - and smaller particles - one to two microns - using measured percentage area covered values obtained from an optical densitometer. The manner in which the particles are deposited on the slide corresponds with the optical measurement of these two quantities. The larger particles adhere onto the slide primarily at the oil entry area, and the smaller particles appear approximately 5 mm further down the slide.

Reports by Scott and Seifert and Westcott (1977) have shown that a lubricated machine operating in a normal manner reaches a state of equilibrium in which the particle loss rate equals the particle production rate. Any change in the wear rate causes the number of particles to increase or decrease in the oil. Hofman and Johnson (1977) report that it is a widely accepted concept that, as a motor tends to failure, both the total particle production rate and the difference in the production of the large particles to small particles increases dramatically.

### 2.2.3 *Magnetic Plug Method*

Magnetic plugs are normally placed at convenient positions in the oil stream of an engine or machine (Eyre, 1984b). Magnetic particles collected on the end of the detector (plug) during operation are periodically removed for examination. This can be done either visually and compared with standards, or more detailed procedures can be adopted. One such procedure is to place the end of the detector against sellotape until all the particles or debris have been removed. The tape can then be used as a replica, and placed on a glass slide for optical examination.

### 2.2.4 *Radio Tracer Method*

The radio-active wear monitoring method was patented in 1943 and the patent was assigned to Atlantic Refining Company (Ferris in Bolis, Johnson & Daavetilla, 1947). The California Research Corporation was one of the first users of the radio-tracer method to study engine wear.

The wear detection method comprises three stages:

1. nuclear excitement of components;
2. use of fluid system to act as a carrier;
3. radio-active detector system to monitor wear particles that enter the fluid carrier system.

This method is used on particular wear mechanisms in a specific area. According to Pinotti, Hull and McLaughlin (1949) this method is fairly successfully used to study the amount of wear of particular components such as piston rings, cam shafts and valve trains, but has many disadvantages such as:

1. the engine has to be stripped and the isolated part activated;
2. stripping and assembling of the engine does affect the results, as it is impossible to strip and assemble the unit in exactly the same way each time;
3. a minimum period of 50 - 100 hours of operation is required before any significant wear can be detected.

### 2.2.5 *Debris Tester*

The Debris Tester, produced by Inspection Instruments Ltd (Moreton and Yardley, 1981) is suited for measuring the amount of wear debris. It quantifies the material collected on a magnetic chip detector and operates on an eddy current principle. Oil samples are taken from a machine in the same way as for ferrography, heated to about 65 °C, and shaken vigorously to get the particles into uniform suspension. A 2 ml sample is drawn off from the bottle, using a disposable plastic syringe, and deposited in a beaker. An arbitrary quantity of a dispersant e.g. petroleum spirit is added and after mixing, the contents of the beaker is filtered through a 5 micron millipore filter. The filter is removed, allowed to dry and placed on the Debris Tester to obtain a reading. The reading is linearly proportional to the amount of ferrous material present and can be used for trend plotting in a similar way as ferrography.

Morton and Yardley (1981) did comparative tests between the Debris Tester and Ferrograph machine, by using both methods to monitor oil samples taken from a 49 kW conveyor gearbox run to failure in a laboratory. The results indicated that the Debris Tester readings responded to changes in wear debris content in a similar fashion to the Ferrograph machine, but that the Debris Tester gave a greater response to failure than the Ferrograph machine.

According to Leng (1984) the morphology of the debris deposited on the millipore filter can be examined through a microscope with vertical illumination.

### 2.2.6 *Summary of Oil Sample Analysis Techniques*

A summary of the various oil sample analysis techniques is given in Table 2.1.

**TABLE 2.1: A SUMMARY OF THE VARIOUS OIL SAMPLE ANALYSIS TECHNIQUES.**

| Parameters | Spectrometric (emission and absorption) Analysis | Ferrographic Analysis | Magnetic Plug Inspection | Radio Tracer Method | Debris Tester |
|---|---|---|---|---|---|
| Main Limitations | - Size and size range of particle<br>- Shape identification | - Ferro and para-magnetic particles | - Ferrous particles of coarse type | - Only radio activated particles | - All particles<br>- No identification or size |
| Type of Analysis | Laboratory off-line | Laboratory off-line or in-field on-line | In-field off-line or on-line | Laboratory on-line | In-field off-line |
| Measurement of Concentration | Excellent | Good (ferrous) | Good (ferrous) | Good | Good |
| Element Composition | Excellent | Good | Good | Good | Fair |
| Particle size Range (microns) | 1 - 8 | > 1 | 25 - 400 | 1 - 400 | > 2 |
| Particle Morphology | - | Excellent | Good | - | Fair |
| Comments | Good for monitoring normal wear | Excellent for prediction of incipient wear | Good for detection of abnormal wear | Good for detection of individual wear | Good for prediction of failure |
| Source of Reference | Eyre, 1984;<br>Bolis, Johnston and Daavetilla, 1977;<br>Hampson, 1981 | Eyre, 1984<br>Barwell, 1978<br>Bolis, Johnston and Daavetilla 1977 | Eyre, 1984<br>Hampson, 1981 | Eyre, 1984<br>Pinotti, Hull and McLaughlin 1949 | Leng, 1984<br>Moreton and Yardley, 1981 |

The summary of the oil sampling techniques discussed gives an overall indication of the inter-compatibility of the various techniques available. A significant observation is that not one method on its own can give an overall account of the type of wear that takes place.

## 2.3 *COMPARISON OF FERROGRAPHIC AND SPECTROMETRIC ANALYSIS TECHNIQUES*

Spectrometric analysis techniques effectively illustrate some aspects of machine wear. However, besides being sophisticated and time consuming between sample taking and resulting feedback, the method does not, according to Barwell (1978), give any idea of what type of wear takes place in a machine. Comparative tests carried out by Seiferts and Westcott (1972) revealed that for well atomised samples, the most commonly used Emission Spectrometer responds accurately to particles in the fractional micrometer size, and is essentially insensitive to particles larger than a few microns.

Hofman and Johnson (1977) emphasised the role played by many factors on the particle population in an oil sample. For example:

- oil consumption
- inputs of fresh oil
- period of time oil is used
- oil filtration
- the continuous grinding down mechanism of the larger particles to smaller ones
- adherence of particles to internal walls of machines.

Owing to these dynamic interactions, Seifert and Westcott (1977) and Barwell (1978) argued that the commonly used method of spectrometric oil analysis is not always an accurate indication of the true operating condition of the machine. They concluded that the ***Severity Index*** has greater sensitivity than spectroscopy due to the particle size selection possibilities inherent in ferrography.

Seifert and Westcott (1977) confirmed in tests carried out on jet engines, that an Emission Spectrometer responds primarily to iron particles in the fractional micrometer size and is essentially insensitive to particles larger than a few micrometers. The graphical comparison (Figure 2.2) done by Seiferts and Westcott (1972) illustrates a typical jet engine history chart comparing the results of the atomic emission analysis method to the ferrographic analysis method. The increase in slope using the ferrographic analysis method emphasises that a much earlier warning of failure is observed.

Jones *et al.*, (1977) confirmed the sensitivity of ferrographic analysis method to detect the presence of ferrous particles in oil samples during a run-in test carried out on an eight cylinder Perkins engine. The results showed that when replacing one piston after 60 hours of running at fixed conditions and then continuing the test procedure, the run-in phase was clearly evident comparing the ferrographic analysis with the spectrometric analysis. Figure 2.3 shows that, spectrometrically, there is an upward trend of the ferrous particles (iron) during the first 60 hours, whereas Figure 2.4 indicates that, ferrographically, the trend is downwards for the first 20 hours, and thereafter upwards for the next 40 hours. After piston change the spectrometric trend (Figure 2.3) is again upwards, whereas ferrographically, the trend is downwards for approximately the first 12 hours. This indicates the period of run-in followed by normal wear conditions.

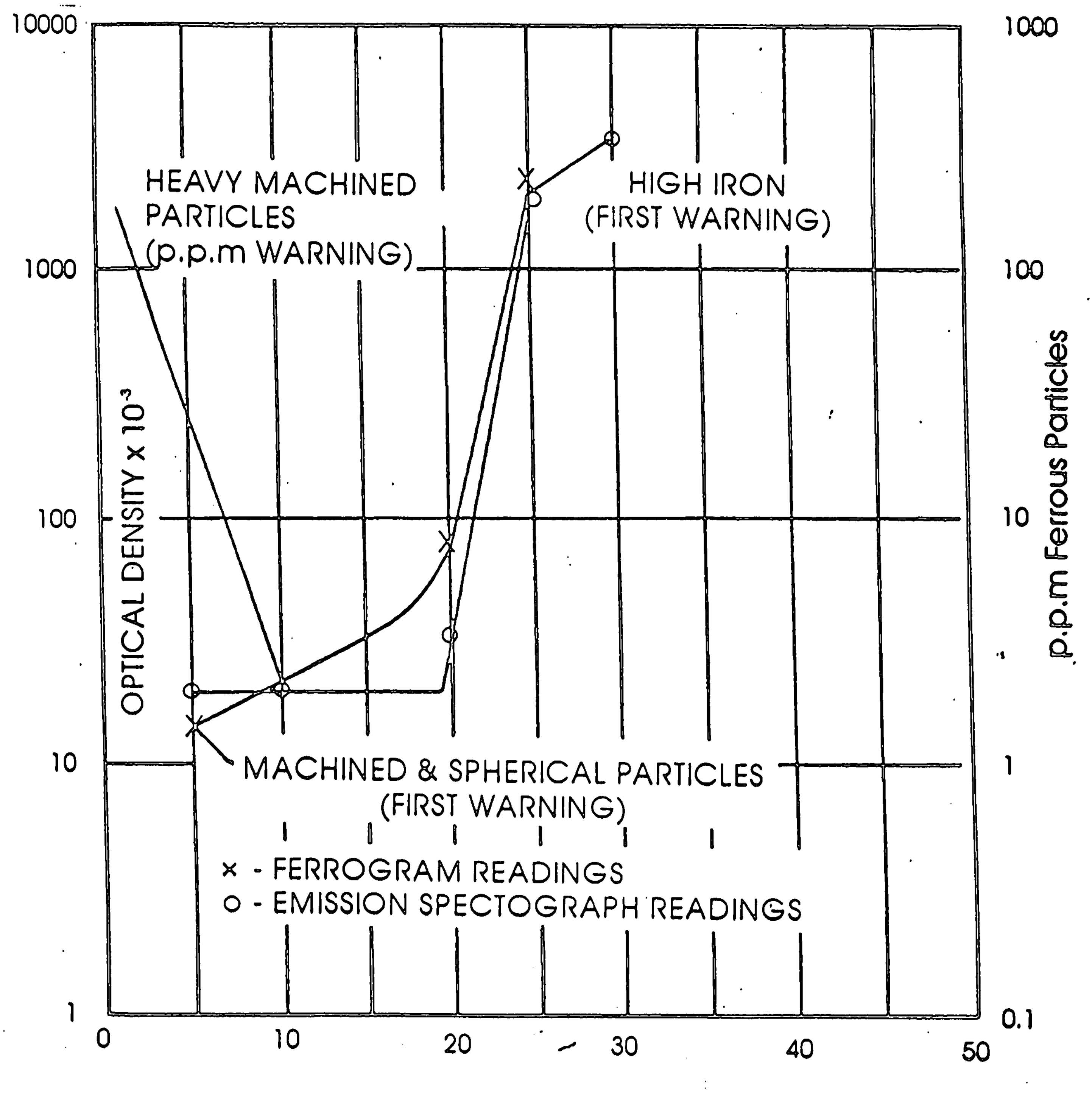


**FIGURE 2.2: Comparison of the Ferrographic to the Spectrometric Analysis (Source: Seiferts and Westcott, 1972)**

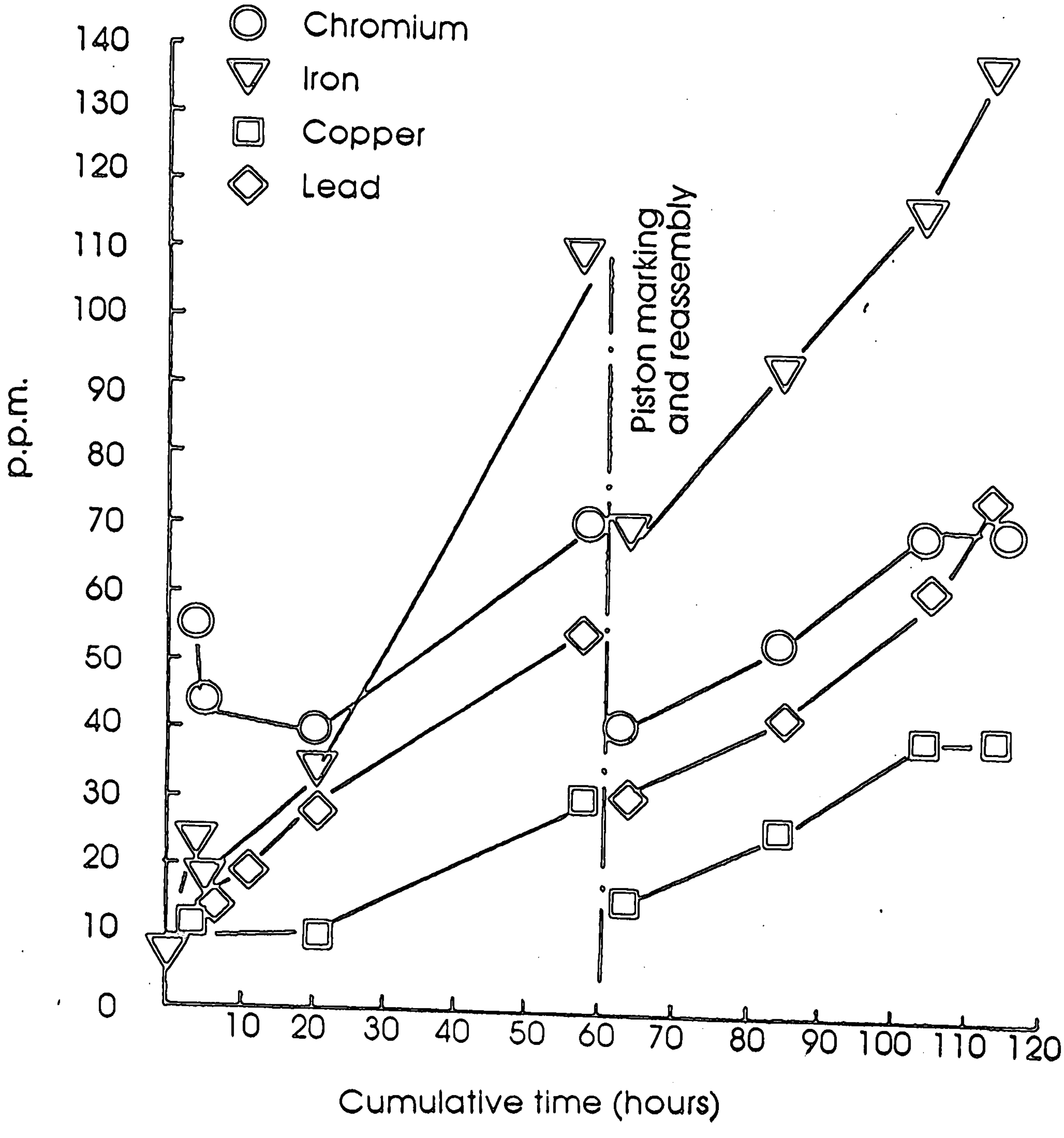


**FIGURE 2.3: Atomic Emission Analysis of Run-in Condition Before and After Piston Change**
(Source: Jones *et al.*, 1977)

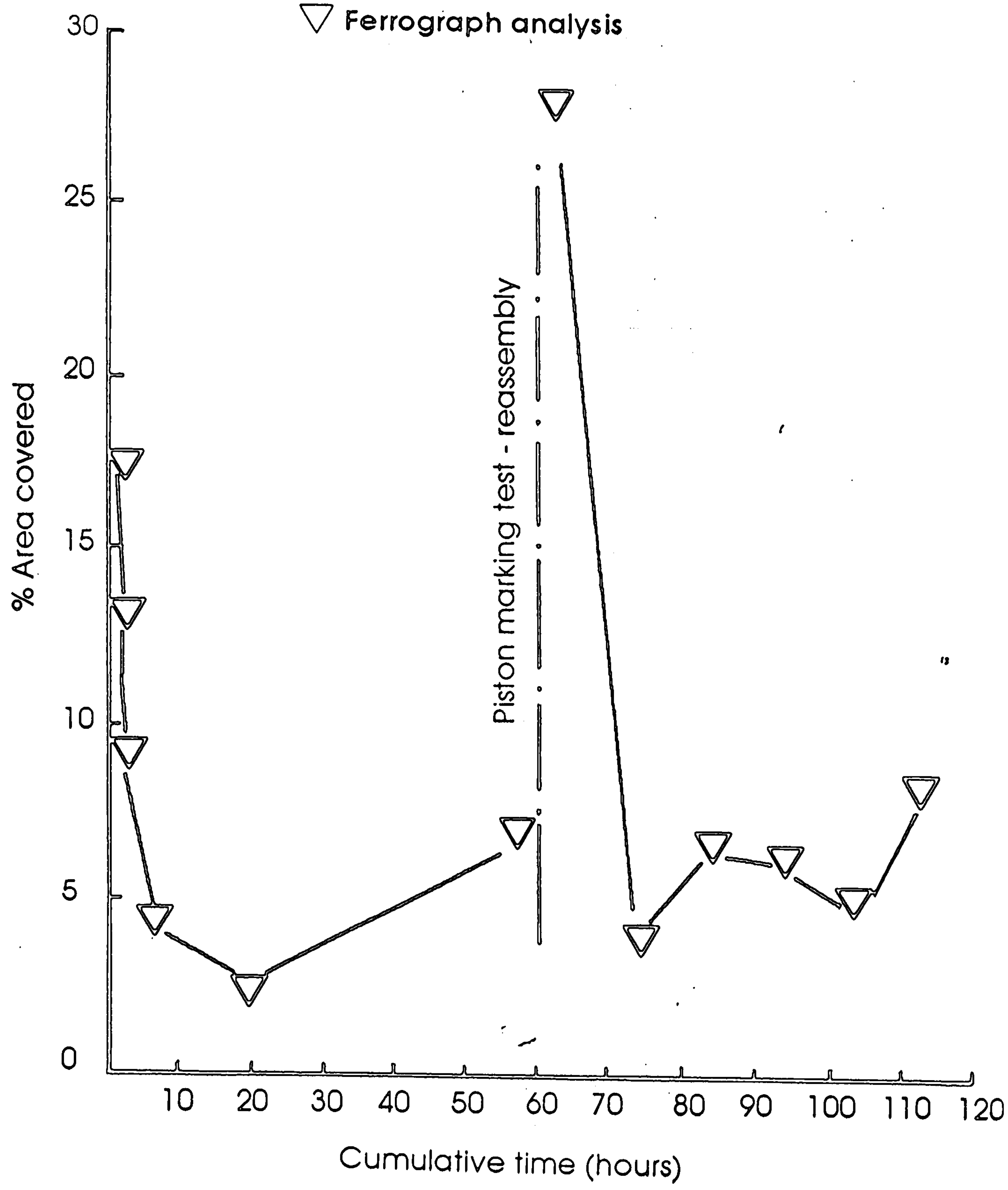


**FIGURE 2.4: Ferrographic Analysis of Run-in Condition Before and After Piston Change**
(Source: Jones *et al.*, 1977)

## 2.4 *DISCUSSION*

Spectrometric techniques as described (Section 2.2.1) are very effective to detect certain aspects of wear such as the presence of non-ferrous particles and additives, but employ relatively sophisticated equipment normally limited to larger laboratories. Besides being sophisticated and time consuming between sample taking and resulting feedback, the method does not indicate what type of wear takes place in a machine (Westcott and Seifert, 1973; Barwell, 1978 ).

The ferrographic technique is more sensitive to particle size variations and therefore able to indicate an early warning of pending failure or change of wear pattern.

# CHAPTER THREE

# LOCAL DEVELOPMENT AND EVALUATION OF THE FERRO-PRECIPITATOR

## 3.1 *INTRODUCTION*

Ferrograph machines are available on the export market. The commercial instrument obtainable from Foxboro/Trans-Sonic Inc. Burlington, USA, is prohibitively expensive. In South Africa the instrument is used mainly in research and development and consequently has very little commercial application for the following reasons:

- it is expensive to buy a Ferrograph machine; and
- it can only be operated in a laboratory environment.

Since the potential of ferrography has not yet been explored in South Africa as a result of the constraints listed, it was decided to construct and develop the portable Ferro-precipitator.

## 3.2 *DEVELOPMENT AND CONSTRUCTION OF THE FERRO-PRECIPITATOR*

### 3.2.1 *Introduction*

The composition of the Ferro-precipitator is characterised by five distinct components, namely:

- the magnet
- substrate holder
- pump assembly
- ferrogram
- densitometer.

The basic objective for the construction of the Ferro-precipitator was to develop a system which could transport oil containing wear particles over a magnetic field. The gradient variation of the magnetic field created by sloping the slide to the magnet should cause the particles to precipitate according to size for the purpose of recording optical readings. **The strength of the magnet and the angle of the slide to the magnet were contrived.** The functions and methods of operation of the various components are described.

### 3.2.2 *The Magnet*

A permanent magnet (Figure 3.1) taken from an ion vacuum pump was utilised (University of Port Elizabeth, Physics Department). The implications of the choice of this magnet is described in Section 5.2.2.

Mounting blocks, manufactured from mild steel (Figure 3.1) were fitted inside the magnet as shown in Figure 3.2, giving a 2 mm pole gap in order to create a high field gradient between the poles. The measured strength of the field, using a Model 3104 Teslameter, was 1000 millitesla (or milli-Webers/m$^2$).

### 3.2.3 *The Substrate Holder*

The untreated glass slide or substrate was placed into the holder (Figure 3.3) which, in turn, was fitted onto the mounting blocks, (Figure 3.2), the design being such that the length of the slide lies centrally over the 2 mm magnet pole gap. The upper jig (Figure 3.4), which directs the flow of the oil centrally over the slide, was fitted into the holder and clamped (Plate 3.1). A wooden box (B) was constructed and fixed to a wooden board into which the magnet assembly and peristaltic pump were fitted as shown in Plate 3.1. The slide or ferrogram was inserted into the holder (E) and clamped down.

Silicate tubing of 1,5 mm internal diameter was used to supply and collect the oil. The suction side (A) was inserted into the oil sample bottle and the supply side connected to the inlet pipe of the upper jig (F). The outlet from the upper jig was then attached to the suction side pipe (G) of the peristaltic pump (C), and the outlet from the pump was inserted into a measuring flask (D).

### 3.2.4 *Pump Assembly*

The peristaltic pump (C) (Type MHRE 200 MC10, H.R. Flow Inducer, supplied by Watson-Marlow Ltd, Felmouth, Cornwall, England) was used, having a pumping rate control within the limits required.

### 3.2.4.1 Method of operation of the peristaltic pump

In most of the tests the pump was normally set to give a pumping rate of approximately 0,5 ml per minute (Section 5.2.3). This flow rate appeared to be acceptable for most of the investigation conducted. The flow rate was checked by timing consecutive samples of oil through the Ferro-precipitator into a measuring flask. Once the correct flow rate was established, the pump was then kept at that value. After 1 ml of sample oil was pumped through, the suction end of the pipe was removed from the oil sample bottle and placed into a bottle containing Ethyl-ether. This process was necessary to remove the oil covering the metal particles precipitated on the glass slide. About 1 ml of solvent at the same flow rate was necessary for adequate washing and rinsing.

Petroleum spirit, 100 to 120 °C boiling, volatile matter 0,002%, was used to dilute the oil samples for testing. The dilution was generally found to be necessary for maximum precipitation of metal particles on the slide. Variation of dilution is directly dependent on concentration of particles in the oil sample collected (Section 5.2.4).

### 3.2.5 *Ferrogram*

The ferrogram (Plate 3.3) was then removed from the holder and allowed to dry, and no further treatment was necessary. The test aim was to examine the ferrogram in the microscope with the densitometer (Plate 3.2), and thereafter density readings were taken as required.

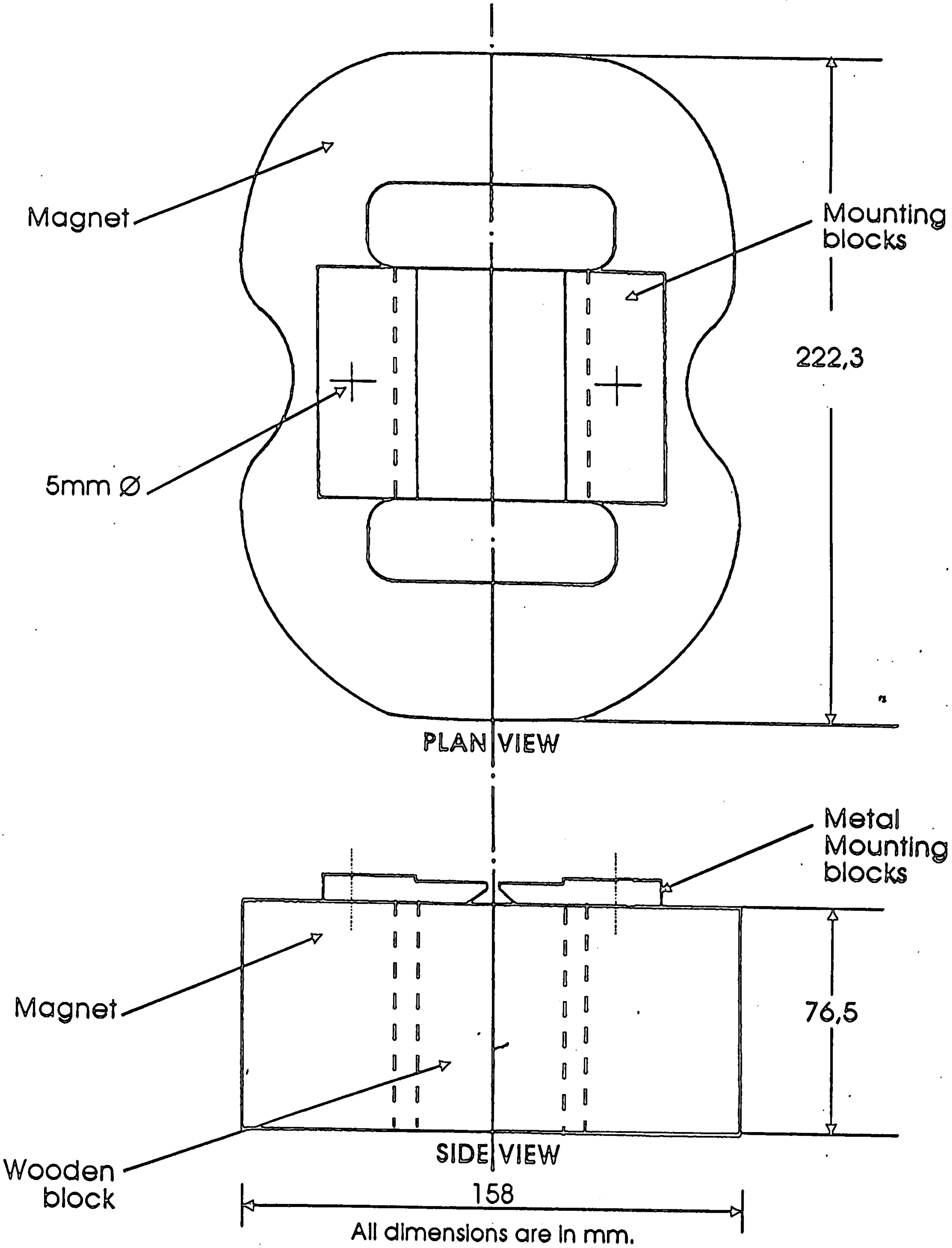
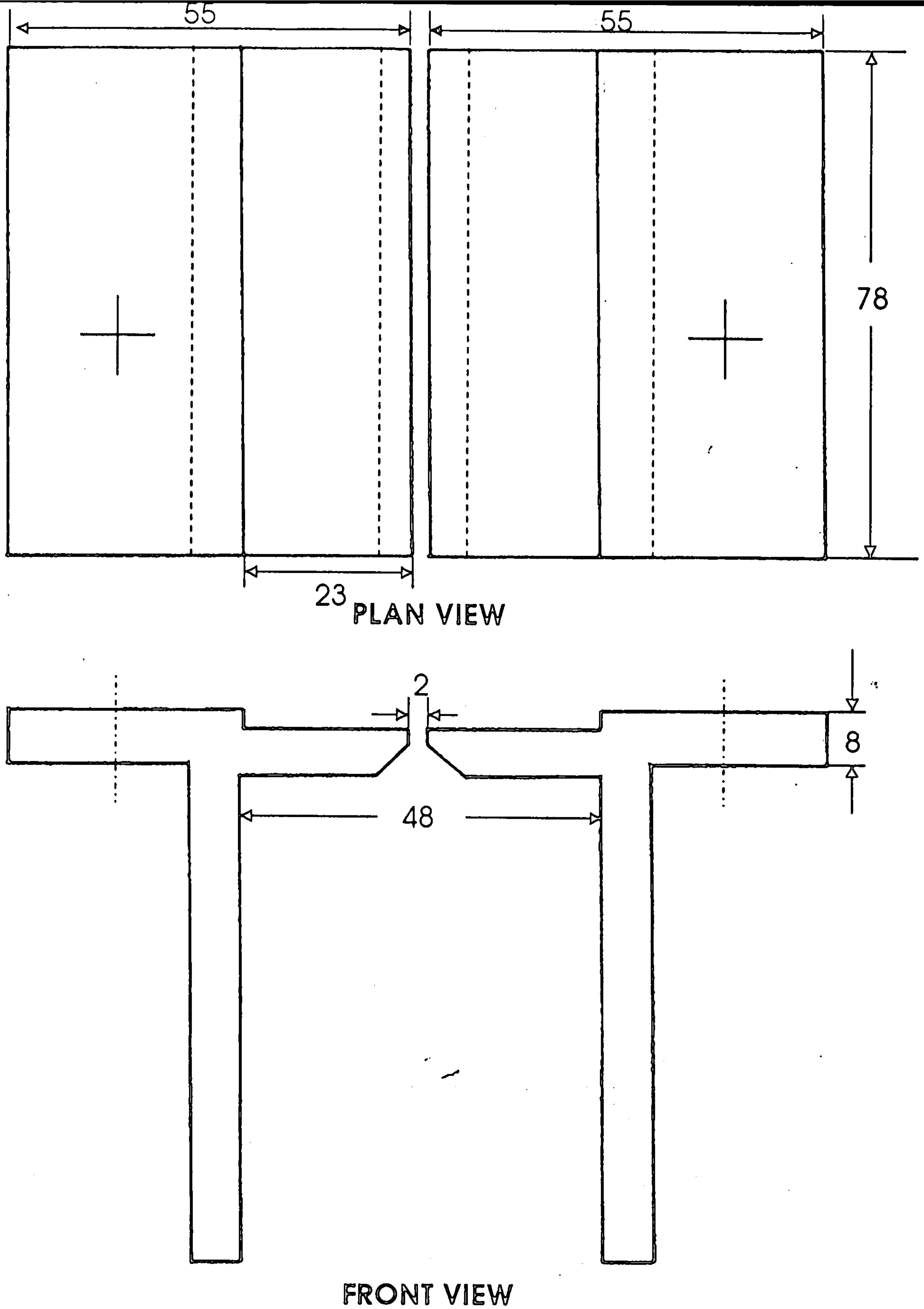
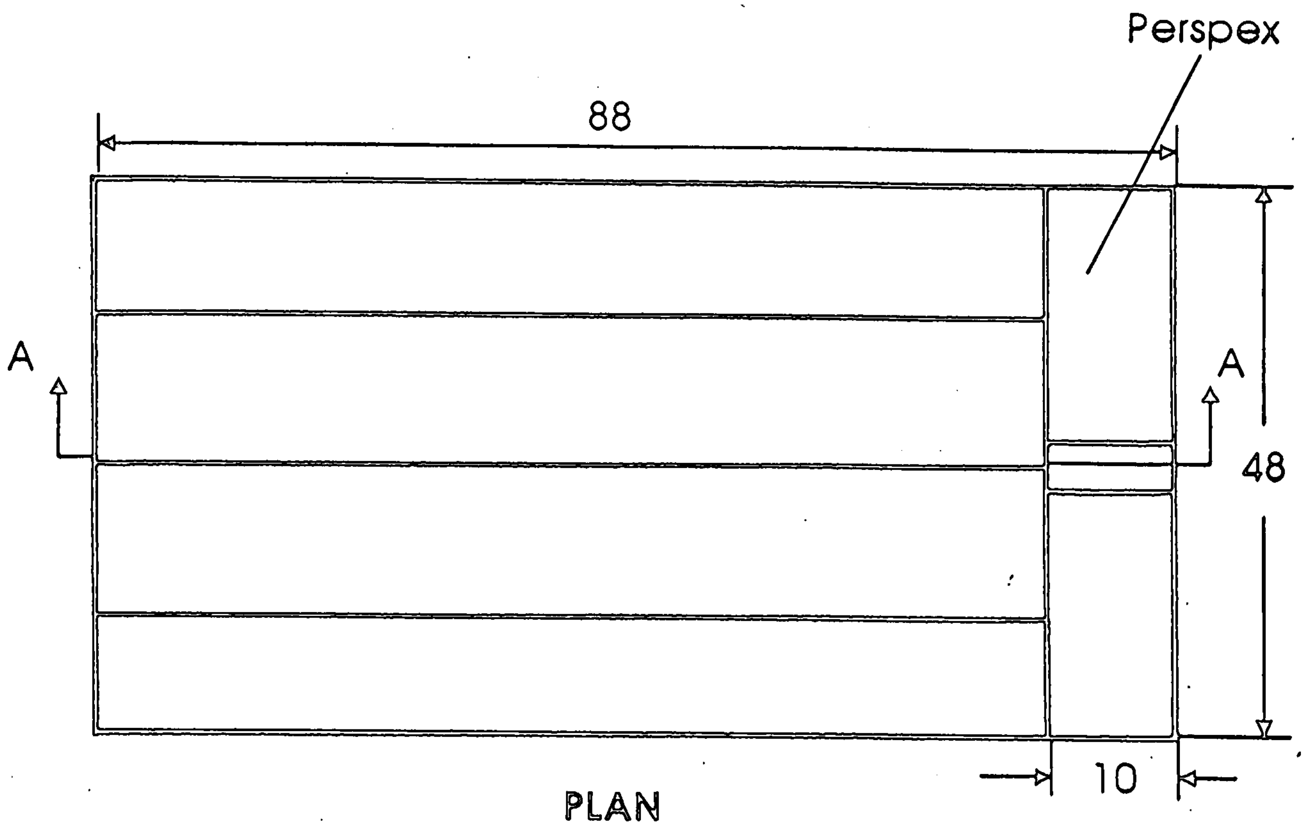


**FIGURE 3.1:** Permanent Magnet Mounting Block Manufactured from Mild Steel

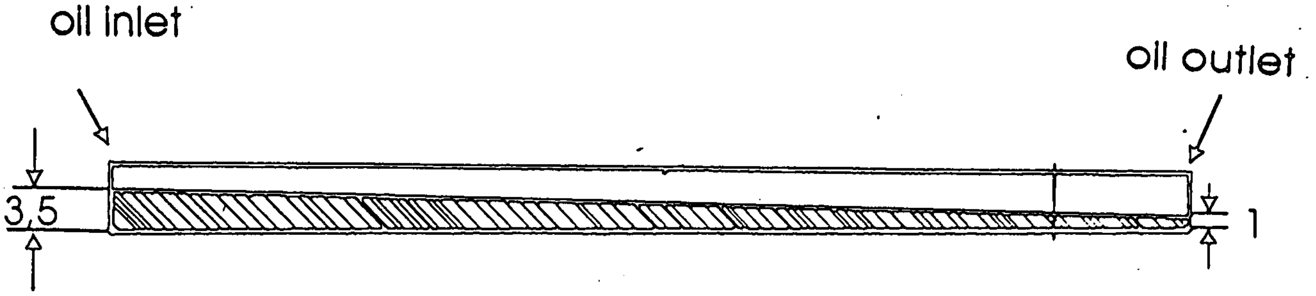


All dimensions are in mm.

**FIGURE 3.2:** **Metal Mounting Blocks**

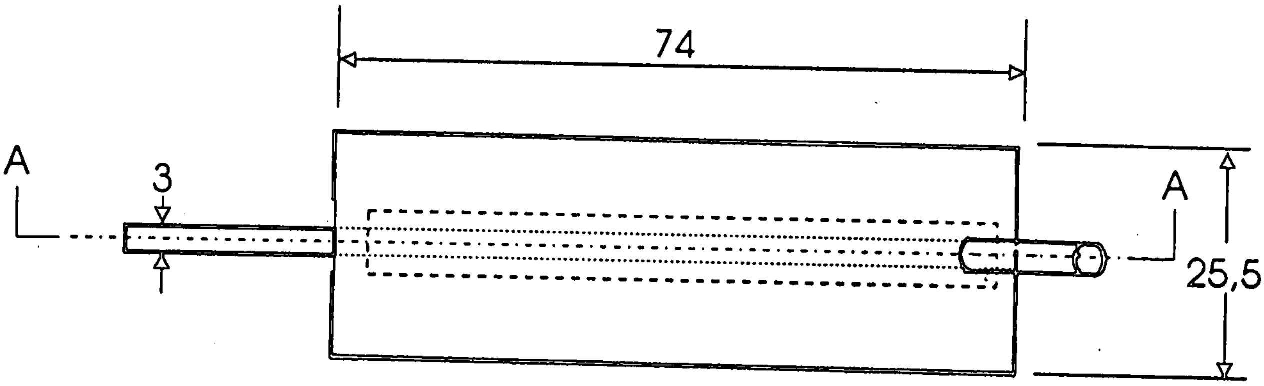


PLAN



SECTIONAL FRONT ELEVATION AA
All dimensions in mm

**FIGURE 3.3:** **Glass Slide Holder**



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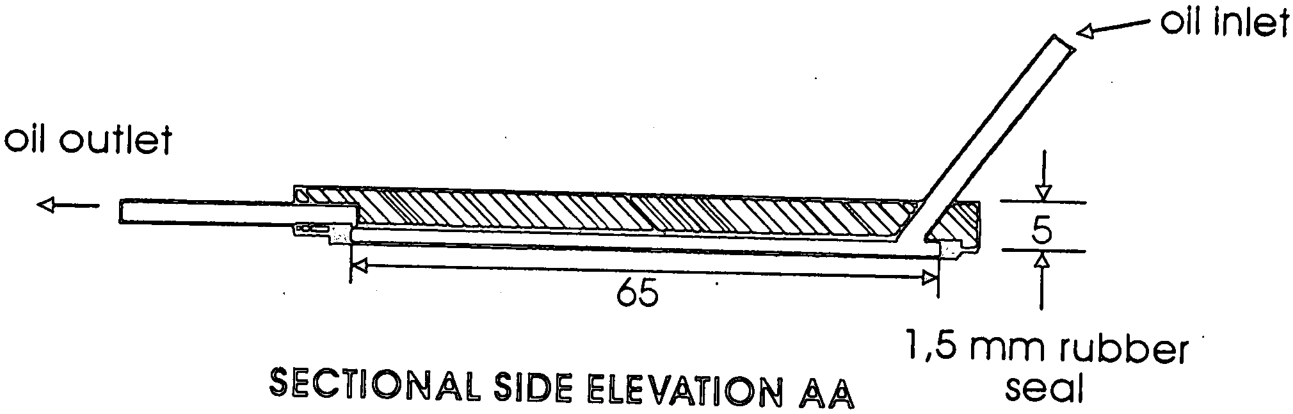


SECTIONAL SIDE ELEVATION AA

All dimensions in mm

**FIGURE 3.4: Upper Jig**

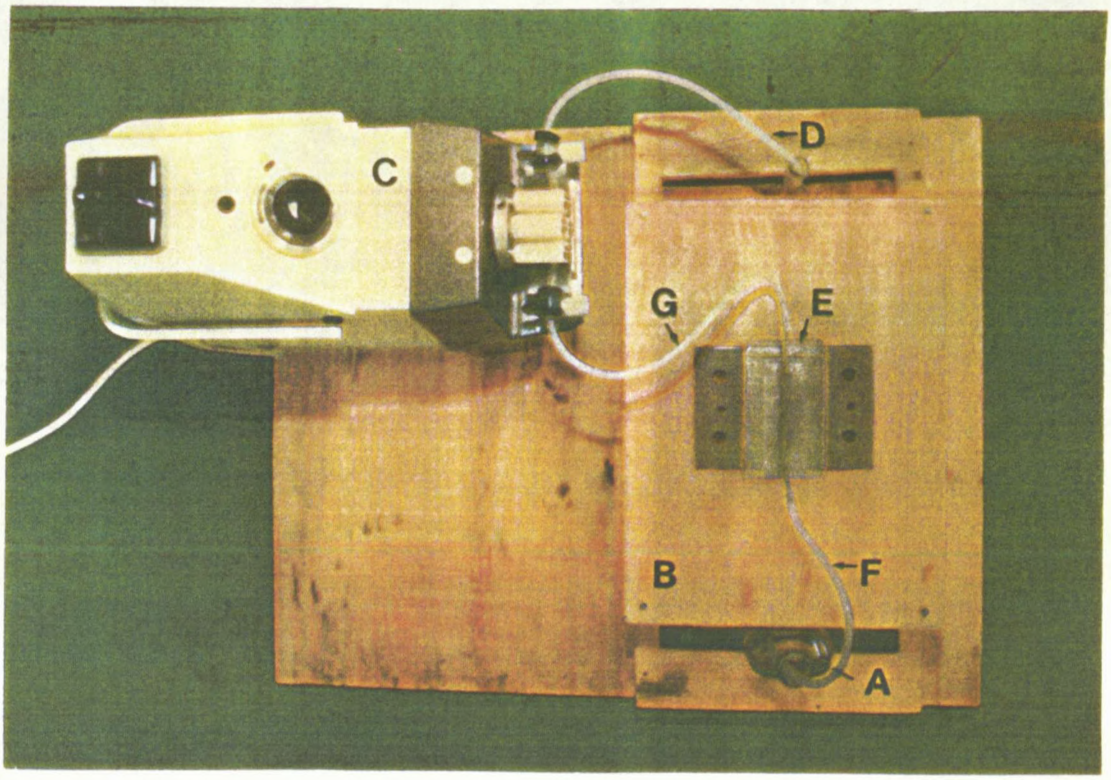


PLATE 3.1: FERRO-PRECIPITATOR ASSEMBLY

| | |
|---|---|
| A | Oil Sample Bottle (Suction Side) |
| B | Wooden Box |
| C | Peristaltic Pump |
| D | Measuring Flask |
| E | Slide Holder |
| F | Inlet Pipe (Upper Jig) |
| G | Outlet Pipe (Upper Jig) |

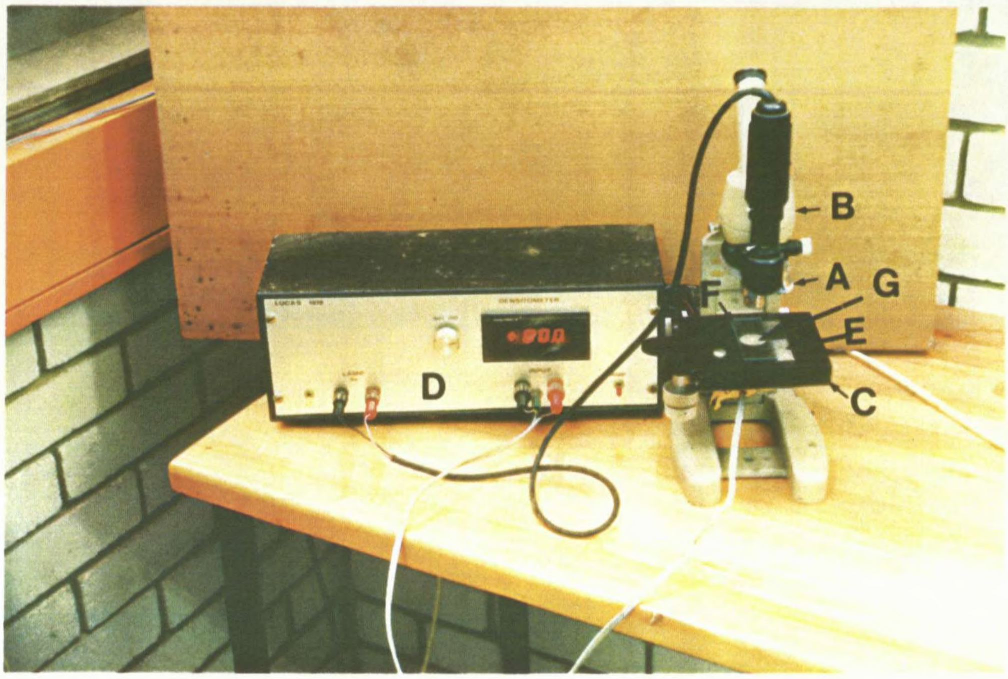
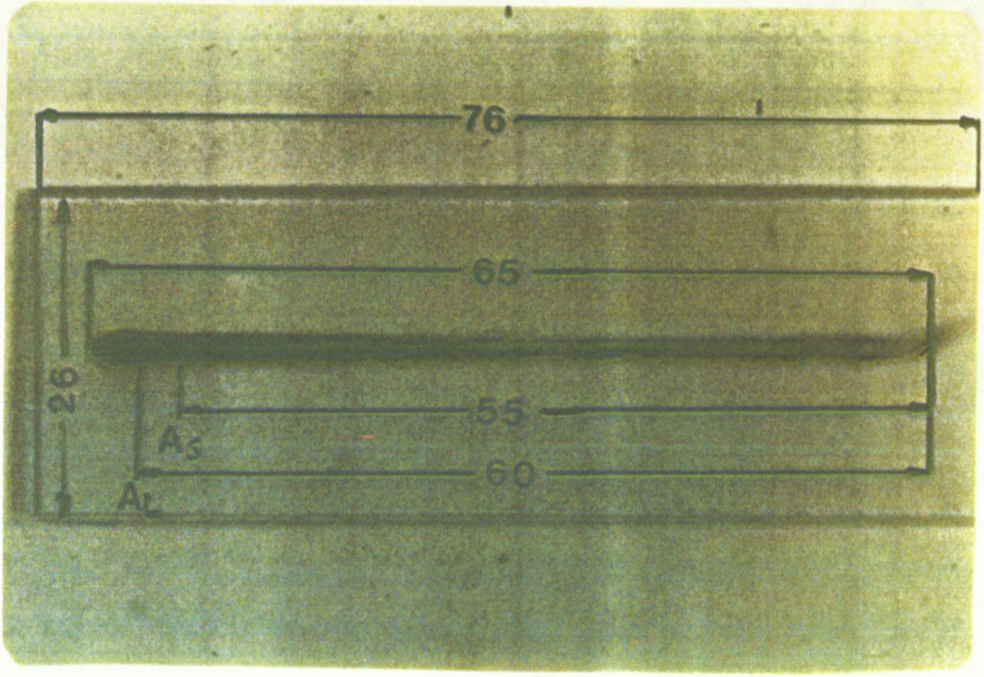


PLATE 3.2: DENSITOMETER ASSEMBLY

| | |
|---|---|
| A | Bulb 6V |
| B | Light Microscope |
| C | Stage Plate |
| D | Digital Panel Meter |
| E | Metallic ruler |
| F | Ferrogram (slide) |
| G | Aperture |



All dimensions in mm

PLATE 3.3: SUBSTRATE PARTICLE PRECIPITATION MORPHOLOGY

$A_L$ = Percentage area of larger particles

$A_S$ = Percentage area of smaller particles

### 3.2.6 *Densitometer*

To be able to calculate the *Severity Index* it was necessary to measure the density of the particles deposited on the slide. A convenient and quick method of obtaining the density or percentage area covered by the particles deposited on the slide, is to measure the diffused optical density by means of an optical densitometer.

## 3.3 *CONSTRUCTION AND DEVELOPMENT OF THE DENSITOMETER*

### 3.3.1 *Introduction*

The development of the densitometer was conducted as follows:

- optical microscope and circuit diagram
- calibration
- operation

### 3.3.2 *Optical Microscope and Circuit Diagram*

The photodiode which is connected to an operational amplifier with a digital read-out (D) was devised by Mr J Lucas (Electronics Technician, University of Port Elizabeth), the circuit diagram of which is shown in Figure 3.5. The photodiode is placed under the stage of a light microscope (B) (Vickers microscope, Model No M123166). The light source is a 6 volt microscope bulb (A). The light passes through a 2 mm aperture (G) drilled through the plate on the stage (C) of the microscope under which is mounted an ***Integrated Photomatrix Limited Photodiode***. The photodiode (IPL 34) is biased by the +9v DC supply. The leakage current thus produced is fed into PIN2 of the LM 308A amplifier whose gain is set by the combination of resistors R2 and R3. This control

(R3) sets the digital panel meter to 100,0 with a clear slide only in the path of the light beam. This represents 1,0 volt, the decimal point is repositioned to have a convenient reading of 0-100,0 % hole coverage (Plate 3.2). Capacitor (C2) acts to smooth the signal thus minimising the flicker on the digital read-out. The diode (D1) is to prevent destruction of the IPL 34 should the leads of the supply be reversed.

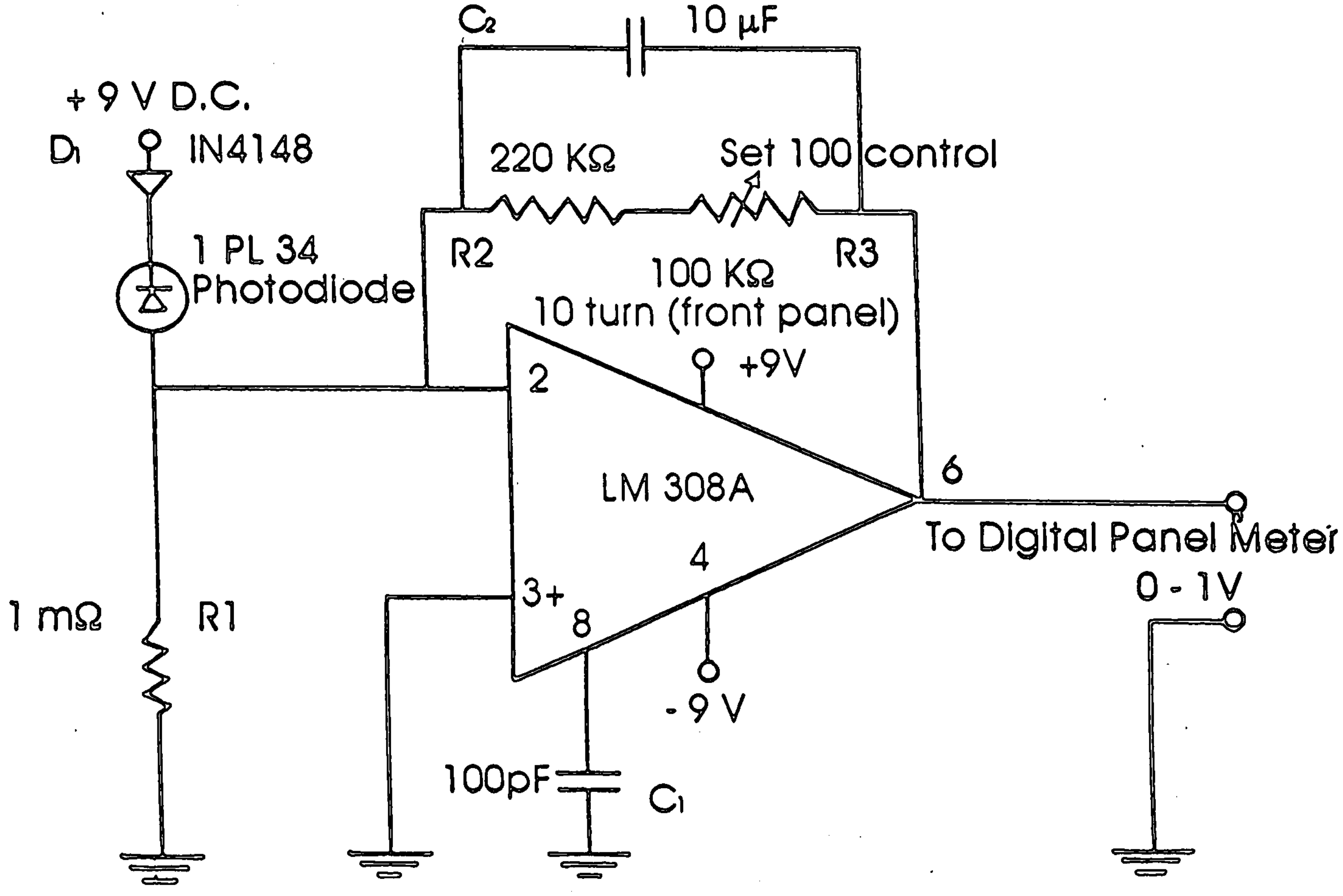


**FIGURE 3.5:** **Optical Densitometer Circuit Diagram**

### 3.3.3 *Calibration*

To calibrate the densitometer a graph was plotted on percentage area covered versus milli-volt reading (Figure 3.6). The calibration was done in two phases, namely:

- setting up the microscope; and
- calibrating the photocell.

#### 3.3.3.1 Setting up the microscope

The stage of a Vickers microscope was adapted to accommodate a disk (G) with a 2 mm diameter hole. The disk was fitted in the base plate of the microscope and the whole stage assembly (C) was then locked. The microscope was then focused and lined up to the 2 mm diameter hole. A clear slide was then placed over the 2 mm hole and the microscope was again focused on the top of the slide for repeatability purposes.

On top of the stage (C) a metallic graduated ruler (E) was glued in such a position that the ferrogram (F) could slide parallel to and in contact with the ruler. The movement along the ruler was such that the precipitated particles on the slide would move in line over the 2 mm aperture (G) of the stage of the microscope (Plate 3.2). The purpose of the ruler was to ensure a reference point for taking readings along the ferrogram (5 mm intervals).

### 3.3.3.2 Calibration of the photocell

The calibration of the photocell was done by using a template with ten known size holes (0.305 - 1,58 mm). These holes were drilled through a thin strip of brass (0,085 mm) plating. This was done with the aid of two supporting plates of 1 mm thickness each on either side of the thin plating to avoid tearing and burring of edges during the drilling operation. The diameter of each hole was then counter-checked with a measuring microscope, and the readings tabulated and recorded (Table 3.1).

To determine the response of the photocell the densitometer was set to read 100.0 milli-volt. This was done by focusing onto a clear part of a glass slide. Thereafter the focus distance was kept constant for all subsequent readings by locking the stage of the microscope. The template was then held on top of the glass slide over the 2 mm aperture, and moved manually until the maximum milli-volt reading was obtained. This process was repeated for each of the ten holes, the idea being that as the aperture of the template holes became smaller in diameter a smaller amount of light would pass through to the photocell. Consequently a lower milli-volt reading would be recorded, implying that the percentage area would have increased. The milli-volt readings were converted to a percentage area covered and the results were presented graphically. (Table 3.1 and Figure 3.6).

**TABLE 3.1:** **TABULATED READINGS OF THE DIAMETER OF HOLES DRILLED AND MILLI-VOLT READINGS TAKEN USING THE DENSITOMETER**

| Diam. of hole drilled mm | Area of hole drilled mm | Milli-volt reading on densitometer | Percentage area covered |
|---|---|---|---|
| 1,58 | 1,96 | 98,60 | 0 |
| 1,50 | 1,79 | 88,40 | 8,70 |
| 1,39 | 1,52 | 76,10 | 22,70 |
| 1,31 | 1,35 | 66,10 | 31,30 |
| 1,17 | 1,08 | 56,00 | 45,20 |
| 1,08 | 0,92 | 48,60 | 53,30 |
| 1,01 | 0,80 | 43,70 | 59,20 |
| 0,75 | 0,45 | 23,00 | 77,20 |
| 0,56 | 0,25 | 12,80 | 87,50 |
| 0,31 | 0,07 | 4,20 | 96,40 |

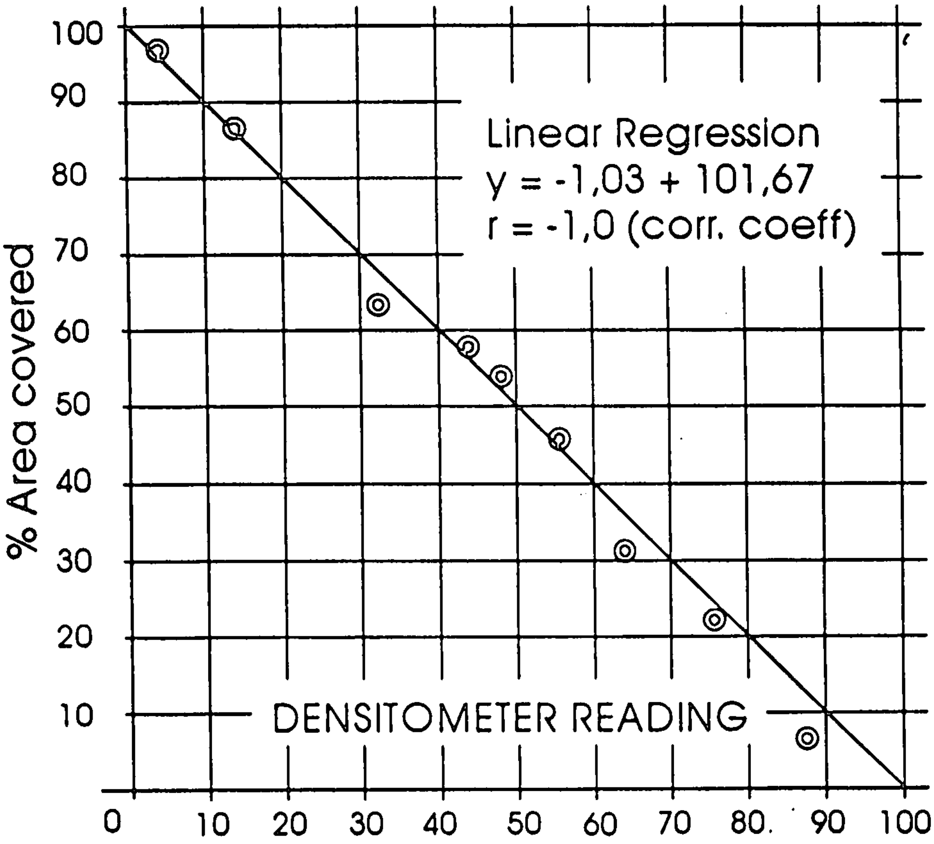


**FIGURE 3.6:** **Calibration Curve for Photo-diode Optical Densitometer**

The calculation of the percentage area covered was done as follows:

The 1,58 mm diameter hole was taken as the closest aperture to the 2 mm hole drilled in the base plate of the microscope. Therefore the area calculated for the 1,58 mm diameter hole was taken as the reference zero percentage area covered and the maximum millivolt reading was then recorded (98,6 milli-volt).

The percentage area covered for the remaining holes was calculated as follows, using the 1,50 mm diameter hole (refer second reading in Table 3.1) as an example:

$$\frac{(1,961 - 1,791)}{1,961} \times 100 = 8,669 \approx 8.7\ \%$$

The results are shown in Table 3.1 and Figure 3.6.

### 3.3.4 *Operation*

To carry out an analysis of the precipitated particles on a slide (ferrogram) the microscope was focused on a clear part of the glass slide and the densitometer set to register 100.0 (1 volt). The microscope was then set to measure readings of particle densities on the ferrogram. Readings of particle density were taken at the 60 mm position (highest density reading) and 55 mm position (lower density reading) measured along the metallic ruler (E) on the stage. (Plate 3.2). The readings are referred to as $A_L$ and $A_S$ where:

- $A_L$ represents the percentage area covered at the 60 mm position consisting of larger particles, and

- $A_S$ represents the percentage area covered at the 55 mm position consisting of particles of the smaller sizes (Plate 3.3).

The more severe the wear situation becomes, the larger the particle size. Seifert and Westcott (1972) reported that the difference in percentage area covered by the large particles to small particles will increase as failure is approached or when the "health" of the machine is deteriorating. Thus the product $(A_L-A_S)A_L$ can be used as a quantitative means of monitoring the condition of operating machinery. This is known as the ***Severity Index*** (***Is***). Hofman and Johnson (1977) show that the difference of squares of the larger readings minus the smaller readings is also used, i.e. $A_L^2-A_S^2 = Is$ giving a slightly bigger difference in parameter than the above.

For the purpose of this investigation the Hofman and Johnson (1977) method of calculating ***Severity Index*** was adopted.

Some useful properties of the ***Severity Index*** (Is) according to Hofman and Johnson (1977) are as follows:

- Being the product of two parameters it will increase rapidly as the wear condition deteriorates.

- Evenly distributed contaminants on the Ferrogram for example sand, will increase both $A_L$ and $A_S$ similarly, thus *Is* will not increase as rapidly as in the case of severe wear condition.

- During break-in of an engine both $A_L$ and $A_S$ decrease with time (Scott *et al.*, 1976). If $A_L$ does not decrease during break-in an abnormal condition then exists that requires immediate attention.

## 3.4 PARTICLE MANUFACTURING METHODS

To be able to validate the sensitivity of the Ferro-precipitator, ferrous particles of known sizes were needed. Since these particles were not readily available in standard form in industry, methods had to be devised to obtain these particles. Two methods, namely surface grinding and sieving, were utilised to produce the particles. Each method as well as the particle validation procedure is discussed separately.

### 3.4.1 *Surface Grinding*

#### 3.4.1.1 Particle manufacture method

A surface grinder, used for polishing and grinding of tool and die equipment in the toolmaking industry, was employed. The setting of the applicable machine was as follows:

| | | |
|---|---|---|
| Grinding wheel speed | 2500-3600 | rpm |
| Table longitudinal feed | 630 | mm |
| Table cross feed | 220 | mm |
| Wheel head vertical feed | 350 | mm |
| Range of cross feed | 0,50 | mm |
| Vertical infeed | 0,01 | mm |
| One division on scale | 0,01 | mm |

The material used was placed on the electro-magnetic base and the electrical current was switched on to secure the workpiece in place. The surface of the mild steel workpiece was machined to a true surface. The machine was then cleaned using an industrial vacuum cleaner. A sheet of paper was placed between the magnetic base of the machine and the mild steel workpiece. Adjustments were made to the vertical infeed to obtain particles of the initial required size. By engaging the crossfeed, these particles were generated and collected on the sheet of paper. Once the surface of the workpiece was traversed, the crossfeed was returned to its initial position and the vertical infeed was then set for the next particle size.

Six size ranges of particles were generated and before each range was machined the grinder surfaces were vacuumed and the paper was changed. The particles collected were placed in 100 ml glass bottles and lubrication oil (100 ml) added to prevent the particles from rusting.

The following six ranges and machine settings were taken:

| Range microns | Machine setting microns |
|---|---|
| 50-60 | 55,0 |
| 40-50 | 45,0 |
| 30-40 | 35,0 |
| 20-30 | 25,0 |
| 10-20 | 15,0 |
| 5-10 | 7,5 |

Upper and lower limits for each range were considered since a variation of machined particle sizes would exist as a result of the temperature created by repetitive cuts executed on the mild steel workpiece and the grinding wheel not being dressed after each cut. Approximately 40 vertical settings were carried out per machine setting so as to obtain a fair amount of particles.

### 3.4.1.2 Validation of particle sizes

The collected oil samples were then shaken in the bottles to obtain a homogeneous mix. Approximately 1 ml of the mix was placed into another 100 ml bottle and 4 ml of solvent (ethyl-ether) was added to aid the mobility of the particles. This solution was then passed through the Ferro-precipitator at a rate of 8,0 ml/min so as to obtain a good spread of particles along the slide for the purpose of measuring particle size only. This process was repeated for each particle range. The particles were then measured per range using a reflected light Vickers microscope with a calibrated eyepiece. The results were tabulated (Appendix 7.1, Table 3.2 and Figure 3.7) and a statistical evaluation was conducted.

Since the particles were produced using the grinding method on a machine set to a predetermined setting, it was necessary to establish whether the sizes of the particles produced correlated with the machine settings within acceptable limitations. The procedure followed was to compare the machine particles with the measured particles, with the objective of establishing the relationship between the machined and optically measured particles. Once the particles were measured, a statistical evaluation was conducted by plotting a linear regression of optical measured particle size (dependant) versus machine ground particle size (independent) (Figure 3.7).

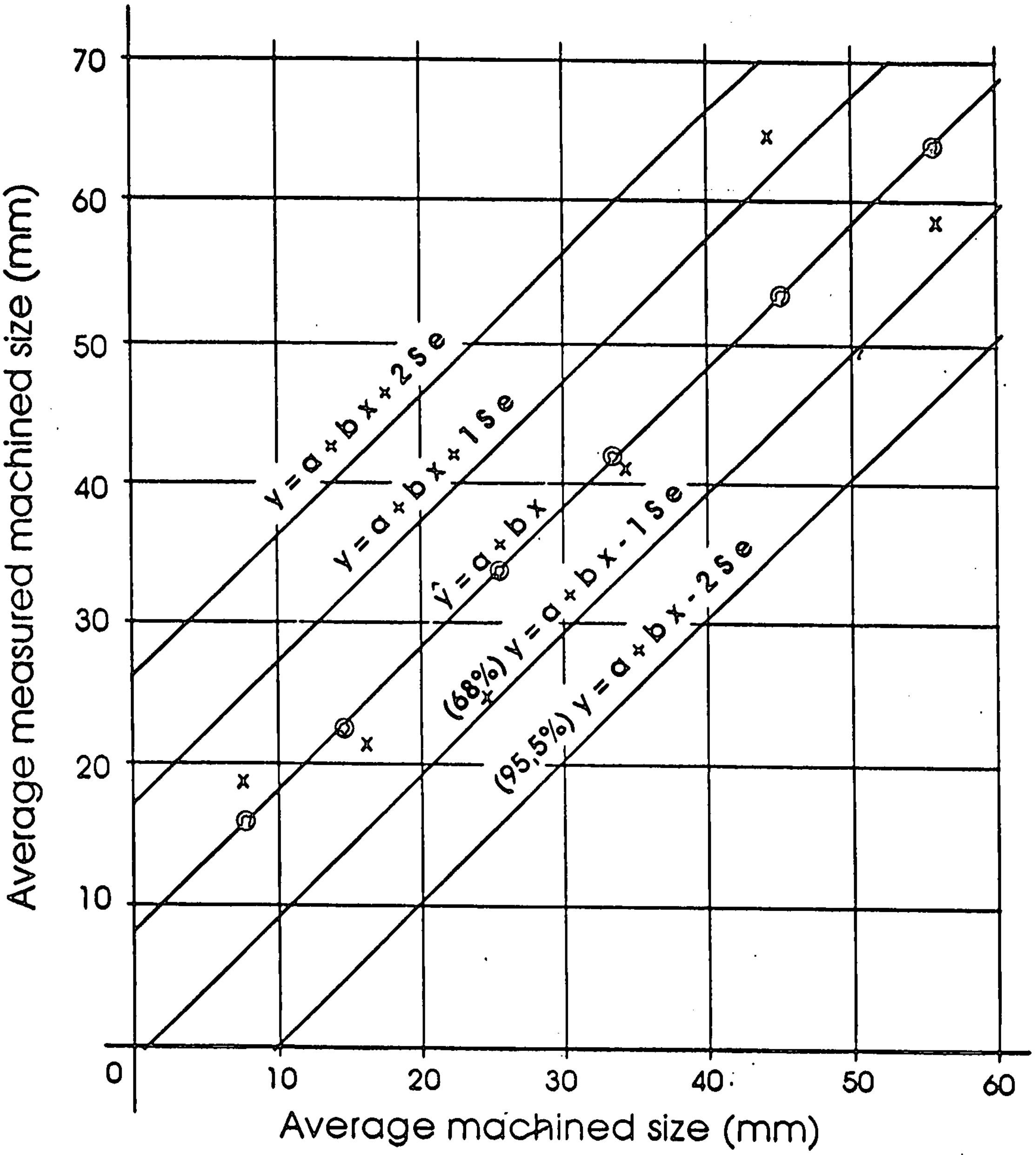


**FIGURE 3.7:** **Calculated Standard Errors of Estimation (Se) around the Regression of Machined and Measured Average Particle Sizes in Millimetres**
*X = actual readings*
*◎ = regression line readings*

### 3.4.1.3 Statistical Evaluation

The results of the grinding method are shown in Table 3.2 and Appendix 7.1.

**TABLE 3.2: SUMMARY OF THE PARTICLE SIZES PRODUCED USING GRINDING METHOD.**

| Particle size (micron) | No. of readings | Mean of each set of readings (micron) | Sample std deviation (micron) | Coefficient of variation* |
|---|---|---|---|---|
| 50-60 | 35 | 56,00 | 10,91 | 0,19 |
| 40-50 | 35 | 47,91 | 7,51 | 0,16 |
| 30-40 | 35 | 37,68 | 7,46 | 0,20 |
| 20-30 | 35 | 24,40 | 5,44 | 0,22 |
| 10-20 | 35 | 15,51 | 6,43 | 0,42 |

* Defined as $= \frac{\text{Sample standard deviation}}{\text{Mean of each set of readings}}$

#### 3.4.1.3.1 Linear Regression Analysis

$\Sigma X$ = Sum total of independent variable (Machined particles)

$\Sigma Y$ = Sum total of dependent variable (Measured particles)

$\overline{X}$ = Mean of values of independent variables

$\overline{Y}$ = Mean of values of dependent variables

n = Number of data points

b = slope of linear regression line

a = Y intercept

Where $\overline{X} = \frac{\Sigma X}{n}$ and $\overline{Y} = \frac{\Sigma Y}{n}$

$Y^1 = bX + a$

Where $b = \frac{\Sigma XY - n\overline{XY}}{\Sigma X^2 - nX^2}$

and $a = \overline{Y} - b\overline{X}$

|  | X (average machined size-mm) | Y (average machined size-mm) | XY | X2 | Y2 |
|---|---|---|---|---|---|
|  | 15 | 15,51 | 232,65 | 225 | 240,56 |
|  | 25 | 24,40 | 610,00 | 625 | 595,36 |
|  | 35 | 37,68 | 1318,80 | 1225 | 1319,78 |
|  | 45 | 47,91 | 2155,95 | 2025 | 2295,37 |
|  | 55 | 56,00 | 3080,00 | 3025 | 3136,00 |
| SUM | 175 | 181,50 | 7397,40 | 7155 | 7687,07 |

### 3.4.3.1.2 Calculation of linear regression formula

$\bar{X} = \Sigma Xn = 175/5 = 35 \quad \bar{Y} = 181{,}5/5 = 36{,}3$

$$b = \frac{7397{,}4 - 5 \times 35 \times 36{,}3}{7155 - 5 \times 35 \times 35} = 1{,}014$$

$a = 36{,}3 - 1{,}014 \times 35 = 0{,}18$

Therefore $\underline{Y^1 = 0{,}18 + 1{,}014X}$

| $Y^1$ | X |
|---|---|
| 15 | 15,39 |
| 25 | 25,53 |
| 35 | 35,67 |
| 45 | 45,18 |
| 55 | 55,95 |

The regression line is shown on a scatter diagram (Figure 3.7)

### 3.4.1.3.3 Calculation of Standard Error of Estimation (Se)

$$Se = \left( \frac{\Sigma Y^2 - a\Sigma Y - b\Sigma XY}{n - 2} \right)^{\frac{1}{2}}$$

$$Se = \left( \frac{7687{,}07 - 0{,}18 \times 181{,}5 - 1{,}014 \times 7397{,}4}{5 - 2} \right)^{\frac{1}{2}}$$

= **7,15**

The Standard Error of Estimation values for ± 1Se (68% points within) and ± 2Se (95,5% points within) are shown on figure 3.7

### 3.4.1.3.4 Calculation of coefficient of correlation

$$r = \left(\frac{a\Sigma Y + b\Sigma X\bar{Y} - nY^2}{\Sigma Y^2 - nY^2}\right)^{½}$$

$$= \left(\frac{0{,}18x181{,}5+1{,}014x7397{,}4-5x36{,}3x36{,}3}{7687{,}07 - 5 \text{ x } 36{,}3x36{,}3}\right)^{½}$$

**= 0,928**

### 3.4.1.4 Particle deposition along the slide - grinding method

To verify particle size spread, using the Ferro-precipitator and the densitometer described in Section 3.3, six oil samples containing particle sizes ranging from 10-20 microns, 20-30 microns, 30-40 microns, 40-50 microns, 50-60 microns and a combined sample mix of 10-60 microns, were made up. The combined sample mix was made up to specifically verify whether the different size particles or ranges of particles would deposit themselves into a size format. A fixed volume of each (1 ml) was pumped through the Ferro-precipitator at approximately 0,5 ml per minute, as flow rates below this value proved to be unstable. Once the rinsing cycle was completed, the slides were then prepared for the densitometer. Readings were taken along each slide (percentage area) at intervals of 5 mm from the slide entry for a distance of 20 mm down the slide. These readings were tabulated (Appendix 7.3) and a super-imposed graph of distance along the slide versus percentage area covered, was plotted (Figure 3.8 and Appendix 7.3).

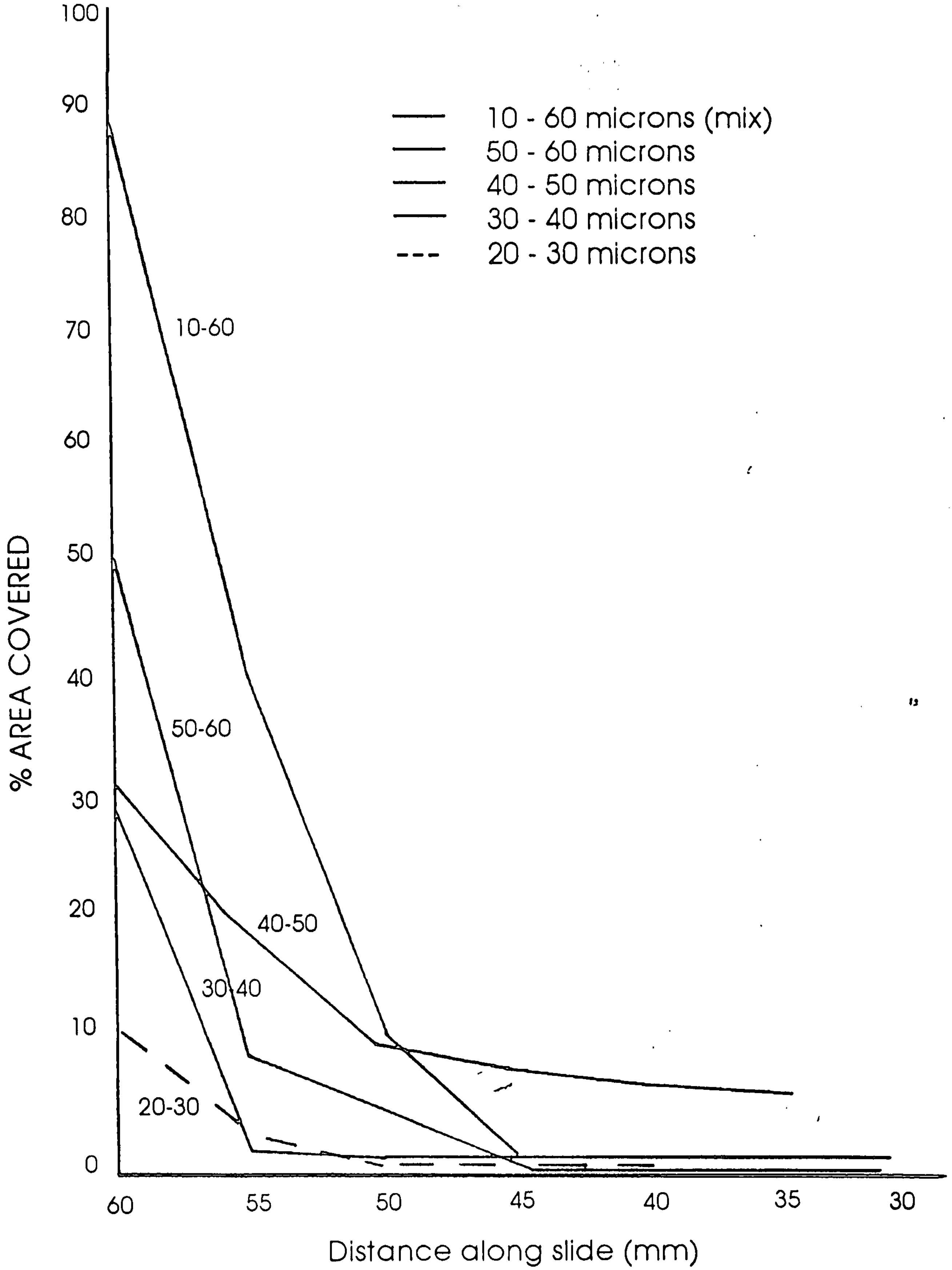


**FIGURE 3.8:** Graphical Demonstration of Variation of Machined Particle Sizes Distributed along the Slide

The graph shows the tendency of the major collection of particles occurring at the entrance of the slide within the first 5 mm, and for the same volume pumped per particle size range, the bigger particle ranges tended to precipitate earlier (referring to the slope of the line of the graphs) than the smaller particles. The graph also demonstrates that the mixed sample of particles followed the same trend. Similar observations were reported by Hofman and Johnson (1977).

### 3.4.1.5 Discussion of the Acceptability of the Grinding Method

The statistical analysis of the grinding method revealed a strong correlation (r = 0,928) between the machined particles and the optically measured particles. Furthermore, the determination of the Standard Error of Estimation (Se = 7,15) indicated that for the ranges ± 1 Se and ± 2 Se, 95,5 % and 86 % of the points respectively fall within the range of the linear regression line.

Optical observations of the machined particles revealed shredding characteristics, i.e. longitudinal particles being produced due to the grinding method used. This is a characteristic of the type of metal used for grinding (mild steel). Consequently, when optical measurements were made only the width of the particle was measured. Although the test carried out (Figure 3.8) indicated diminishing particle size to distance along the slide, it was felt that an alternative means of producing particle sizes should be investigated. The objective was to produce particles that were more uniform.

### 3.4.2 Sieving Method

#### 3.4.2.1 Particle manufacture method

Judging from the results obtained using the grinding method, it was desired to find an alternative means of manufacturing micron size ferrous particles. A sieving procedure was then adopted to manufacture a particle size range up to 75 microns. Star Screen stainless steel sieves of sizes 75, 63, 53, 38, 32 and 25 microns were used. The 10 micron sieve was not available on the market.

An Endecotts Test Sieve shaker was used, borrowed from the Civil Engineering Department, Technikon, Natal. Nickel/chromium (95% Ni/5% Cr) metal particles were obtained (90 micron maximum size) from U.T.P. Welding, 9 Telford Road, Industria, Johannesburg. These particles were then sieved using the above mentioned sieves and shaker. The sieves were stacked one below the other, starting from the biggest 75 microns to the smallest 25 microns. Sieving was carried out on a daily six hour basis and checked at the end of each day, by removing the sieves from the shaker and tilting each sieve in a sideways motion so as to avoid bunching of particles. The sieves were then attached to the shaker again and the shaking process was continued. This process was repeated for 5 days and the particles per sieve size 75-63, 63-53, 53-38, 38-32, 32-25 and 25-0 microns were then bottled in 100 ml cleaned glass bottles.

To confirm the particle range sizes, specimens were morphometrically evaluated using a "Zetopan" Reichart light microscope with a X10 objective interfaced with a Noran "Voyager 2001" EDX and micro-imaging system (SEM Department, University of Durban/ Westville). When examining the measurements obtained for the particle range

25-0 microns, it was found that very few of the particles measured fell below 10 microns in size. It was therefore accepted that the lower particle range could be taken as 25-10 microns. These particles were measured in length and breadth and the average was used as representing the particle size (refer Appendix 7.2 Picturegrams). The same procedure of statistical evaluation as in Section 3.4.1.2 was followed.

### 3.4.2.2 Statistical evaluation

The results of the sieving method are shown in Table 3.3 and Appendix 7.2 and the regression graph (Figure 3.10) was plotted.

TABLE 3.3: SUMMARY OF THE PARTICLE SIZES USING THE SIEVING METHOD.

| Particle size (micron) | No. of readings | Mean of each set of readings (micron) | Sample std deviation (micron) | Coefficient of variation* |
|---|---|---|---|---|
| 10-25 | 50 | 4,21 | 4,21 | 0,21 |
| 25-32 | 50 | 6,19 | 6,19 | 0,23 |
| 32-38 | 50 | 32,38 | 7,11 | 0,22 |
| 38-53 | 50 | 42,00 | 6,16 | 0,15 |
| 53-63 | 50 | 49,45 | 10,04 | 0,20 |
| 63-75 | 50 | 59,10 | 12,54 | 0,21 |

$$* \text{ Defined as } = \frac{\text{Sample standard deviation}}{\text{Mean of each set of readings}}$$

The linear regression of sieved particles to optical measured particles was plotted and the correlation coefficient was calculated (Figure 3.9)

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| Particle size (micron) | No. of readings | Mean of each set of readings (micron) | Sample std deviation (micron) | Coefficient of variation* |
|---|---|---|---|---|
| 10-25 | 50 | 4,21 | 4,21 | 0,21 |
| 25-32 | 50 | 6,19 | 6,19 | 0,23 |
| 32-38 | 50 | 32,38 | 7,11 | 0,22 |
| 38-53 | 50 | 42,00 | 6,16 | 0,15 |
| 53-63 | 50 | 49,45 | 10,04 | 0,20 |
| 63-75 | 50 | 59,10 | 12,54 | 0,21 |

Sample standard deviation
* Defined as = = Mean of each set of readings

The linear regression of sieved particles to optical measured particles was plotted and the correlation coefficient was calculated (Figure 3.9)

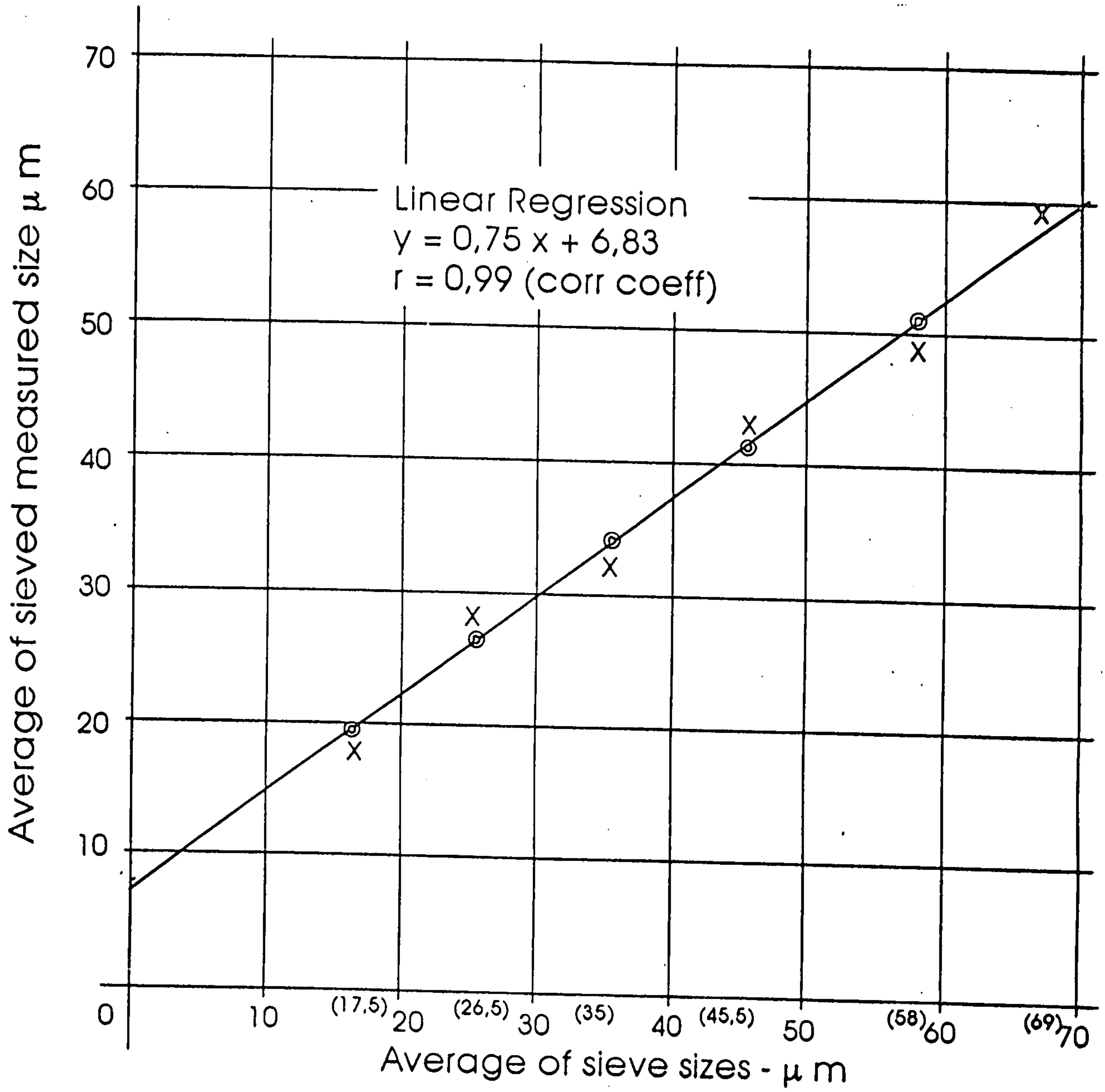


**FIGURE 3.9:** **Linear Regression for Averaged Measured and Sieved Particle Sizes**
*X = actual readings*
*⊚ = regression line readings*

### 3.4.2.3 Particle deposition along the slide - sieve method

To verify particle size spread, using the Ferro-precipitator described in Section 3.2, a mass of 0,05 grams of each sample sieved, i.e. 10-25, 25-32, 32-38, 38-53, 53-63 and 63-75 microns, was weighed using a METTLER PJ 3600 DELTA RANGE electronic scale with an accuracy of 0,00 g, by placing the 100ml glass bottle on the scale and zero-ing the scale, then adding the particles into the bottle. Oil (Caltex - multigrade) and ethyl-ether were then added into each bottle to promote mixing in the ratio of 10:1 by volume, using a measuring flask.

Prior to test, each sample was heated to approximately 70 $^{0}$C and well shaken to avoid particles adhering to the sides of the bottle. A pump speed of 0,5ml/min. was chosen, since it was found that speeds below this value tended to create unsteady flow.

To avoid magnetic field interference when pumping the samples through the Ferro-precipitator, the sample bottles were held vertically, upside-down, above the entrance. This was achieved by drilling a hole through the top of a 100ml bottle. The hole was large enough to pass the suction side of the silicon tube through and allow it to protrude about 2 cm into the bottle. For each sample tested, this top was attached to the sample bottle. Care was also taken to ensure that the sample bottles were not under pressure due to the heating and shaking carried out prior to the commencement of the pumping cycle.

A fixed volume of each sample above (1 ml) was pumped through the Ferro-precipitator. Once the rinsing cycle was completed, the slides were then prepared for the densitometer. Readings were taken along the length of each slide, at 5 mm intervals for a distance of 20 mm starting at entry, and converted to percentage area covered (refer to Section 3.4.1.4).

These readings were tabulated (Appendix 7.4) and a super-imposed graph of distance along the slide versus percentage area covered, was plotted (Figure 3.10).

The graph shows the tendency of the major collection of particles to occur at the entrance side of the slide within the first 5 mm; and for the volume pumped per particle size range, the bigger particles tended to precipitate earlier (referring to slope of graphs) than the smaller particles. This is due to the varying strength of the magnetic field created by the tilt of the slide to the magnet. A similar observation was reported by Hofman and Johnson (1977). The significance of this phenomenon is discussed in Section 5.2.2.

### 3.4.2.4 Discussion of the Acceptability of the Sieving Method

The statistical analysis of the sieving method revealed that a strong correlation ($r = 0{,}99$) existed between the sieved particles and the same optically measured particles. Furthermore, the determination of the Standard Error of Estimation ($Se = 0{,}864$) indicated that for the ranges ± 1 Se and ± 2 Se i.e. 86 % and 95,5 % of the points respectively, fall within the 95,5 % region on either side of the linear regression line ( Figure 3.9).

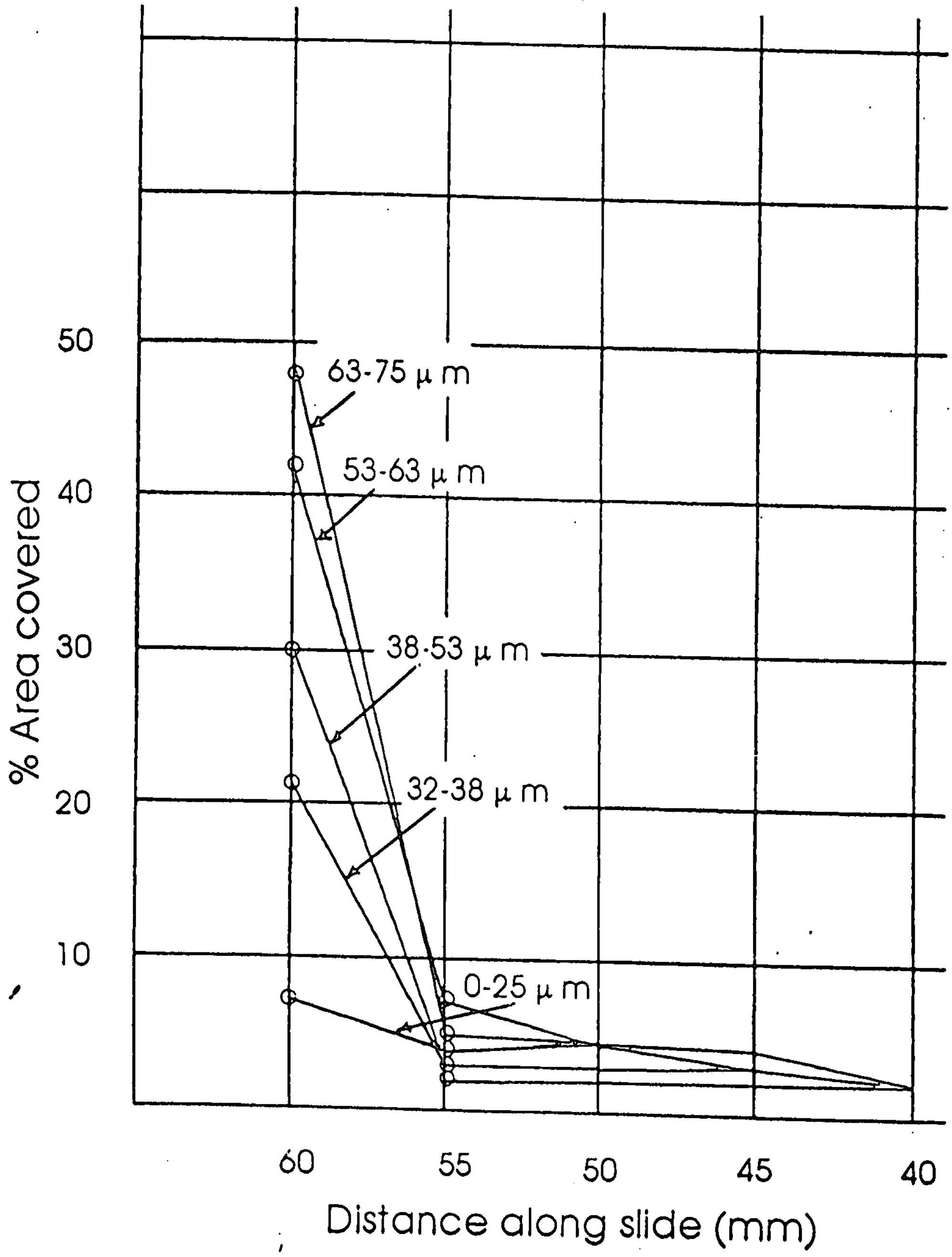


**FIGURE 3.10:** Graphical Demonstration of Variation of Sieved Particle Sizes Distributed along the Slide

The morphometrical evaluation of the particles (Appendix 7.2) revealed that a more uniform particle was produced. This observation explains the high correlation value recorded between the sieved and optically measured particles. A strong similarity in the distribution of particle sizes along the slide between the grinding method (Figure 3.8) and the sieving method (Figure 3.10) for particles produced, was also evident. A combined sample mix could not be evaluated in this case since the particles were weighed, making it almost impossible to obtain a representative mix.

## 3.5 *DISCUSSION OF LOCALLY DEVELOPED FERRO-PRECIPITATOR*

During the design of the Ferro-precipitator the following variables were kept constant:

- the strength of the magnetic field (Section 3.2.2)
- the substrate holder (Section 3.2.3)
- densitometer operation (Section 3.3.4).

The results obtained (Figure 3.8 and 3.10) demonstrate that the variable constraints proved to be acceptable for the design considered. The instrument was tested using two different methods of manufacturing and measurement of particles. The results indicated that the Ferro-precipitator was sensitive to both types of particles subjected to the system and that an overall sensitivity range of 10 to 75 microns was established. The hypothesis that the Ferro-precipitator would be sensitive to particle sizes 1 to 75 microns has therefore been accepted.

It appears that the sensitivity of the Ferro-precipitator is directly dependent on the area occupied by the particles on the slide. This is borne out by the fact that since two different methods of particle manufacture were evaluated, (Section 3.4) and although the morphological characteristics of the particles produced differed, the results (Figure

3.8 and 3.10) are similar. Because the shapes of the particles differed (shredded for grinding and uniform for sieving), it can be concluded that the similarity is due to the relativity of the densities (percentage area covered) of the particles deposited along the slide, which is influenced by the magnetic field and the flow rate over the slide.

# CHAPTER FOUR

# PRACTICAL EVALUATION OF THE FERRO-PRECIPITATOR

## 4.1 *INTRODUCTION*

As stated in the introduction in Chapter One, the practical application was adapted so as to confirm the authenticity of the Ferro-precipitator to monitor the health of a machine outside a laboratory environment. Since the Ford Motor Company, Port Elizabeth, Quality Control Section Engine Plant, were carrying out continuous bench and dynomometer tests, it was possible to extract oil from these engines at specific intervals according to their Test Schedule (Appendix 7.5). Engine running-in tests (Figure 4.1) and distribution of particles along the slide tests (Figure 4.2) were carried out on two Ford engines.

A comprehensive dynomometer test was conducted on a Volkswagen air-cooled engine donated by Volkswagen SA, Uitenhage. These results were compared with the Spectrometric method of oil analysis (Figure 4.2) conducted by Wearcheck, Durban.

As the oil sampling technique from an engine is of paramount importance to ensure consistency in sampling oil quantities for evaluation purposes, a method generally utilised (Bowen and Westcott, 1976), was adopted.

## 4.2 *OIL SAMPLING TECHNIQUES FOR FERRO-PRECIPITATOR MACHINE HEALTH MONITORING*

In order to monitor the condition and health of a machine, it is imperative that the lubricant sample taken should contain a representative selection of particles (Bowen and Westcott, 1976).

Bowen and Westcott (1976) suggested the following guidelines for use when sampling procedures for machines are specified:

1. Samples should be drawn from a single appropriate location in a system, i.e. different locations will have varied concentrations such as before and after the filter.

2. During operating conditions samples should be taken during stabilised periods, as different load conditions give varied concentrations.

3. If the machine is required to be shut down prior to sampling oil, then it is essential that the sample be taken as soon as possible after shut-down to avoid settling.

4. Changing oil is a factor which has an effect since the majority of the wear particles are then removed from the system. It is therefore necessary to consider the operational period required for the oil to return to normal equilibrium after oil change. Each machine has its own necessary characteristic operating time.

5. The frequency of sampling is normally determined by the nature of the machine. If a system is new or has just been overhauled then it is advisable to take samples every few hours to ensure proper break-in(normally 10 - 20 hours).

Bowen and Westcott (1976) demonstrated that in a high percentage of failure, evidence of an abnormality existed at, or close to, the initial stages of the machine's running. Once break-in has been established then, depending on the degree of reliability of failure prediction required, the sampling intervals can be established.

6. Oil samplings should be stored in glass containers, preferably with teflon caps, to ensure that no chemical reaction takes place.

7. Two principal errors in oil sump sampling related to the natural tendency of the particles to settle are listed:

    a. Samples removed from the bottom of the sump will contain high particle concentration due to sedimentation;

    b. Samples taken from the main body of the oil after machine shut-down, i.e. a low particle volume, could be due to debris settlement.

## 4.3 *MACHINE HEALTH MONITORING*

### 4.3.1 *Running-in Tests*

The running-in tests were conducted to demonstrate the ability of the Ferro-precipitator to monitor and identify the running-in period of an engine.

#### 4.3.1.1 Engine tests: Quality Control Schedule SA-101

The running-in tests were conducted at Ford Motor Co, Engine Plant at Port Elizabeth by their Quality Control Inspectors as normal routine checks. Two similar new engines (Table 4.1) were tested (Quality Control Test Numbers QD 1463 and QD 1468) according to Ford specifications for oil economy and performance (Ford Quality Control Schedule SA-101, Appendix 7.5). Oil samples taken at intervals listed in Tables 4.2 and 4.3 were taken and a running-in test was carried out by passing the oil through the Ferro-precipitator and the *Severity Index* versus time graphs were plotted (Figure 4.1).

**TABLE 4.1: SPECIFICATION OF THE ENGINES USED BY FORD MOTOR COMPANY FOR QUALITY CONTROL TESTS**

| | |
|---|---|
| Model | 2.0 litre O.H.C. |
| No. of cylinders | 4 |
| Bore | 90.8 mm |
| Stroke | 76.95 mm |
| Displacement | 1993 cm |
| Compression ratio | 9.2:1 |
| Carburettor | Weber 77 HF-DA |
| Distributor | GPD 76 HF-DA |
| Spark Plugs | Motorcraft BF 32 |
| Fuel | Premium 98-99 Octane |
| Oil | Caltex 20 W-30 |

### 4.3.1.2 Test schedule

The test schedule according Ford Quality Control Schedule SA-101 (Appendix 7.5) can be summarised broadly into the following steps:

1. A three-hour economy test at 3 000 r.p.m., at full throttle.
2. A three-hour oil economy test at 3 000 r.p.m., at full throttle.
3. A full throttle performance test for three hours.
4. A three-hour oil test at 1500 r.p.m. and 450 mm Hg intake depression.

During the quality control tests oil samples were taken during engine stops at intervals of 3, 6, 11,75 and 15,25 hours for engine test QD 1463 (Table 4.2) and 3, 6, 12,25 and 16,75 for engine test QD 1468 (Table 4.3). Only the running-in aspect of the test was considered for ***Severity Index*** versus time evaluation.

The oil samples collected were diluted with solvent (petroleum spirits) to a ratio of 4 to 1, by volume (Oil/Solvent) to improve precipitation, since the concentration of the wear particles in the oil collected was too high to obtain readings on the densitometer. The results were tabulated (Tables 4.2 and 4.3) and a ***Severity Index*** vs Time graph was plotted (Figure 4.1).

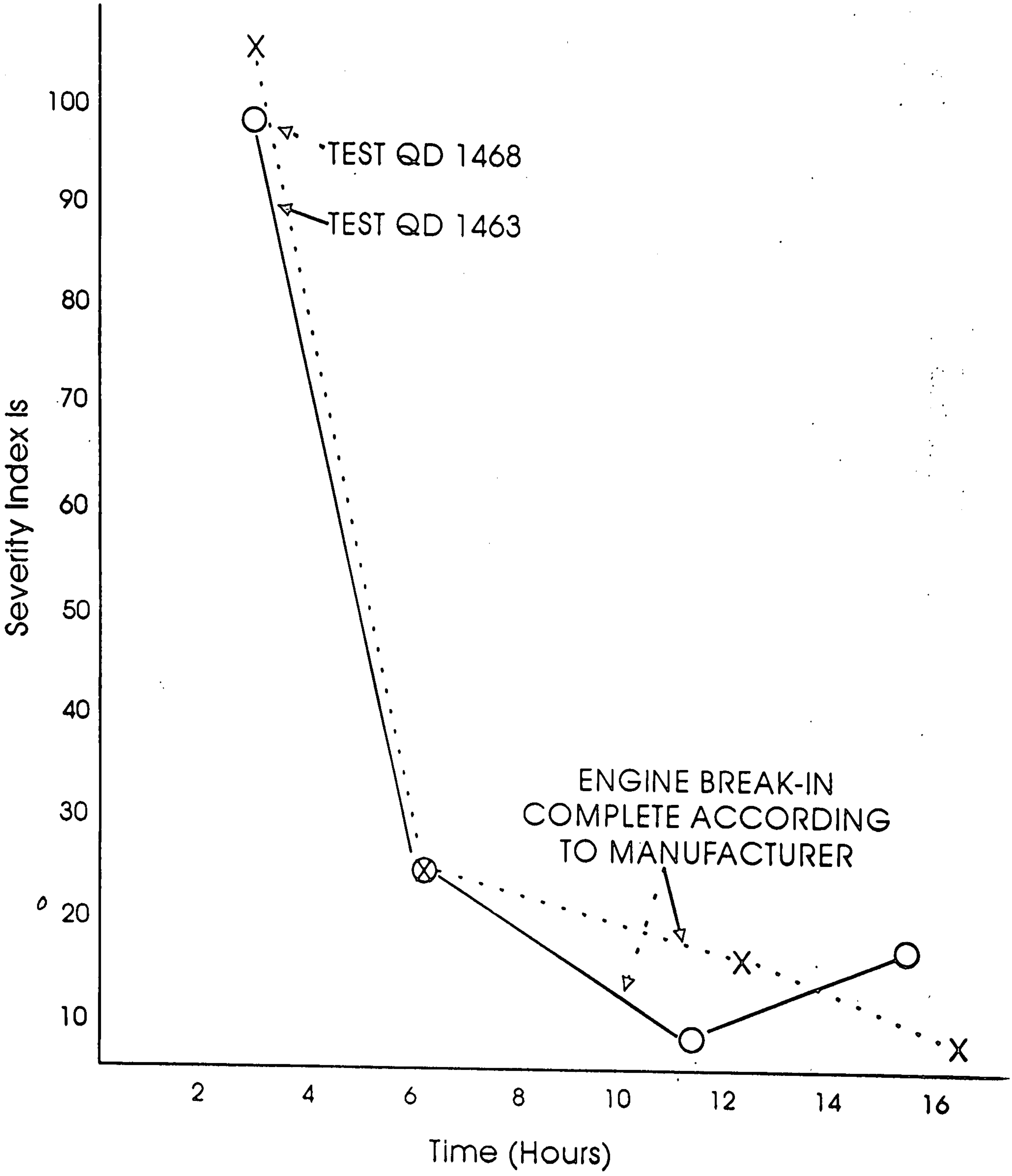


**FIGURE 4.1:** **Engine Run-in Profile of Ford Engines Quality Control Test**

### 4.3.1.3 Results

**TABLE 4.2: QUALITY CONTROL ENGINE TEST QD 1463. OIL SAMPLES TAKEN DURING ENGINE STOP INTERVALS USED TO CALCULATE THE *SEVERITY INDEX (Is)***

| Time (hours) | $A_L$* | $A_S$* | *Is* |
|---|---|---|---|
| 3,00 | 11 | 5 | 96 |
| 6,00 | 7 | 5 | 24 |
| 11,75 | 3 | 1 | 8 |
| 15,25 | 5 | 3 | 16 |

$A_L$* = percentage area covered of the larger particles at entrance on the slide.

$A_S$* = percentage area covered of the smaller particles (5 mm below $A_L$) on the slide.

**TABLE 4.3: QUALITY CONTROL ENGINE TEST QD 1468. OIL SAMPLES TAKEN DURING ENGINE STOP INTERVALS USED TO CALCULATE THE *SEVERITY INDEX (Is)***

| Time (hours) | $A_L$* | $A_S$* | *Is* |
|---|---|---|---|
| 3,00 | 15 | 11 | 104 |
| 6,00 | 7 | 5 | 24 |
| 12,25 | 5 | 3 | 16 |
| 16,25 | 3 | 1 | 8 |

$A_L$* = percentage area covered of the larger particles at entrance on the slide.

$A_S$* = percentage area covered of the smaller particles (5 mm below $A_L$) on the slide.

### 4.3.1.4 Discussion

Figure 4.1 illustrates a high wear rate associated with the running-in processes in the two engines tested. Low equilibrium wear values were achieved after about 6 - 14 hours of testing, indicating that the run-in process had apparently been completed. These results demonstrate the ability of the Ferro-precipitator to monitor engine run-in conditions. Jones *et al.*, (1977), using a ferrograph machine, obtained similar results when testing an eight cylinder Perkins engine during a piston research programme.

### 4.3.2 *Oil Filter Test*

Since the oil filters had been available for both engines after the run-in tests had been completed, it was decided to demonstrate the concept of particle distribution along the length of the slide. These tests confirm the phenomenon of particles distribution as shown in Figures 3.8 and 3.10.

#### 4.3.2.1 Test Schedule

The Oil Filter test was conducted after the Quality Control test described in Section 4.3.1, on engines QD 1463 and QD 1468, had been completed. The oil filter holders of the respective engines were removed, drained and diluted as specified in Section 4.3.1.2. One ml of each sample was then passed through the Ferro-precipitator, and then densitometer readings were then taken along the length of the slide at 5 mm intervals and tabulated (Table 4.4). The distance along slide versus percentage area covered was plotted (Figure 4.2).

#### 4.3.2.2 Results

**TABLE 4.4: OIL FILTER TESTS CARRIED OUT ON ENGINE QD 1463 AND QD 1468 AFTER TERMINATION OF QUALITY CONTROL SCHEDULE TEST**

| Distance along slide (mm) | QD 1463 Percentage area covered by particles along slide | QD 1468 Percentage area covered by particles along slide |
|---|---|---|
| 63 | 75 | 84 |
| 58 | 59 | 56 |
| 53 | 47 | 42 |
| 48 | 35 | 39 |
| 43 | 28 | 36 |
| 38 | 23 | 32 |
| 33 | 19 | 28 |
| 28 | 13 | 25 |
| 23 | 13 | 25 |
| 18 | 13 | 25 |
| 13 | 5 | 22 |
| 8 | 5 | 21 |
| 3 | 5 | 20 |

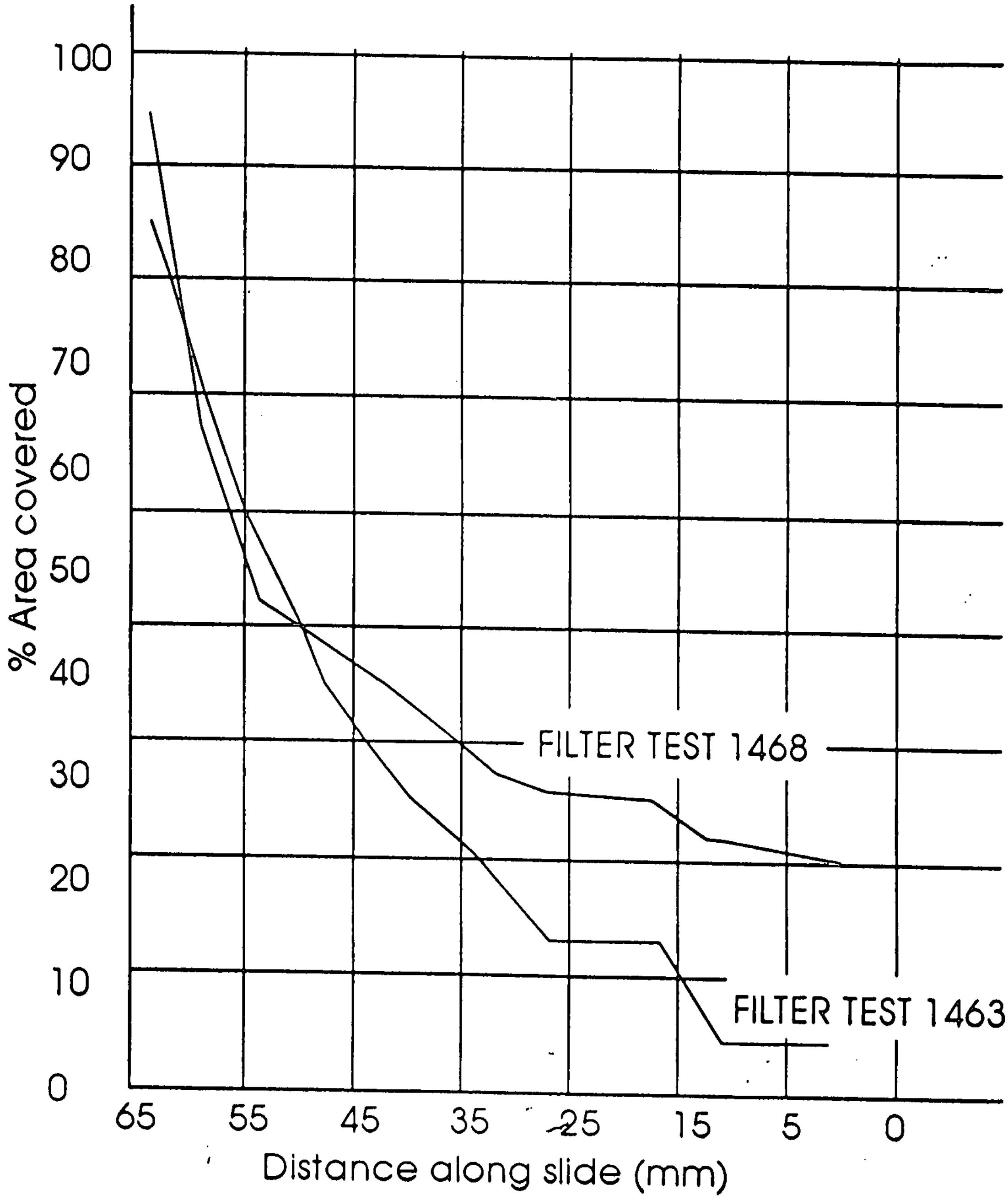


**FIGURE 4.2:** Engine Oil Filter Test of Ford Engines. Quality Control Test

### 4.3.2.3 Discussion

Figure 4.2 verifies the principle of particle distribution along the slide using the ferro-precipitator method. The larger particles precipitated at the oil entry point on the slide, and the smaller towards the exit point of the slide. This verifies the particle distribution concept of the grinding and sieving test carried out as illustrated in Section 3.4.

### 4.3.3 *96-hour Spectrometric and Ferro-precipitator Comparison Test*

The purpose of the 96-hour engine test was to compare the Ferro-precipitator with the Spectrometric analysis as conducted by Wearcheck, Durban.

### 4.3.3.1 Engine Test Information

A reconditioned four-cylinder four-stroke air-cooled petrol engine, donated by Volkswagen S.A., Uitenhage, was fitted to a 150 h.p. rated Waterbrake-type Dynamometer. The engine was run under controlled conditions according to the schedule described in Section 4.3.3.2 and oil samples were taken at fixed intervals and sent to Wearcheck, Durban for spectrometric analysis. The results were tabulated (Appendix 7.6.3) and compared.

The engine specifications were as follows:

| | | |
|---|---|---|
| Model | ................................ | 1600 cc single-port air-cooled |
| Bore | ................................ | 85,5 mm |
| No. of cylinders | ................................ | 4 |
| Stroke | ................................ | 69 mm |
| Displacement | ................................ | 1584 cc |
| Compression ratio | ................................ | 7,5:1 |
| Carburettor | ................................ | Solex 30 PICT-2 |
| Distributor | ................................ | Bosch |
| Spark Plugs | ................................ | Champion L87Y |
| Fuel | ................................ | Premium 93 Octane |
| Oil | ................................ | 20W-50 |

### 4.3.3.2 Test Schedule

The engine was mounted to a Heennen and Froude waterbrake-type dynomometer and was run at a constant speed of 2000 r.p.m. The brake load was increased gradually from 0 to 21 kW. A tap was fitted to the drain plug of the sump with an extended pipe protruding 30 mm into the sump casing of the engine to:

1. ensure the collection of a better spread of particles in the oil sample collected;

2. avoid collecting the accumulated particles settlement in the engine sump.

The engine was switched off every three hours so that a sample of oil could be collected as soon as possible after each engine stop to avoid settlement. At intermediate intervals as tabulated (Appendix 7.6.3), extra samples of oil were taken and sent to Wearcheck Durban, for Spectrographic analysis. The oil samples were collected in special containers provided by Wearcheck, Durban. After 36 hours of running (loaded at 21 kW), two fans were utilised to reduce engine temperature.

In order to demonstrate the sensitivity of the Ferro-precipitator to register above normal wear patterns in the engine, 4 grams of laboratory treated sand was added to the engine oil after 63 hours of running. Oil samples for spectrometric comparison were also collected.

The test was terminated after 96 hours of running due to permanent damage caused by the addition of the sand. The results are shown in Appendix 7.6.1 and Figure 4.3.

### 4.3.3.3 Results

The oil samples were collected over the 96-hour test period (approximately 15 days) and the oil analyses on the samples were only carried out after the engine test had been completed, due to time limitations. The results are plotted in Figure 4.3.

By comparison the two methods appear to be relatively compatible with each other, with the exception of the following factors:

1. Only ferrous particle values, from the spectrometric results (Appendix 7.6.3) obtained from Wearcheck, were considered for comparison purposes since ferrous particles are magnetically orientated.

2. The Ferro-precipitator method indicates clearly the running-in period of the engine (A-B) which is not highlighted spectrometrically (a-b).

3. It appeared that after 57 hours, just prior to adding the sand, the engine already indicated signs of failure. The Ferro-precipitator (C-D) had given an early indication of the pending failure whereas the Spectrometric method (c-d) indicated normal engine behaviour.

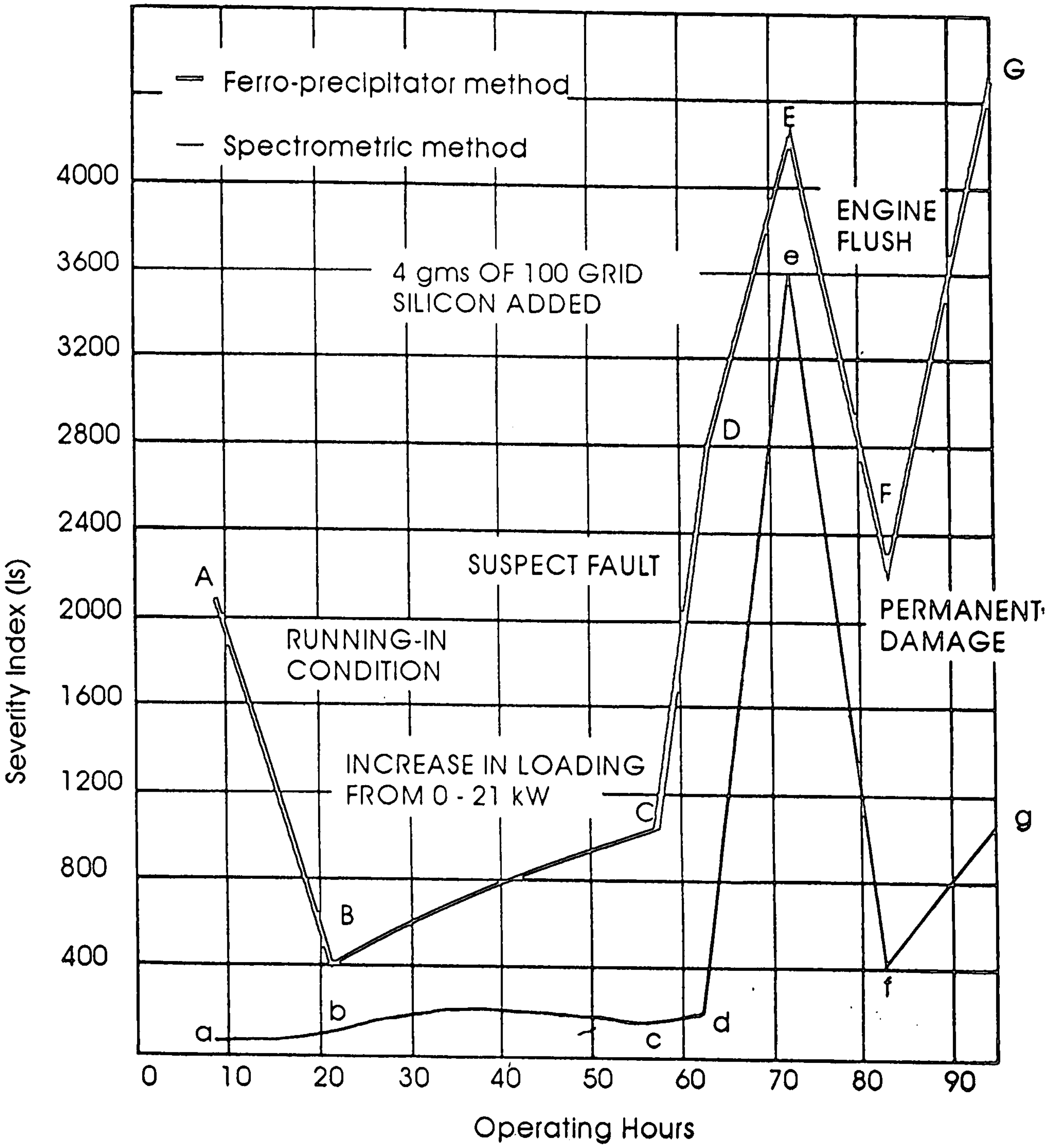


**FIGURE 4.3:** Comparison and Compatibility Test carried out on Volkswagen Air-cooled Engine. The Ferro-precipitator and Spectrometric Methods were Compared.

## 4.4 *DISCUSSION ON FERRO-PRECIPITATOR APPLICATION*

During the engine tests the sensitivity, compatibility and functional aspects of the Ferro-precipitator were demonstrated by comparing the Ferro-precipitator method with the Spectrometric (profile) method under the same test conditions (Figures 4.1 and 4.3). The correlation of the two tests is evident on the graph within the regions b-c, D-E, e-f and f-g, the exceptions being the differences that are apparent in the run-in period, and in the C-D section.

The run-in period of the engine produced abnormal wear. This was evaluated by monitoring the percentage area covered of the larger ($A_L$) to smaller ($A_S$) particles and plotting the ***Severity Index (Is)*** versus time (Figures 4.1 and 4.3).

In an investigation carried out by Seifrets and Westcott (1972) (Figure 2.2) where the ferrographic and spectrometric analysis methods were compared, a wear profile similar to that of the present investigation was demonstrated. The hypothesis that the status of engine health and the results obtained would be compatible with current research is thus accepted.

The region C-D showed excessive wear which cannot be explained without carrying out further investigations. The implications of this observation are discussed in Section 5.4.

# CHAPTER FIVE

# GENERAL DISCUSSION

## 5.1 *INTRODUCTION*

During the validation and evaluation of the Ferro-precipitator it became evident that certain aspects of the operation and specifications of the instrument needed further investigation to ensure repeatable results.

Although it was not part of the study, the literature (Bowen, Bowen and Anderson, 1978; Dalley, 1989) reported that the particles deposited on the slide could be optically analysed. Once the evaluation of the Ferro-precipitator had been completed, it was felt that further investigations could be carried out on the Volkswagen engine, using the Scanning Electron Microscope with X-Ray attachment (UPE University). The implications of this are also discussed.

## 5.2 *ASPECTS CONCERNING THE SPECIFICATIONS OF THE FERRO-PRECIPITATOR*

### 5.2.1 *The Compatibility Factor*

During the testing of the Volkswagen engine it could have been possible to evaluate the oil samples using the Ferro-precipitator immediately after the samples were taken. This was not done due to time restrictions associated with the supervision and controlling of conditions during the 96-hour test period.

By comparing this aspect of the same oil sample spectrometrically the results would only be made available after samples were tested by Wearcheck, Durban. The turn-around time for such an analysis averages a couple of days. The implications of this are manifested itself in the cost of each Wearcheck analysis and also the time lost between sampling and the results becoming available. In real terms the time delay could imply that a vehicle could be sent on the road with a possible major engine problem which should have been repaired.

The method of analysis using the Ferro-precipitator is not time consuming because once the oil sample has been collected (50 - 80ml), readings could be made on site. Because a small volume of oil is necessary for the analysis (approximately 0,5ml per minute) (Section 5.2.2.), a second test sample or more could be processed through the Ferro-precipitator. The information is therefore immediately available and the cost for the analysis relatively low.

The ability of the Ferro-precipitator to detect engine wear relatively early during the normal run-in period has also been demonstrated (Figure 4.3). The role particle sizes play during this period was emphasized since it was shown that the sensitivity was directly dependent on the area occupied by the ferrous wear particles on the slide. No other detail regarding the wear particles could be concluded except that ferrous particles were involved. In contrast, the spectrometric analysis method, although more time consuming, could provide quantitative and qualitative information (ferrous and non-ferrous) regarding the wear particles. For example, the presence of high elemental content may indicate that some constituent parts have a higher than normal wear pattern while at the same time the presence of chemical elements related to cooling water additives can be shown. It is therefore concluded that the Ferro-precipitator and Spectrographic methods complement each other in terms of time and spread of information regarding wear particles in the oil (Appendix 7.6.2 and 7.6.3).

### 5.2.2 *The Magnet and its Relation to the Slope of the Slide*

The acceptance of a magnet of 1000 millitesla and the selection of the slide-angle to magnet of 3°, was made on a trial and error basis since the literature provided no information regarding these values. For the current investigation the magnet and slope combination appeared to be acceptable according to the results obtained.

It appears that the strength of the magnet is directly dependent on the rate at which the ferrous particles are attracted and therefore the slope of the slide to the magnet should follow the same theory (Seifert and Westcott 1977). This phenomenon should be further investigated when the industrial model is being developed.

### 5.2.3 *Flow Rates*

The peristaltic pump acquired, was the most appropriate one available for this study in terms of cost and stable flow rate control. Any flow rates chosen below a flow rate of 0,5 ml/min. produced unsteady flow conditions. This flow rate proved to be acceptable for the engine tests and associated tests carried out. However, this flow rate will have to be evaluated if any further development of the Ferro-precipitator for industrial application is undertaken.

### 5.2.4 *Dilution*

Since concentrations of wear particles vary from machine to machine and as the densitometer operates on the principle that a light passing through the deposited wear particles is measured, the oil samples in certain instances need to be diluted. As the dilution of the oil samples is dependent on concentration, it is therefore necessary to establish the dilution required for each machine, and this dilution should be retained for that machine during the entire testing period.

### 5.2.5 *Test limitations*

1. Non-ferrous particles

The Ferro-precipitator is limited to ferrous particles only. However, in the working engine the crankshaft journal is in contact with the non-ferrous bearing. Consequently, during normal engine wear, the ferrous particles embed themselves into the non-ferrous particles which precipitate lower down on the slide. Consequently certain non-ferrous particles can be identified.

2. Densitometer incorporation

The portable Ferro-precipitator, described in Chapter Three, should have the densitometer incorporated as part of the machine making it possible for readings to be taken quicker after the sample collection. This should be considered should the industrial model be developed. A typical layout (actual scale) is illustrated in Appendix 7.7.

3. Sampling technique

Sampling of oils from engines and/or machinery will have to be carried out strictly and meticulously according to the sampling technique described in Section 4.2 to obtain meaningful and/or repetitive results.

## 5.3 *POTENTIAL FOR COMMERCIAL APPLICATION*

Initial cost investigations revealed that the Ferro-precipitator could be manufactured, as a portable unit, well below R20 000,00, which would make it fairly acceptable to the larger transport and/or factory maintenance establishments. This cost would justify the use of the Ferro-precipitator in terms of maintenance savings within a short period of time.

## 5.4 *APPLICATION OF FERRO-PRECIPITATOR*

### 5.4.1 ***Engine tests***

This investigation was delimited to the demonstration of the Ferro-precipitator's ability to proclaim engine health (Section 1.6). However, after the 96-hour test on the air-cooled Volkswagen engine two further preliminary tests were conducted in order to:

1. examine the wear particles on the slide (throughout each oil sample stage) and to investigate the particle morphology by using a Scanning Electron Microscope and X-Ray attachment;

2. examine actual wear pattern by dismantling the Volkswagen engine. Various engine parts were sectioned for examination under a microscope.

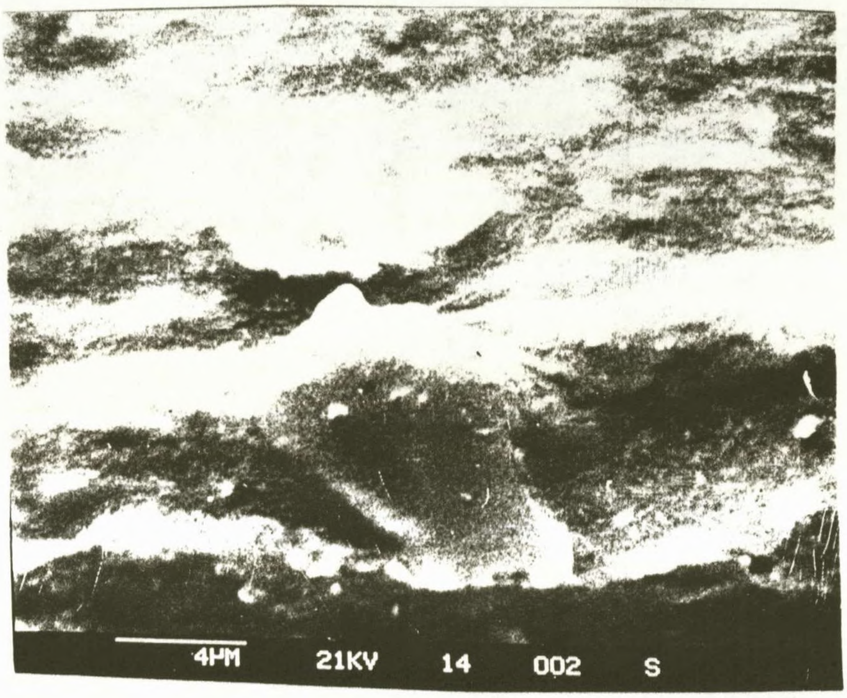
The initial investigation revealed that during the run-in period disc-shaped (plate-shaped) particles were evident as illustrated in Plate 5.1 (A - B Figure 4.3). These particles disappeared after the run-in period was completed, a phenomenon that was confirmed by Jones *et al.*, (1977). It can be speculated that such particles originate from between the honing grooves of the engine cylinders, and once the rings are 'bedded' (engine run-in), these particles tend to disappear and presumably disintegrate into smaller particles. Furthermore, generally the wear pattern of the engine appeared normal during the loading period (B - C, Figure 4.3) but between C and D something happened which could not be explained in this study. Examination of the slide under the Scanning Electron Microscope revealed non-ferrous particles deposited along the middle to the lower end of the slide (Plate 5.2 and X-Ray Plate 5.3 and Appendix 7.6.3), a possible indication of bearing failure.

The non-ferrous particles tend to deposit themselves lower on the slide due to the phenomenon (Pocock, 1977) that the bearing bushes (non-ferrous) are always in contact with the crankshaft (ferrous), with the result that small ferrous particles imbed themselves into the non-ferrous material. Since the magnetic strength is stronger at that point on the slide (due to angle of slide to magnet) the smaller ferrous particles which are attached to the non-ferrous parts are attracted. Since these observations were only carried out after the completion of the 96-hour test, no further investigations were conducted.

At D (Figure 4.3) 100 grams of silicone was added to the engine oil to promote wear. The results were catastrophic as can be seen by the cutting-type wear particles appearing on Plates 5.4 and 5.5 and the ploughing grooves shown on the crankshaft in

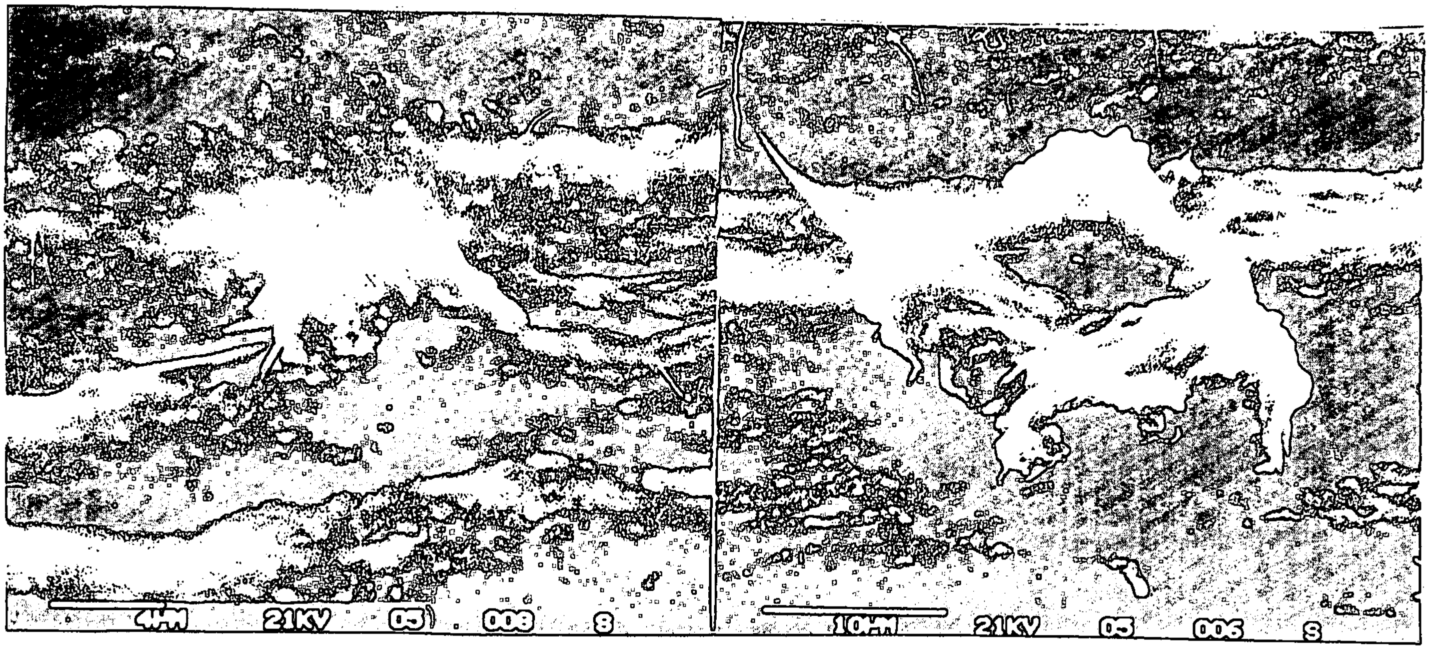
Plate 5.6. This type of wear pattern is also evident on the rings, barrels, camshaft and small-end bushes examined. The engine was flushed out F (Figure 4.3) and fresh oil was added, but after a few hours of running the damage appeared to be permanent F-G and f-g.

Further investigations in these areas need to be carried out to illustrate the nature of engine wear throughout various engine parts.



4500X

**PLATE 5.1: PLATE TYPE (DISK) FERROUS PARTICLES DURING RUN IN PERIOD**



2400X 3500X

PLATE 5.2: NON-FERROUS PARTICLE TAKEN FROM TWO ANGLES

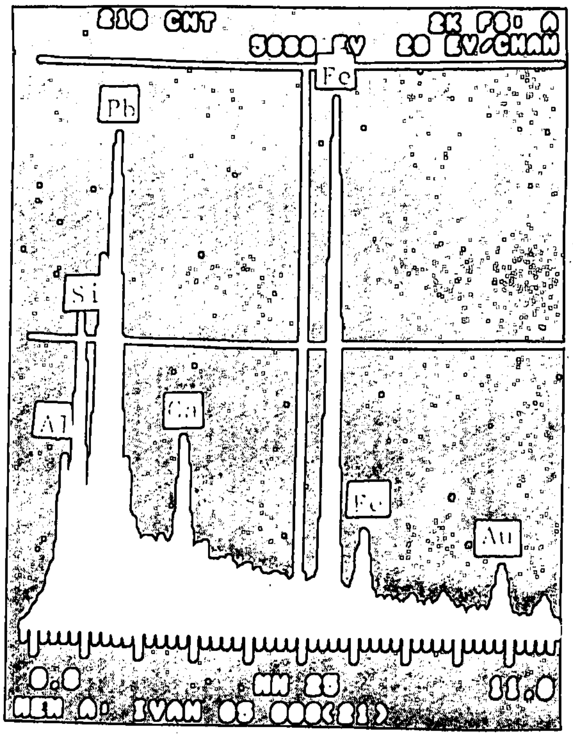
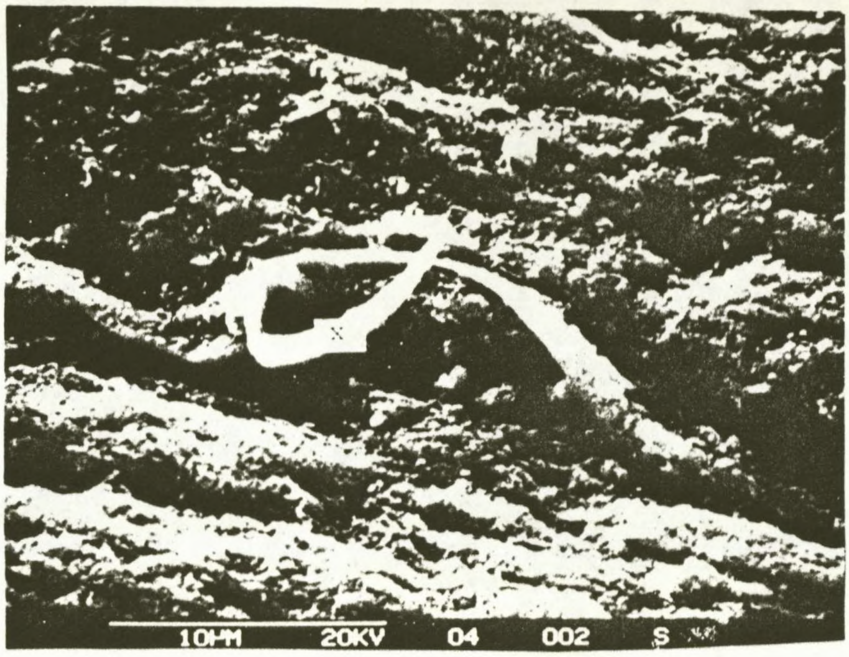


PLATE 5.3: X-RAY OF NON-FERROUS PARTICLE SHOWING HIGH CONTENT OF LEAD. THE Fe IS IN THE BACKGROUND OF THE Pb



3600X

PLATE 5.4: CUTTING TYPE FERROUS PARTICLE

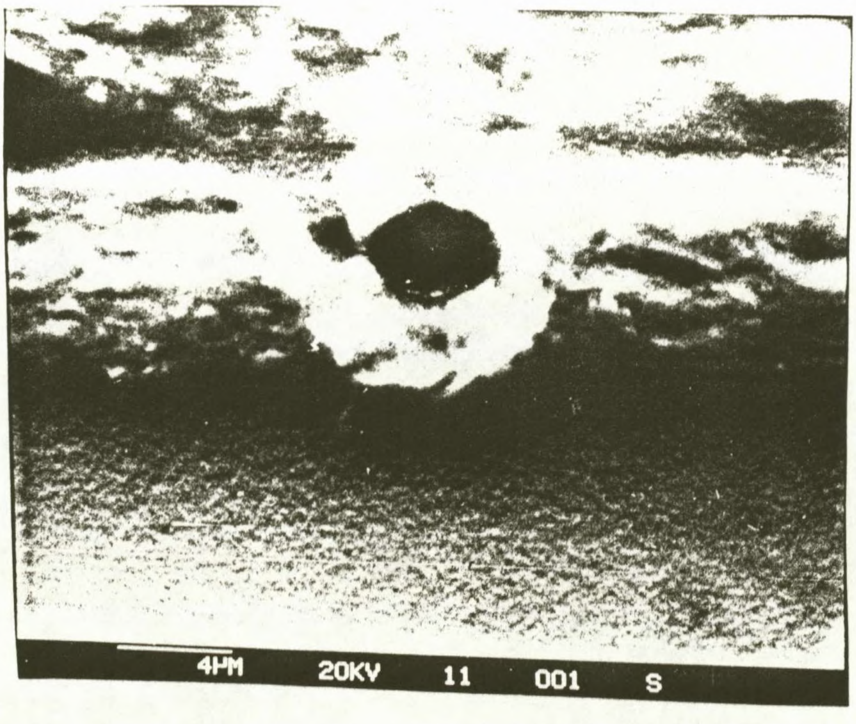
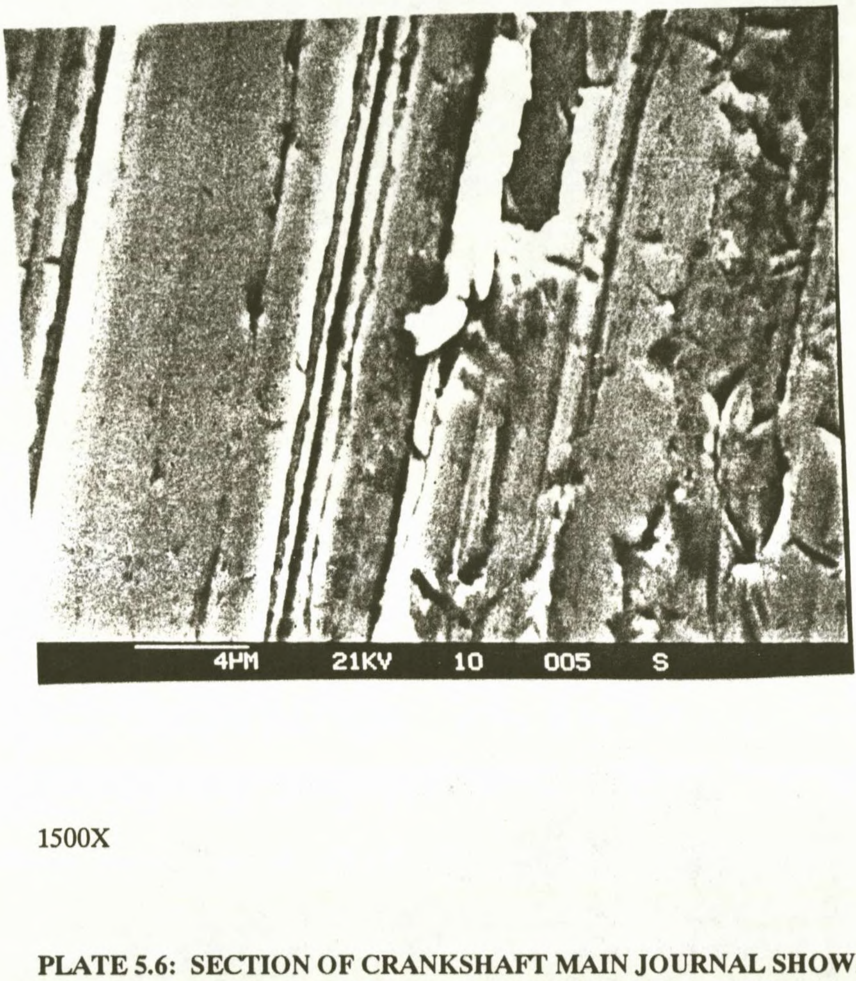


PLATE 5.5: MORE SEVERE TYPE CUTTING FERROUS PARTICLE



1500X

PLATE 5.6: SECTION OF CRANKSHAFT MAIN JOURNAL SHOWING BREAK-AWAY PARTICLE AND GROOVING/PLOUGH EFFECT

# CHAPTER SIX

## LITERATURE REFERENCES

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NOTE: The literature survey covers the period 1972 - 1990. The relevant documents only deal with methods or a method of machine health monitoring. No documents, to my knowledge, exist on the development of a portable type Ferrograph machine.

# CHAPTER SEVEN

# APPENDICES

## 7.1 *TABULATED RESULTS OF GRINDING METHOD: OPTICAL READINGS*

Particle Range (50 - 60 microns)

| | | | | | | |
|---|---|---|---|---|---|---|
| 47,34 | 55,23 | 55,23 | 78,90 | 55,23 | 78,90 | N = 35,00 |
| 63,12 | 63,12 | 63,12 | 55,23 | 55,23 | 55,23 | X = 56,00 |
| 47,34 | 55,23 | 47,34 | 47,34 | 71,00 | 47,34 | S = 10,90 |
| 55,23 | 78,90 | 47,34 | 63,12 | 40,00 | 47,34 | S/X = 0,19 |
| 51,30 | 63,12 | 39,45 | 55,23 | 55,23 | 47,34 | |
| 78,00 | 53,23 | 55,23 | 47,40 | 39,45 | | |

Particle Range (40 - 50 microns)

| | | | | | | |
|---|---|---|---|---|---|---|
| 55,23 | 47,34 | 39,45 | 55,23 | 55,23 | 39,45 | N = 35,00 |
| 47,34 | 47,34 | 47,34 | 39,45 | 63,10 | 47,34 | X = 47,90 |
| 63,12 | 31,56 | 55,23 | 55,23 | 47,34 | 51,20 | S = 7,52 |
| 55,23 | 39,34 | 47,34 | 47,34 | 55,23 | 47,34 | S/X = 0,16 |
| 36,00 | 51,20 | 55,23 | 51,20 | 51,20 | 39,45 | |
| 39,45 | 47,34 | 47,34 | 39,45 | 39,45 | | |

Particle Range (30 - 40 microns)

| | | | | | | |
|---|---|---|---|---|---|---|
| 43,00 | 31,56 | 43,00 | 31,56 | 39,45 | 55,23 | N = 35,00 |
| 31,56 | 39,45 | 47,34 | 55,23 | 43,00 | 31,56 | X = 37,73 |
| 35,00 | 35,50 | 43,00 | 47,34 | 39,45 | 39.45 | S = 7,36 |
| 39,45 | 31,56 | 31,56 | 24,00 | 47,34 | 39.45 | S/X = 0,20 |
| 36,00 | 31,56 | 24,00 | 31,56 | 39,45 | 31.56 | |
| 39,45 | 39,45 | 31,56 | 31,56 | 39,45 | | |

Particle Range (20 - 30 microns)

| | | | | | | |
|---|---|---|---|---|---|---|
| 22,00 | 32,00 | 22,00 | 40,00 | 26,00 | 18,00 | N = 35,00 |
| 26,00 | 20,00 | 22,00 | 24,00 | 22,00 | 16,00 | X = 24,40 |
| 30,00 | 24,00 | 28,00 | 26,00 | 20,00 | 20,00 | S = 5,44 |
| 20,00 | 34,00 | 22,00 | 26,00 | 24,00 | 28,00 | S/X = 0,22 |
| 16,00 | 28,00 | 20,00 | 26,00 | 30,00 | 22.00 | |
| 34,00 | 20,00 | 16,00 | 24,00 | 26,00 | | |

Particle Range (10 - 20 microns)

| | | | | | | |
|---|---|---|---|---|---|---|
| 18,00 | 18,00 | 14,00 | 18,00 | 10,00 | 18,00 | N = 35,00 |
| 24,00 | 26,00 | 10,00 | 18,00 | 10,00 | 8,00 | X = 15,51 |
| 26,00 | 18,00 | 18,00 | 18,00 | 8,00 | 10,00 | S = 6,44 |
| 16,00 | 12,00 | 11,00 | 20,00 | 20,00 | 36.00 | S/X = 0,42 |
| 8,00 | 14,00 | 16,00 | 6,00 | 10,00 | 18.00 | |
| 14,00 | 12,00 | 8,00 | 12,00 | 24,00 | | |

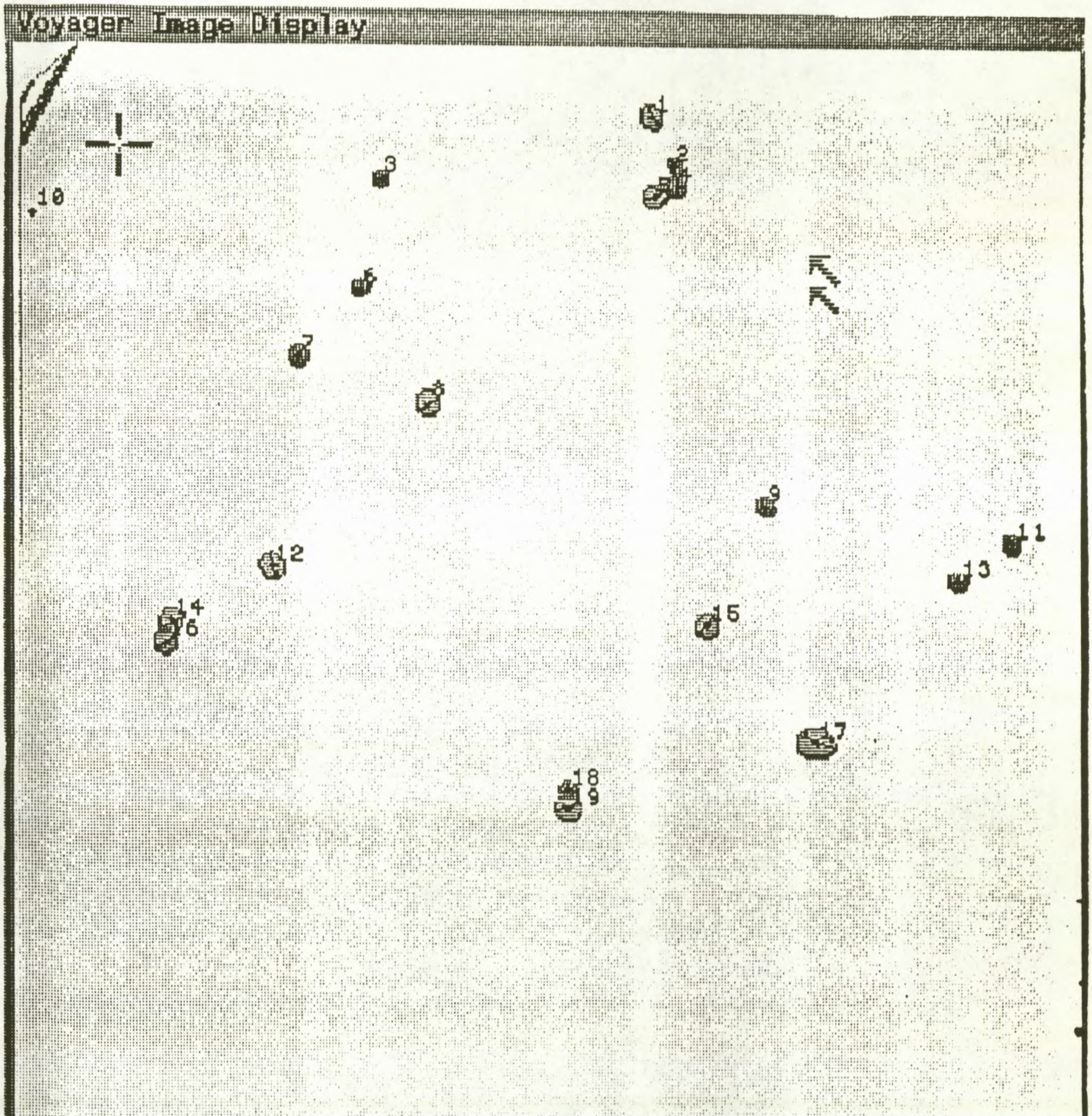
## 7.2 *TABULATED RESULTS OF SIEVING METHOD, AND SUPPORTING PICTUREGRAM*

### 7.2.1 *Particle Range 10 - 25 Microns*

| NUMBER | MICRON LENGTH | MICRON WIDTH | AVERAGE DIMENSION |
|---|---|---|---|
| 1 | 10.9728 | 8.2560 | 9.62 |
| 2 | 18.0526 | 14.1531 | 16.10 |
| 3 | 17.3986 | 14.1531 | 15.78 |
| 4 | 28.0696 | 23.5855 | 25.83 |
| 5 | 18.3122 | 15.3325 | 16.82 |
| 6 | 18.8798 | 17.6913 | 18.28 |
| 7 | 21.0002 | 18.8708 | 19.94 |
| 8 | 26.1232 | 21.2296 | 23.68 |
| 9 | 14.2521 | 11.7942 | 13.02 |
| 10 | 28.2702 | 23.5885 | 25.93 |
| 11 | 19.8276 | 14.1531 | 16.99 |
| 12 | 27.9753 | 21.2296 | 24.60 |
| 13 | 21.8076 | 18.8708 | 20.34 |
| 14 | 20.9054 | 16.5119 | 18.71 |
| 15 | 23.7083 | 18.8708 | 21.29 |
| 16 | 18.8935 | 15.3325 | 17.11 |
| 17 | 26.2985 | 17.6913 | 21.99 |
| 18 | 13.3130 | 9.4354 | 13.88 |
| 19 | 21.5849 | 17.6913 | 19.64 |
| 20 | 16.8746 | 12.9737 | 14.92 |
| 21 | 25.8739 | 21.2296 | 23.53 |
| 22 | 23.9198 | 20.0502 | 21.98 |
| 23 | 26.2141 | 21.2296 | 23.72 |
| 24 | 20.9115 | 16.5119 | 18.71 |
| 25 | 26.9087 | 17.6913 | 22.30 |
| 26 | 28.2257 | 20.0502 | 24.14 |
| 27 | 22.9829 | 17.6913 | 20.34 |
| 28 | 19.6770 | 17.6913 | 18.68 |
| 29 | 23.1769 | 18.8708 | 21.02 |
| 30 | 23.6102 | 18.8708 | 21.24 |
| 31 | 25.1711 | 20.0502 | 22.61 |
| 32 | 22.6408 | 18.8708 | 20.76 |
| 33 | 24.2684 | 18.8708 | 21.57 |
| 34 | 28.4976 | 22.4090 | 25.45 |
| 35 | 24.2595 | 18.8708 | 21.56 |
| 36 | 20.9158 | 16.5119 | 18.71 |
| 37 | 27.0903 | 20.0502 | 23.57 |
| 38 | 23.1865 | 18.8708 | 21.03 |
| 39 | 28.9059 | 23.5885 | 26.25 |
| 40 | 23.8581 | 18.8708 | 21.36 |
| 41 | 20.4365 | 14.1531 | 17.29 |
| 42 | 10.0585 | 7.0765 | 8.57 |
| 43 | 25.9165 | 20.0502 | 22.98 |
| 44 | 18.4760 | 14.1531 | 7.81 |
| 45 | 18.0357 | 14.1531 | 16.09 |
| 46 | 20.7101 | 16.5119 | 18.61 |
| 47 | 24.1525 | 21.2296 | 22.69 |
| 48 | 20.3389 | 16.5119 | 18.43 |
| 49 | 22.9735 | 17.6913 | 20.33 |
| 50 | 26.1861 | 21.2296 | 23.71 |

N = 50
X = 19,79
S = 4,21
S/X = 0,21

*7.2.1A: 10-25 Microns Particle Picturegram*



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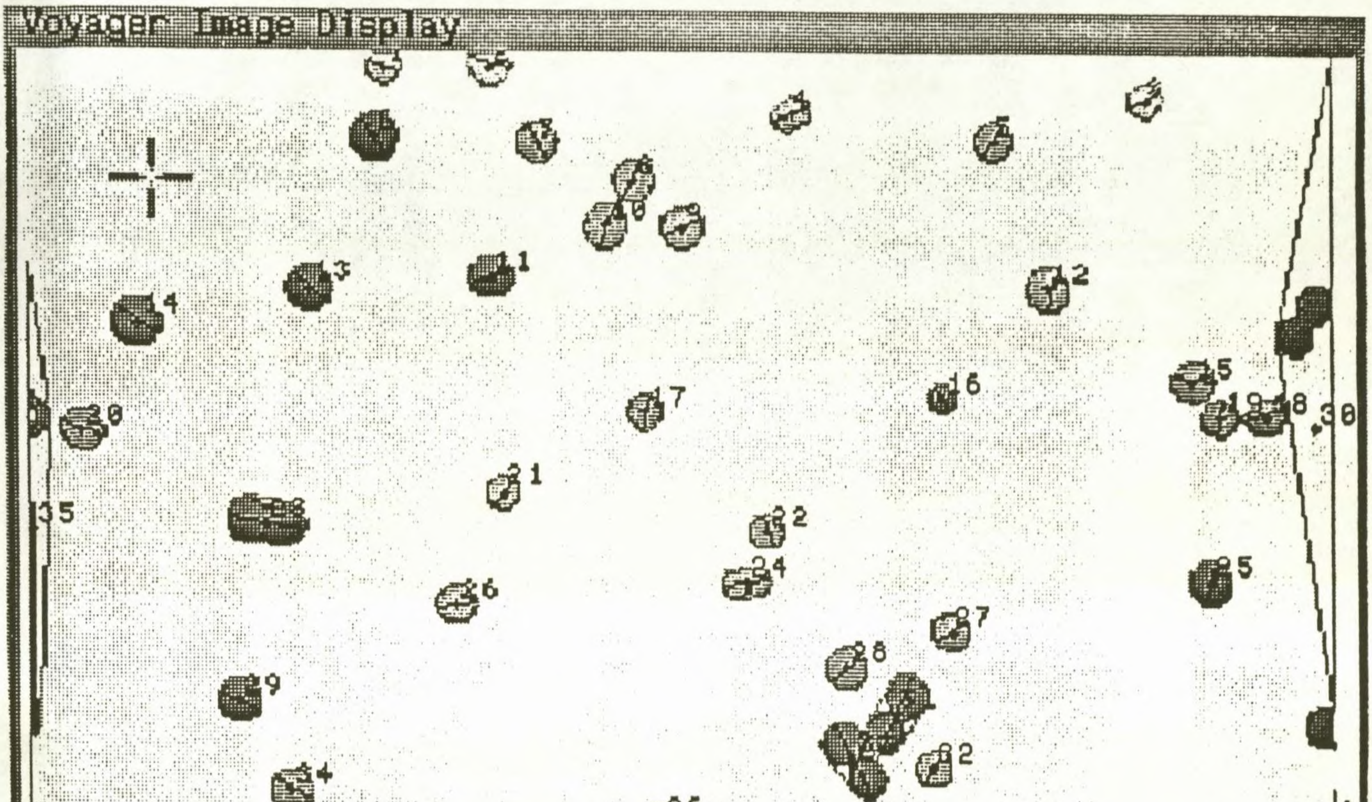
x:37          y:37          i:0          Grey1:Sized field 2
```

### 7.2.2: *Particle Range 25 - 32 Microns*

| NUMBER | MICRON LENGTH | MICRON WIDTH | AVERAGE DIMENSION |
|---|---|---|---|
| 1 | 29.3044 | 23.5885 | 26.59 |
| 2 | 29.1766 | 20.0502 | 24.61 |
| 3 | 23.1896 | 18.8708 | 21.03 |
| 4 | 33.5914 | 28.3062 | 30.95 |
| 5 | 26.3661 | 18.8708 | 22.62 |
| 6 | 32.7649 | 27.1267 | 29.95 |
| 7 | 25.6154 | 18.8708 | 22.24 |
| 8 | 29.2088 | 24.7679 | 26.99 |
| 9 | 27.6674 | 21.2296 | 24.45 |
| 10 | 31.2403 | 23.5885 | 27.41 |
| 11 | 27.0312 | 21.2296 | 24.13 |
| 12 | 29.1532 | 24.7679 | 26.96 |
| 13 | 27.9262 | 21.2296 | 24.58 |
| 14 | 26.5936 | 24.7679 | 25.68 |
| 15 | 33.2780 | 27.1267 | 30.20 |
| 16 | 24.9196 | 21.2296 | 23.07 |
| 17 | 22.7762 | 18.8708 | 20.82 |
| 18 | 32.8144 | 27.1267 | 29.97 |
| 19 | 28.7650 | 23.5885 | 26.18 |
| 20 | 33.3396 | 25.9473 | 29.64 |
| 21 | 25.0800 | 20.0502 | 22.56 |
| 22 | 27.0317 | 21.2296 | 24.13 |
| 23 | 34.8170 | 28.3062 | 31.56 |
| 24 | 46.8323 | 25.9473 | 36.39 |
| 25 | 28.9503 | 23.5885 | 26.27 |
| 26 | 21.8126 | 16.5119 | 19.16 |
| 27 | 36.6362 | 30.6650 | 36.65 |
| 28 | 58.3248 | 24.7679 | 41.54 |
| 29 | 34.5261 | 28.3062 | 31.42 |
| 30 | 32.9020 | 27.1267 | 30.01 |
| 31 | 30.9438 | 24.7679 | 27.86 |
| 32 | 19.3485 | 17.6913 | 18.52 |
| 33 | 30.6095 | 24.7679 | 27.69 |
| 34 | 17.0135 | 11.7942 | 14.38 |
| 35 | 33.0649 | 25.9473 | 29.51 |
| 36 | 29.0509 | 23.5885 | 26.32 |
| 37 | 33.9255 | 22.4090 | 28.17 |
| 38 | 37.9525 | 31.8444 | 34.90 |
| 39 | 62.3604 | 29.4856 | 45.92 |
| 40 | 18.9635 | 15.3325 | 17.15 |
| 41 | 56.7685 | 27.1267 | 41.95 |
| 42 | 30.2717 | 24.7679 | 27.52 |
| 43 | 37.8195 | 30.6650 | 34.24 |
| 44 | 27.4342 | 21.2296 | 24.33 |
| 45 | 27.8354 | 22.4090 | 25.12 |
| 46 | 31.4223 | 23.5885 | 27.51 |
| 47 | 32.1780 | 27.1267 | 29.65 |
| 48 | 25.5900 | 20.0502 | 22.82 |
| 49 | 30.5779 | 24.7679 | 27.67 |
| 50 | 23.4343 | 9.4354 | 16.44 |

N = 50
X = 27,31
S = 6,20
S/X = 0,23

***7.2.2A: 25 - 32 Microns Particle Picturegram***

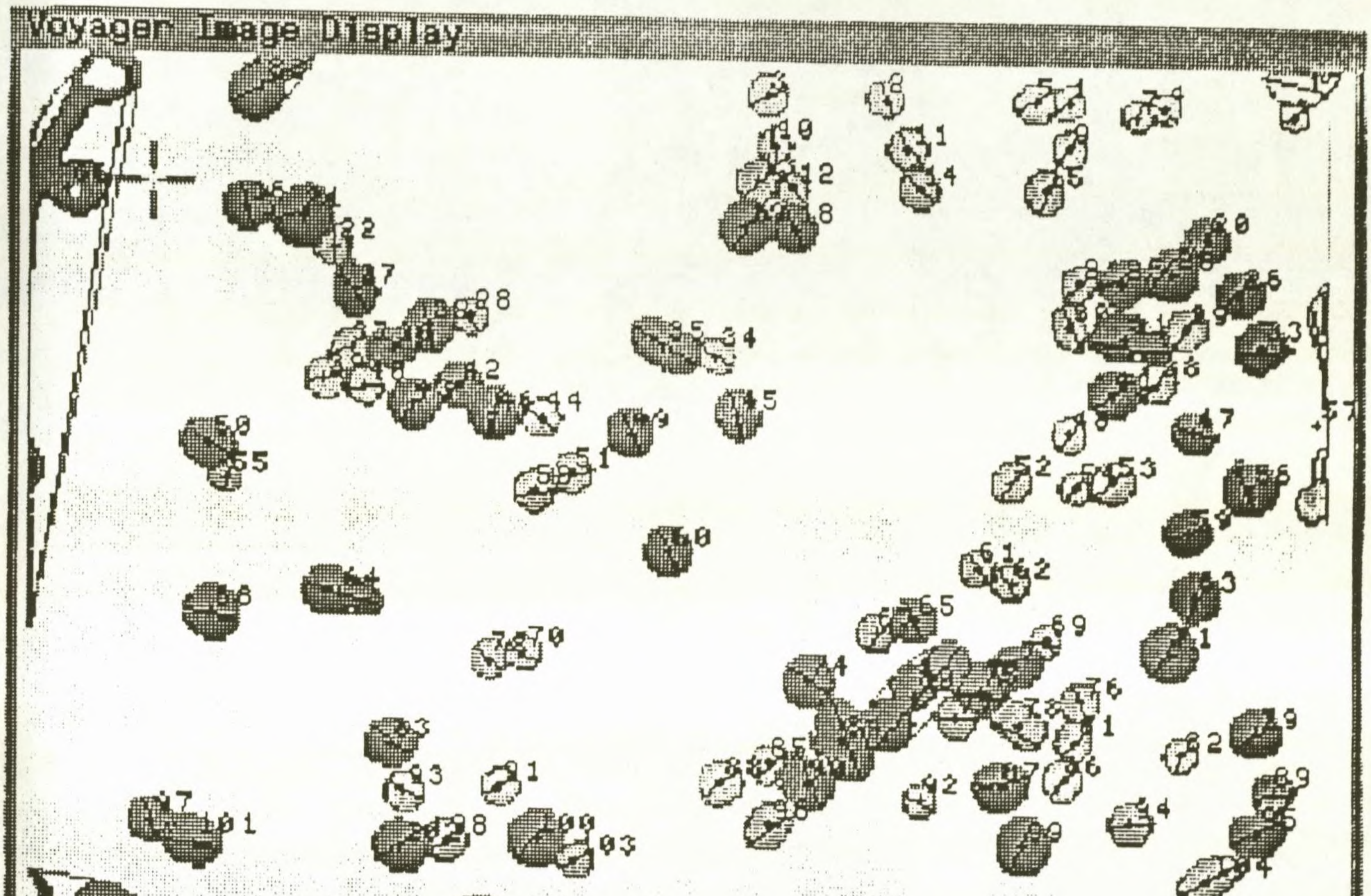


### 7.2.3: *Particle Range 32 - 38 Microns*

| NUMBER | MICRON LENGTH | MICRON WIDTH | AVERAGE DIMENSION |
|---|---|---|---|
| 1 | 26.9034 | 23.5885 | 25.25 |
| 2 | 31.3206 | 24.7679 | 28.04 |
| 3 | 34.8344 | 29.4856 | 32.16 |
| 4 | 24.5184 | 21.2296 | 28.87 |
| 5 | 33.5169 | 29.4856 | 31.50 |
| 6 | 24.5410 | 22.4090 | 23.48 |
| 7 | 25.4828 | 22.4090 | 23.95 |
| 8 | 62.5472 | 40.1004 | 51.32 |
| 9 | 32.0492 | 25.9473 | 29.00 |
| 10 | 29.5271 | 23.5885 | 26.56 |
| 11 | 32.5481 | 28.3062 | 30.43 |
| 12 | 26.0491 | 22.4090 | 24.23 |
| 13 | 33.7283 | 29.4856 | 31.61 |
| 14 | 34.8081 | 28.3062 | 31.56 |
| 15 | 35.5687 | 28.3062 | 31.94 |
| 16 | 40.6405 | 34.2033 | 37.42 |
| 17 | 41.2178 | 28.3062 | 34.76 |
| 18 | 35.6012 | 31.8444 | 33.72 |
| 19 | 42.0192 | 36.5621 | 39.29 |
| 20 | 35.4798 | 30.6650 | 33.07 |
| 21 | 49.4782 | 44.8181 | 47.15 |
| 22 | 27.7064 | 25.9473 | 26.83 |
| 23 | 43.4109 | 35.3827 | 39.40 |
| 24 | 31.2284 | 23.5885 | 27.41 |
| 25 | 36.3723 | 30.6650 | 33.52 |
| 26 | 38.9276 | 31.8444 | 35.39 |
| 27 | 39.4242 | 31.8444 | 35.63 |
| 28 | 30.5064 | 25.9473 | 28.00 |
| 29 | 35.2834 | 28.3062 | 31.80 |
| 30 | 31.6492 | 23.5885 | 27.62 |
| 31 | 56.1727 | 34.2033 | 45.20 |
| 32 | 40.1205 | 34.2033 | 37.16 |
| 33 | 36.5284 | 36.5621 | 36.55 |
| 34 | 29.0620 | 24.7679 | 26.91 |
| 35 | 44.5670 | 30.6650 | 37.62 |
| 36 | 35.4582 | 30.6650 | 33.06 |
| 37 | 31.0259 | 29.4856 | 30.27 |
| 38 | 32.0926 | 27.1267 | 29.61 |
| 39 | 29.5253 | 29.4856 | 29.51 |
| 40 | 29.7817 | 24.7679 | 27.28 |
| 41 | 40.7629 | 33.0238 | 36.90 |
| 42 | 37.9267 | 33.0238 | 35.48 |
| 43 | 40.9756 | 36.5621 | 38.75 |
| 44 | 33.5120 | 27.1267 | 30.32 |
| 45 | 40.2219 | 30.6650 | 35.44 |
| 46 | 42.0584 | 37.7415 | 39.90 |
| 47 | 36.1273 | 30.6650 | 33.40 |
| 48 | 30.7652 | 24.7679 | 27.22 |
| 49 | 40.1944 | 33.0238 | 36.97 |
| 50 | 41.9342 | 34.2033 | 38.07 |

N = 50
X = 32,38
S = 7,11
S/X = 0,22

*7.2.3a: 32 - 38 Microns Particle Picturegram*



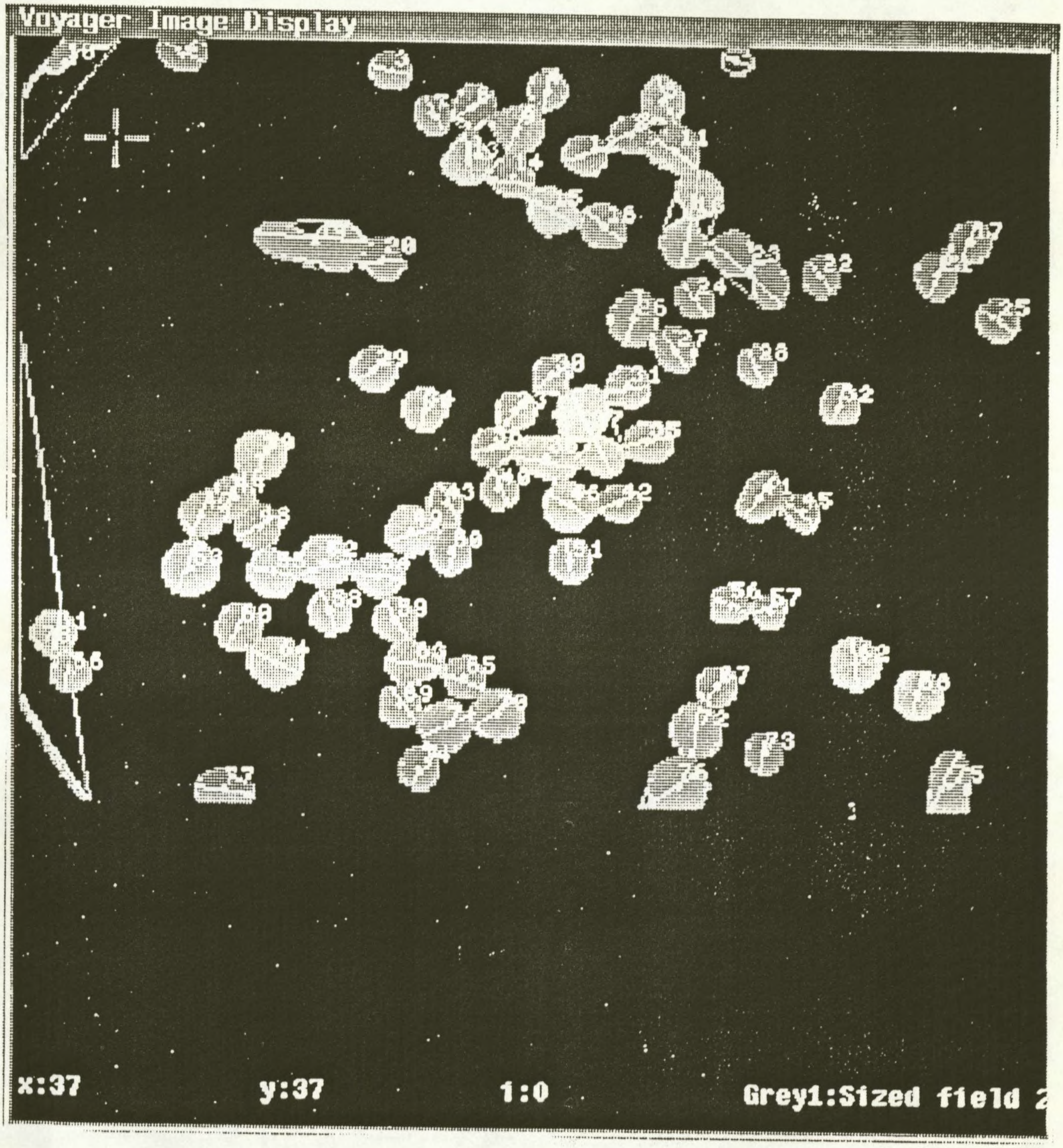
x:37 y:37 i:0 Grey1:Sized field 1

### 7.2.4: *Particle Range 38 - 53 Microns*

| NUMBER | MICRON LENGTH | MICRON WIDTH | AVERAGE DIMENSION |
|---|---|---|---|
| 1 | 42.0031 | 30.6650 | 36.33 |
| 2 | 46.0484 | 41.2798 | 43.66 |
| 3 | 59.3949 | 43.6387 | 51.52 |
| 4 | 43.4066 | 37.7415 | 40.57 |
| 5 | 40.7468 | 33.0238 | 36.89 |
| 6 | 42.9650 | 33.0238 | 37.99 |
| 7 | 44.9619 | 38.9210 | 41.94 |
| 8 | 38.7463 | 22.4090 | 30.58 |
| 9 | 43.2454 | 35.3827 | 39.31 |
| 10 | 40.0917 | 34.2033 | 37.15 |
| 11 | 46.0985 | 40.1004 | 43.10 |
| 12 | 44.3362 | 45.9975 | 45.17 |
| 13 | 52.5482 | 44.8181 | 48.68 |
| 14 | 47.4153 | 40.1004 | 43.76 |
| 15 | 40.0776 | 34.2033 | 37.14 |
| 16 | 42.9170 | 35.3827 | 39.15 |
| 17 | 42.6336 | 36.5621 | 39.60 |
| 18 | 46.2084 | 38.9210 | 42.56 |
| 19 | 52.9327 | 45.9975 | 49.47 |
| 20 | 43.4106 | 34.2033 | 38.81 |
| 21 | 49.0480 | 41.2798 | 45.16 |
| 22 | 53.0601 | 43.6387 | 48.35 |
| 23 | 42.6780 | 34.2033 | 38.44 |
| 24 | 41.5475 | 35.3827 | 38.47 |
| 25 | 56.4855 | 44.8181 | 50.65 |
| 26 | 28.3737 | 25.9473 | 27.16 |
| 27 | 46.3528 | 33.0238 | 39.69 |
| 28 | 35.0587 | 29.4856 | 32.27 |
| 29 | 49.6318 | 42.4592 | 46.05 |
| 30 | 49.5196 | 42.4592 | 45.99 |
| 31 | 38.1983 | 30.6650 | 34.43 |
| 32 | 52.2620 | 42.4592 | 47.36 |
| 33 | 47.3062 | 40.1004 | 43.70 |
| 34 | 48.5415 | 41.2798 | 49.91 |
| 35 | 49.2610 | 40.1004 | 44.68 |
| 36 | 49.0540 | 41.2798 | 45.17 |
| 37 | 44.3403 | 35.3827 | 39.86 |
| 38 | 49.9011 | 37.7415 | 43.82 |
| 39 | 50.7662 | 42.4592 | 46.61 |
| 40 | 50.1220 | 42.4592 | 46.29 |
| 41 | 41.0850 | 38.9210 | 40.00 |
| 42 | 79.1131 | 40.1004 | 59.61 |
| 43 | 49.1316 | 40.1004 | 44.62 |
| 44 | 48.8425 | 43.6387 | 46.24 |
| 45 | 47.4401 | 42.4592 | 44.95 |
| 46 | 53.0790 | 44.8181 | 48.95 |
| 47 | 43.2911 | 35.3827 | 39.34 |
| 48 | 38.7132 | 30.6650 | 34.69 |
| 49 | 30.8664 | 24.7679 | 27.82 |
| 50 | 38.7851 | 34.2033 | 36.49 |

N = 50
X = 42,00
S = 6,16
S/X = 0,15

*7.2.AA: 38 - 53 Microns Particle Picturegram*

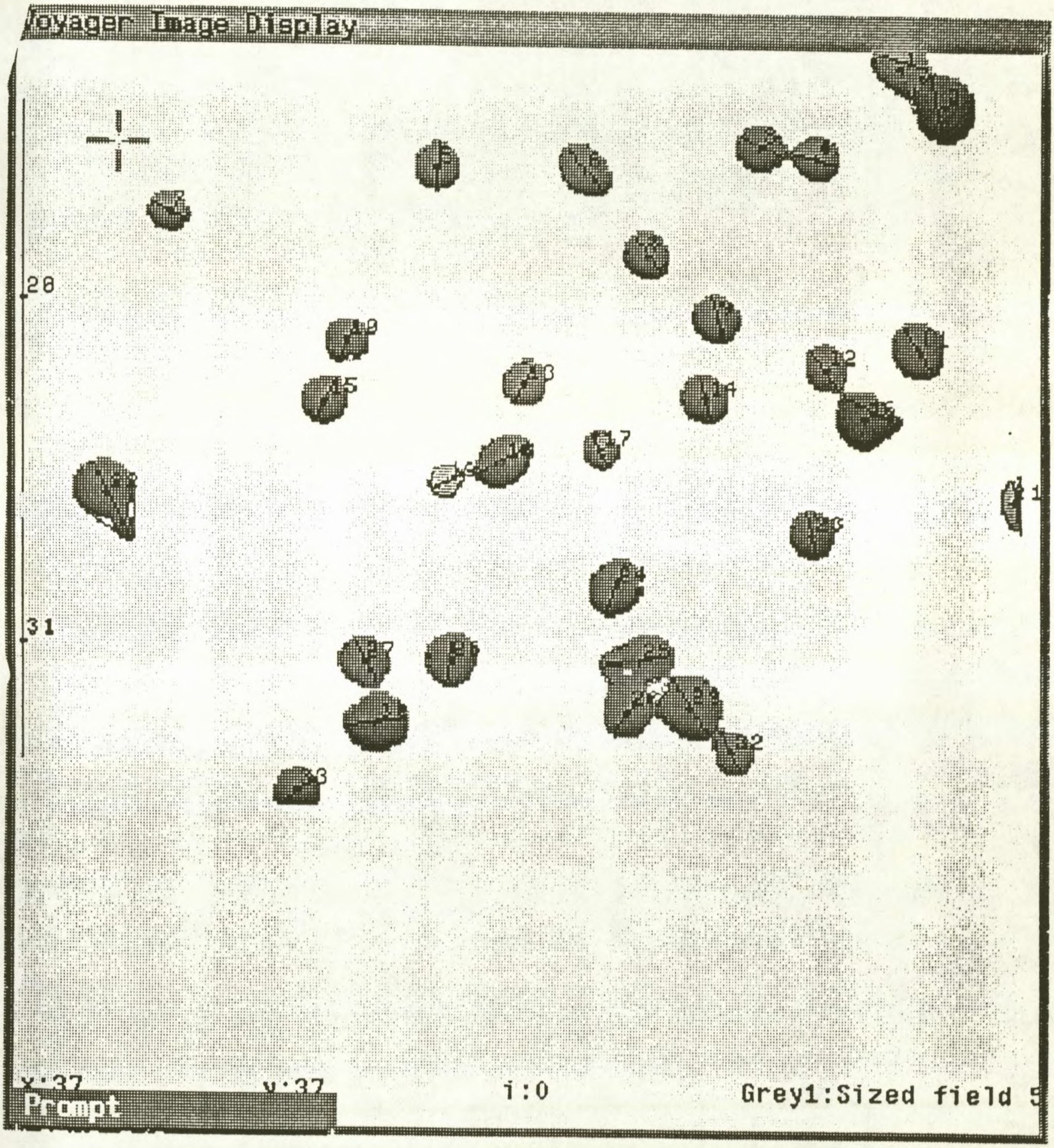


### 7.2.5: *Particle Range 53 - 63 Microns*

| NUMBER | MICRON LENGTH | MICRON WIDTH | AVERAGE DIMENSION |
|---|---|---|---|
| 1 | 55.6373 | 47.1769 | 51.41 |
| 2 | 56.1079 | 45.9975 | 51.05 |
| 3 | 45.3474 | 38.9210 | 42.13 |
| 4 | 61.7169 | 66.0477 | 63.88 |
| 5 | 36.7882 | 30.6650 | 33.73 |
| 6 | 66.4931 | 53.0740 | 59.78 |
| 7 | 46.6301 | 40.1004 | 43.37 |
| 8 | 68.9051 | 54.2535 | 61.58 |
| 9 | 40.9711 | 33.0238 | 37.00 |
| 10 | 45.9308 | 37.7415 | 41.52 |
| 11 | 58.9753 | 48.3564 | 53.67 |
| 12 | 41.2317 | 34.2033 | 37.72 |
| 13 | 34.6733 | 28.3062 | 31.49 |
| 14 | 44.2529 | 36.5621 | 40.41 |
| 15 | 35.9220 | 28.3062 | 37.11 |
| 16 | 55.0379 | 43.6387 | 49.34 |
| 17 | 92.2474 | 42.4592 | 67.35 |
| 18 | 56.5033 | 44.8181 | 50.67 |
| 19 | 44.9503 | 44.8181 | 44.88 |
| 20 | 59.6642 | 44.8181 | 52.24 |
| 21 | 59.5108 | 50.7152 | 55.11 |
| 22 | 68.3728 | 49.5358 | 58.95 |
| 23 | 64.9282 | 54.2535 | 59.59 |
| 24 | 63.2309 | 55.4329 | 59.33 |
| 25 | 56.2853 | 47.1769 | 51.73 |
| 26 | 55.8131 | 48.3564 | 52.08 |
| 27 | 67.0414 | 55.4329 | 61.24 |
| 28 | 63.7296 | 53.0740 | 58.40 |
| 29 | 38.0261 | 29.4856 | 33.76 |
| 30 | 58.3161 | 49.5358 | 53.92 |
| 31 | 67.2200 | 48.3564 | 57.79 |
| 32 | 43.6909 | 40.1004 | 41.90 |
| 33 | 53.5235 | 48.3564 | 50.94 |
| 34 | 44.8445 | 36.5621 | 40.70 |
| 35 | 67.1387 | 69.5860 | 68.36 |
| 36 | 55.2611 | 54.2535 | 54.76 |
| 37 | 30.0347 | 28.3062 | 29.17 |
| 38 | 51.6632 | 50.7152 | 51.19 |
| 39 | 64.0270 | 42.4592 | 53.24 |
| 40 | 72.2524 | 37.7415 | 55.00 |
| 41 | 62.3746 | 51.8946 | 57.13 |
| 42 | 26.8866 | 24.7679 | 25.83 |
| 43 | 51.2297 | 44.8181 | 48.02 |
| 44 | 55.4384 | 47.1769 | 51.31 |
| 45 | 54.4643 | 50.7152 | 52.59 |
| 46 | 46.1877 | 47.1769 | 46.68 |
| 47 | 49.6005 | 44.8181 | 47.21 |
| 48 | 39.3796 | 34.2033 | 36.79 |
| 49 | 65.3006 | 53.0740 | 59.19 |
| 50 | 57.7055 | 53.0740 | 55.39 |

N = 50
X = 49,45
S = 10,04
S/X = 0,20

*7.2.5A: 53 - 63 Microns Particle Picturegram*

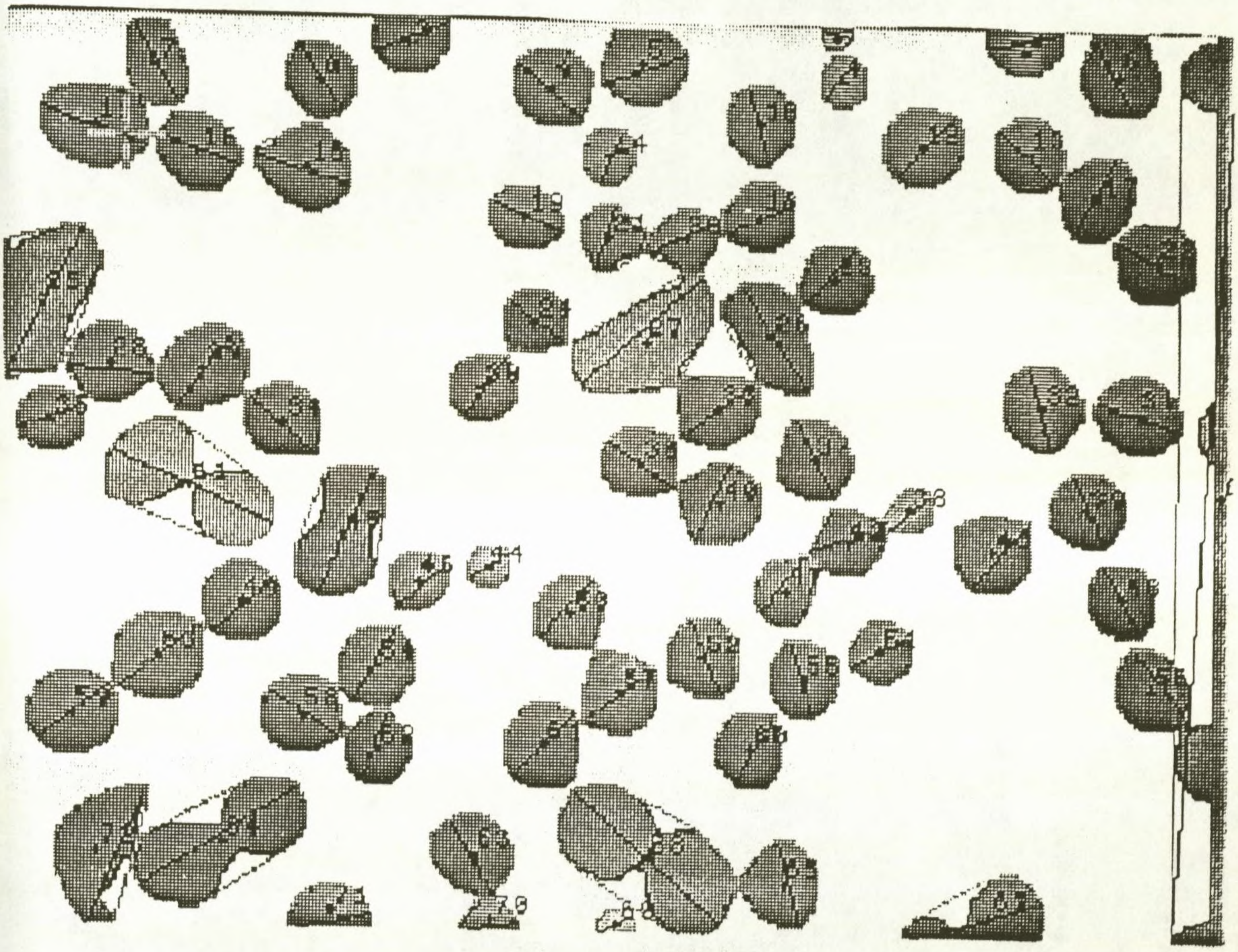


### 7.2.6: *Particle Range 63 - 75 Microns*

| NUMBER | MICRON LENGTH | MICRON WIDTH | AVERAGE DIMENSION |
|---|---|---|---|
| 1 | 20.5803 | 20.0502 | 20.32 |
| 2 | 58.7912 | 53.0740 | 55.93 |
| 3 | 59.6358 | 55.4329 | 57.53 |
| 4 | 68.0666 | 58.9712 | 63.52 |
| 5 | 46.6742 | 41.2798 | 44.00 |
| 6 | 70.9976 | 62.5094 | 66.75 |
| 7 | 82.1970 | 70.7654 | 76.48 |
| 8 | 66.2995 | 60.1506 | 63.23 |
| 9 | 79.0031 | 68.4065 | 73.70 |
| 10 | 64.5614 | 53.0740 | 58.82 |
| 11 | 65.3522 | 56.6123 | 60.98 |
| 12 | 79.5070 | 63.6889 | 71.60 |
| 13 | 72.6553 | 58.9712 | 65.81 |
| 14 | 59.8216 | 50.7152 | 55.27 |
| 15 | 72.0024 | 61.3300 | 66.67 |
| 16 | 80.0478 | 68.4065 | 74.23 |
| 17 | 66.9322 | 54.2535 | 60.59 |
| 18 | 69.9945 | 60.1506 | 65.07 |
| 19 | 98.8336 | 67.2271 | 83.03 |
| 20 | 74.4705 | 68.4065 | 71.44 |
| 21 | 27.6350 | 25.9473 | 26.79 |
| 22 | 57.6832 | 44.8181 | 51.25 |
| 23 | 49.1794 | 49.5358 | 49.36 |
| 24 | 65.4480 | 56.6123 | 61.03 |
| 25 | 38.8740 | 37.7415 | 38.31 |
| 26 | 62.1420 | 62.5094 | 62.32 |
| 27 | 65.1134 | 61.3300 | 63.22 |
| 28 | 78.3572 | 54.2535 | 66.30 |
| 29 | 73.1243 | 55.4329 | 64.28 |
| 30 | 56.2321 | 55.4329 | 55.83 |
| 31 | 78.8405 | 68.4065 | 73.62 |
| 32 | 87.1348 | 64.8683 | 76.00 |
| 33 | 56.0943 | 54.2535 | 55.17 |
| 34 | 51.7020 | 48.3564 | 50.03 |
| 35 | 70.9929 | 64.8683 | 67.93 |
| 36 | 53.5709 | 49.5358 | 51.55 |
| 37 | 54.4900 | 51.8946 | 53.19 |
| 38 | 70.2140 | 58.9712 | 64.59 |
| 39 | 61.4791 | 54.2535 | 57.87 |
| 40 | 50.3285 | 47.1769 | 48.75 |
| 41 | 71.3469 | 58.9712 | 65.03 |
| 42 | 66.6849 | 64.8683 | 65.78 |
| 43 | 57.6010 | 47.1769 | 53.39 |
| 44 | 67.0031 | 57.7917 | 62.40 |
| 45 | 50.1042 | 43.6387 | 46.75 |
| 46 | 80.8848 | 64.8683 | 72.88 |
| 47 | 75.7408 | 61.3300 | 68.54 |
| 48 | 38.7512 | 28.3062 | 33.53 |
| 49 | 56.7849 | 51.8946 | 54.34 |
| 50 | 60.4344 | 20.0502 | 40.24 |

N = 50
X = 59,10
S = 12,54
S/X = 0,21

***7.2.6A: 63 - 75 Microns Particle Picturegram***



## 7.3 *TABULATED RESULTS OF GRINDING METHOD PARTICLE SPREAD*

| Distance along slide in mm | Percentage Area Covered per Particle Size Range | | | | | |
|---|---|---|---|---|---|---|
| | 10-20 | 20-30 | 30-40 | 40-50 | 50-60 | 10-60 |
| 60 | 10 | 11 | 30 | 32 | 51 | 85 |
| 55 | 7 | 2 | 2 | 21 | 9 | 42 |
| 50 | 7 | 1 | 1 | 10 | 5 | 10 |
| 45 | 3 | 1 | 1 | 8 | 1 | 5 |
| 40 | 5 | 1 | 1 | 7 | 1 | 1 |

## 7.4 *TABULATED RESULTS OF SIEVING METHOD PARTICLE SPREAD*

| Distance along slide in mm | Percentage Area Covered per Particle Size Range | | | | | |
|---|---|---|---|---|---|---|
| | 10-20 | 20-30 | 30-40 | 40-50 | 50-60 | 10-60 |
| 60 | 7 | 22 | 22 | 30 | 42 | 48 |
| 55 | 4 | 3 | 4 | 2 | 7 | 5 |
| 50 | 1 | 3 | 3 | 2 | 4 | 4 |
| 45 | 1 | 3 | 3 | 2 | 3 | 3 |
| 40 | 1 | 2 | 2 | 2 | 2 | 2 |

## 7.5 *TABULATED FORD ENGINE TEST SCHEDULE - ATTACHED DOCUMENT*

APPENDIX 7.5

# TEST SCHEDULE

Title: QUALITY CONTROL CHECK SA-101

Reference:, Schedule "A" "B" & "D" of Essex and Kent Validation Programme.

| Step No. | Time/Stage Hours | Total Time Hours | RPM | Int. Dep. Ins. Hg. | Instructions Step No's to be recorded on data sheet |
|---|---|---|---|---|---|
| 1 | | | Idle* | | Thermostat to be out on all engines.<br>Check oil level, top up (10W30).<br>Set initial spark advance-record before re-setting. |
| 2 | 0.5 | 0.5 | 1000 | N/L | Record oil pressure and temp.<br>Observe engine noises. |
| 2a | | | Idle* | | Record oil pressure and temp. |
| 3 | | | | | Stop. Torque cylinder head bolts to 65-70 lb./ft. Adjust tappets to specification.<br>All Essex .010" In. .018" Ex.<br>Kent Std. .010" In. .020" Ex.<br>Kent Gt .012" In. .022" Ex. |
| 4 | 0.5 | 1.0 | 1500 | 15.5 | Maintain water outlet temp. at 180° ± 5°F.<br>Oil temp. not to exceed 250°F.<br>Record time, scale load, manifold vacuum, fuel flow, oil pressure, spark advance and all temperatures.<br>Note oil leaks, identifying source of leakage.<br>Calculate Obs. kW torque, specific fuel. |
| 5 | 0.5 | 1.5 | 2000 | 10.7 | |
| 6 | 0.5 | 2.0 | 2500 | 5.6 | |
| | 0.5 | 2.5 | 3000 | 3.1 | |
| 8 | | | | | Stop. If oil leakage is severe, inform Engineer and correct leaks.<br>Install dummy oil filter (Essex only). Check oil and top up.<br>Fit oil pull-over bottle. |

* 550 RPM Essex 2500 cm$^3$
650 RPM Essex 3000 & 2000 cm$^3$
600 RPM Kent 1100, 1300 & 1600 cm$^3$
700 RPM Kent 1300 & 1600 GT

| Step No. | Time/Stage Hours | Total Time Hours | RPM | Int. Dep. ins. Hg. | Instructions |
|---|---|---|---|---|---|
| 9 | ~~0.25~~<br>0.3 | ~~2.75~~<br>3.00 | 3000 | F/L | Oil conditioning. Take blow-by readings. Record and calculate all readings. |
| 10 | | | | | Stop. Drain oil and weigh. Weigh pull-over bottle. Refill with weighed oil to correct level. |
| 11 | 3.00 | 5.75 | 3000 | F/L | Oil economy test No. 1. Record and calculate a complete set of readings each hour. Record any oil leakage source. |
| 12 | | | | | Stop. Drain and weigh oil. Weigh pull-over bottle. Refill with correct amount of oil. Install engine oil cooler. |
| 13 | 0.25 | 6.00 | 2000 | 10.7 | Maintain water outlet temp. at 180° ± 5°F. Oil temperature not to exceed 25 Record for each step; Time, scale load, fuel flow, oi pressure, fuel pressure, int. dep., all temperatures, spark advance. Calculate all readings. |
| 14 | 0.25 | 6.25 | 3250 | F/L | |
| 15 | 0.25 | 6.50 | 3500 | F/L | |
| 16 | 0.25 | 6.75 | 3750 | F/L | |
| 17 | 0.25 | 7.00 | 4000 | F/L | |
| 18 | 0.25 | 7.25 | 4250 | F/L | |
| 19 | 0.25 | 7.5 | 4500 | F/L | |
| 20 | 0.25 | 7.75 | 4750 | F/L | |
| 21 | 0.25 | 8.00 | 5000 | F/L | |
| 22 | | | Idle* | | Set and record best idling intak depression. |

* See [illegible] No. 1

| Step No. | Time/Stage Hours | Total Time Hours | RPM | Int. Dep. Ins. Hg. | Instructions |
|---|---|---|---|---|---|
| 23 | | | | | Stop. <u>Install dummy</u> oil <u>filter</u> (Essex only). Check oil, top up. |
| 24 | 0.25 | 8.25 | 3000 | F/L | Repeat Step No. 9. Take blow-by readings. |
| 25 | | | | | Repeat Step No. 10. |
| 26 | 3.00 | 11.25 | 3000 | F/L | Oil economy test No. 2.<br>Repeat Step No. 11. |
| 27 | | | | | Repeat Step No. 12.<br>Fit oil cooler. |
| 28 | 1.00 | 12.25 | | F/L | Ensure all engine adjustments are to specification.<br>Warm engine to operating temp.<br>Full throttle performance test:<br>Commence at 1000 RPM full load, and then in increments of 500 RPM to 5000 RPM. Kent & 2.0L Capri & RS. to 5500 RPM.<br>Additional readings:<br>See note below.<br>Maintain water temp. at 180° ± 5°F.<br>Oil temp. not to exceed 230°F.<br>Record and calculate all readings.<br>Record compression pressures with WOT at 300 RPM for Essex and 1600cc Kent. 360 RPM for other Kent engines. |

<u>ADDITIONAL READINGS:</u>

Kent 1100 6000 RPM
Kent 1300 5700 RPM
Kent 1300 GT 6000 RPM
Kent 1600 2600 RPM
Kent 1600 GT 5700 RPM

Essex 2000 $cm^3$ 2800 & 4800 RPM
Essex 2500 $cm^3$ 2800 & 4800 RPM
Essex 3000 $cm^3$ 4800 RPM
Essex 2000 $cm^3$ Capri & RS 5500 RPM

| Step No. | Time/Stage Hours | Total Time Hours | RPM | Int. Dep. ins. Hg. | Instructions |
|---|---|---|---|---|---|
| 29 | | | | Idle* | Remove oil cooler. Fit dummy oil filter (Essex only). Record oil pressure and temperature. |
| 30 | 0.5 | 12.75 | 1500 | 17.7 | Oil conditioning. Record a complete set of readings including blow-by. |
| 31 | | | | | Stop. Drain and weigh oil. Weigh pull-over bottle. Refill with correct amount of weighed oil. |
| 32 | 3.00 | 15.75 | 1500 | 17.7 | Oil economy test No. 3. Record a complete set of readings at the end of each hour. |
| 33 | | | | | Repeat Step No. 12.<br>Record any oil leakage and source |

* See Page No. 1.

## SPECIAL INSTRUCTIONS FOR OIL ECONOMY TESTS: Page 5 of 5

| | |
|---|---|
| Drain Procedure: | Stop engine and immediately turn engine to T.D.C. No. 1. Turn over engine 90° at one minute intervals until one complete revolution is completed. Open drain tap and drain oil for 15 minutes.<br>Total Time: 19 Minutes. |
| Leakage: | Place clean rags under engine at the beginning of the oil conditioning steps. Before starting oil economy tests wipe the engine to remove all traces of oil, and then weigh rags. Place rags back under engine.<br>At the completion of each oil economy test wipe any oil leakage from the engine with the same rags and weigh. |
| Weighing: | Always include the funnel when weighing the oil can, empty or full, if available.<br>Oil pull-over and blow by are to be recorded during all oil economy tests. |

## APPENDIX 7.6: *TABULATED VOLKSWAGEN ENGINE TEST RESULTS*

### 7.6.1 *96-Hour Engine Test Results*

| DAY | SAMPLE NO. | HOURS | LOAD KW | SAMPLE TAKEN | | OIL PRESS. kPa | OIL TEMP C | |
|---|---|---|---|---|---|---|---|---|
| | | | | LAB. ml | S.O.A.P. ml | | | |
| 1 | 1 | 3 | 0 | 80 | 0 | 220 | 72 | |
| 1 | 2 | 6 | 4 | 80 | 0 | 220 | 75 | |
| 2 | 3 | 9 | 6,50 | 80 | 70 | 220 | 78 | |
| 2 | 4 | 12 | 6,50 | 80 | 0 | 220 | 78 | |
| 3 | 5 | 15 | 10,50 | 80 | 0 | 220 | 82 | |
| 3 | 6 | 18 | 10,50 | 80 | 0 | 220 | 82 | |
| 4 | 7 | 21 | 10,50 | 80 | 70 | 220 | 84 | |
| 4 | 8 | 24 | 13 | 80 | 0 | 220 | 84 | |
| 4 | 9 | 27 | 13 | 80 | 0 | 220 | 84 | |
| 5 | 10 | 30 | 13 | 80 | 70 | 220 | 84 | |
| 6 | 11 | 33 | 21 | 80 | 0 | 220 | 94 | |
| 6 | 12 | 36 | 21 | 80 | 0 | 220 | 88 | Two blower fans installed |
| 6/7 | 13 | 39 | 21 | 80 | 70 | 220 | 87 | |
| 7 | 14 | 42 | 21 | 80 | 0 | 220 | 88 | |
| 7 | 15 | 45 | 21 | 80 | 0 | 220 | 88 | |
| 7/8 | 16 | 48 | 21 | 80 | 70 | 220 | 88 | |
| 8 | 17 | 51 | 21 | 80 | 0 | 220 | 88 | |
| 8 | 18 | 54 | 21 | 80 | 0 | 220 | 88 | |
| 8/9 | 19 | 57 | 21 | 80 | 70 | 220 | 88 | |
| 9 | 20 | 60 | 21 | 80 | 0 | 220 | 88 | |
| 9/10 | 21 | 63 | 21 | 80 | 70 | 220 | 88 | 4 grams of 100 grid sand added |
| 10 | 22 | 66 | 21 | 80 | 0 | 200 | 98 | |
| 10 | 23 | 69 | 21 | 80 | 0 | 200 | 98 | |
| 11 | 24 | 72 | 21 | 80 | 70 | 208 | 92 | |
| 12 | 25 | 75 | 21 | 80 | 0 | 180 | 98 | |
| 12/13 | 26 | 79 | 21 | 80 | 0 | 190 | 92 | |
| 13 | 27 | 83 | 21 | 80 | 70 | 190 | 92 | |
| 13/14 | 28 | 87 | 21 | 80 | 0 | 190 | 92 | |
| 14 | 29 | 91 | 21 | 80 | 0 | 190 | 90 | |
| 14/15 | 30 | 96 | 21 | 80 | 0 | 190 | 90 | |

### 7.6.2 *Ferro-precipitator Summarised Results*

| Sample number | Engine hours | Dyno. reading kW | % Area ($A_L$) covered at 55 mm position on slide | % Area ($A_S$) covered at 50 mm position on slide | Severity Index Is Ai - As | Remarks |
|---|---|---|---|---|---|---|
| 3 | 9 | 6,5 | 70 | 53 | 2091 | Start of "run-in" |
| 7 | 21 | 10,5 | 43 | 38 | 405 | End of "run-in" |
| 10 | 30 | 13 | 46 | 39 | 595 | |
| 13 | 39 | 21 | 51 | 43,5 | 709 | |
| 16 | 48 | 21 | 60 | 52 | 896 | |
| 19 | 57 | 21 | 94 | 88 | 1092 | |
| 21 | 63 | 21 | 64 | 36 | 2800 | 4 grams of 100 grid purified laboratory sand added to engine |
| 24 | 72 | 21 | 96,5 | 72 | 4218 | High wear pattern |
| 27 | 83 | 21 | 99 | 87 | 2232 | Engine flushed |
| 39 | 96 | 21 | 98 | 68 | 4980 | Excess wear permanent |

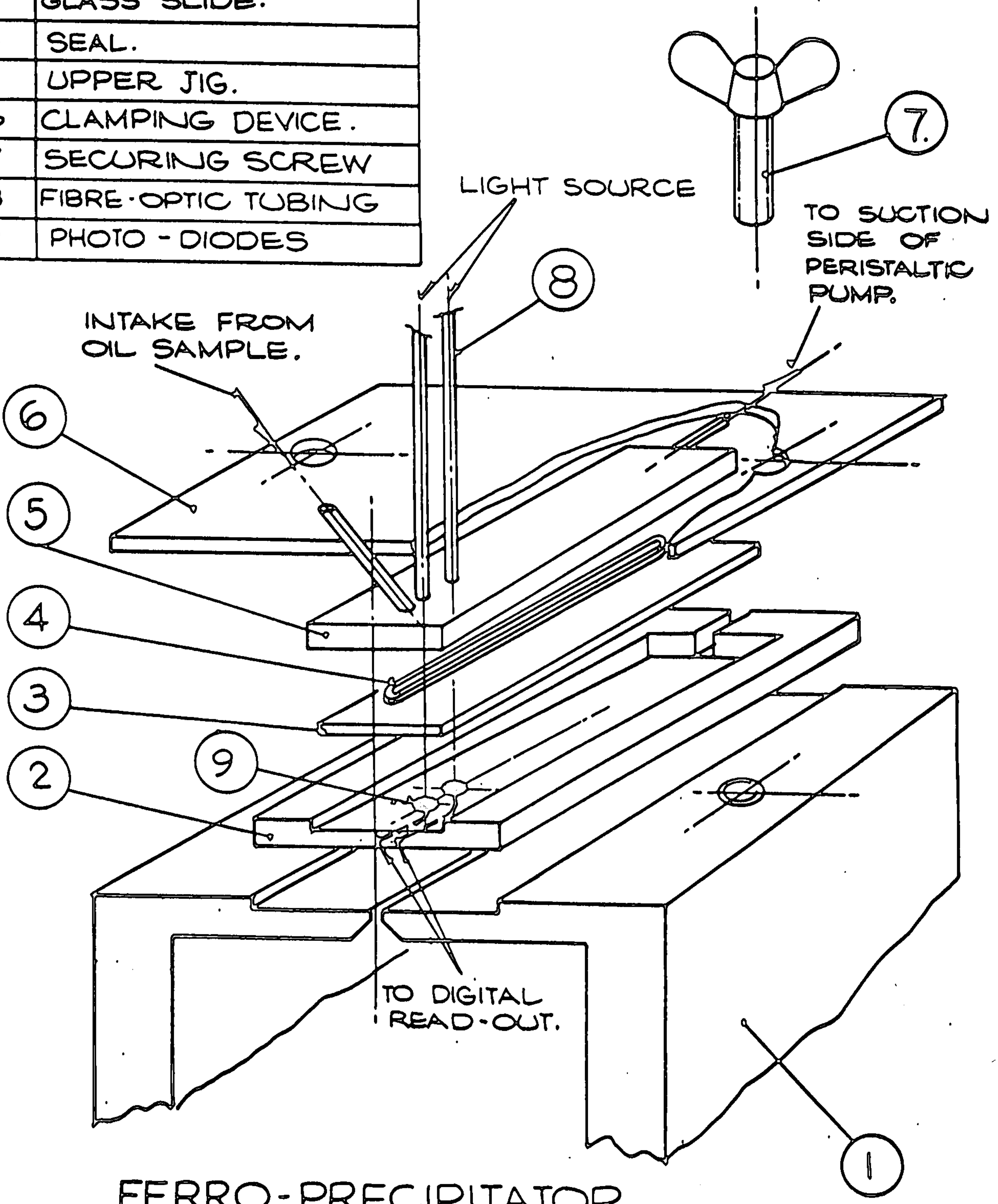
### 7.6.3 *Spectrometric Summarised Results*

| Sample No. | Engine Hours | Dyno. Reading kW | Fe p.p.m. | Pb p.p.m. | Ca p.p.m. | Zn p.p.m. | Al p.p.m. | Si p.p.m. | Visc. cSt at 40 C | Remarks |
|---|---|---|---|---|---|---|---|---|---|---|
| 3 | 9 | 6,5 | 53 | 429 | 1769 | 832 | 7 | 1 | 132,9 | |
| 7 | 21 | 10,5 | 98 | 1425 | 1835 | 787 | 11 | 5 | 138 | |
| 10 | 30 | 13 | 176 | 2017 | 2049 | 785 | 16 | 11 | 134,8 | |
| 13 | 39 | 21 | 216 | 2819 | 2605 | 826 | 32 | 15 | 136,8 | |
| 16 | 48 | 21 | 127 | 2091 | 1835 | 787 | 16 | 9 | 138 | |
| 19 | 57 | 21 | 134 | 2032 | 1866 | 786 | 15 | 10 | 139,5 | |
| 21 | 63 | 21 | 171 | 2603 | 2093 | 864 | 8 | 14 | 143 | 4 grams of 100 grid purified laboratory sand added |
| 24 | 72 | 21 | 3961 | 4459 | 2366 | 927 | 296 | 228 | 157,4 | High wear pattern |
| 27 | 83 | 21 | 400 | 1522 | 1878 | 1011 | 32 | 16 | 127 | Engine flushed |
| 30 | 96 | 21 | 1078 | 2625 | 2493 | 1074 | 46 | 46 | 137,7 | |

APPENDIX 7.7: Industrial Model of Ferro-precipitator

PARTS LIST.

| ITEM | DESCRIPTION |
|---|---|
| 1 | PERMANENT MAGNET. |
| 2 | GLASS SLIDE HOLDER. |
| 3 | GLASS SLIDE. |
| 4 | SEAL. |
| 5 | UPPER JIG. |
| 6 | CLAMPING DEVICE. |
| 7 | SECURING SCREW |
| 8 | FIBRE-OPTIC TUBING |
| 9 | PHOTO-DIODES |



FERRO-PRECIPITATOR.

I. SUNJKA.