CORROSION AND WEAR OF PLATES IN THE PRODUCTION OF REFINER MECHANICAL PULP

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BY

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ABSTRACT

Disk refining has become an increasingly important process for the manufacture of mechanical pulp for the production of newsprint and other "groundwood" speciality papers. The history of the development of chip refiners beginning with their use in pulp property modifications in the early 1900's and their use for semichemical and mechanical pulping processes at present is briefly reviewed.

Disk refining, as a pulping process, has in spite of its promise to replace chemical pulp not been without its technical difficulties; the major ones being the high energy inputs required as compared to stone groundwood, variations in quality and inadequate plate life. Each of the variables associated with these difficulties is reviewed in an extensive literature review.

Since refiner plate wear and refiner plate corrosion both involve loss of plate material and are critical factors in plate life, the review of literature was extended to cover these variables. Although literature on wear and corrosion of refiner plates is extensive, little was found directly pertaining to refiner plate life. Because of this deficiency of information in both these important areas, experimental work was conducted on both the wear and corrosion of Ni-hard refiner plates.

The wear of refiner plates run on a Sprout Waldron 42-1B refiner at Price (Nfld.) Pulp and Paper Company

Limited, Grand Falls, Newfoundland, was monitored using a systems analytical approach coupled with standard metallurgical techniques. The refiner plates after use were found to have worn in sharply defined annular zones at randomly defined radii. In each zone the wear was asymmetrical, with one of the opposing plates wearing more than the other. The location of the wear zone and the disk experiencing wear (rotor or stator) were found to be random.

At first, it was believed that this unusual wear pattern was the result of plate clashing and/or damage by foreign material. Metallurgical and electrochemical studies of the plates within the framework of systems analysis clearly showed that this was not the case, and that the metal removal patterns observed were indicative of that produced by a process not dissimilar to electrochemical machining.

The corrosion characteristics of Ni-Hard plates were analyzed by potentiostatic polarization methods using an intact refiner plate as the working electrode. A potential was impressed upon this electrode causing it to corrode. The resultant current density as a function of applied potential was plotted giving a polarization curve for Ni-Hard. The procedure followed was based upon ASTM Standard Method G5, modified such that an intact refiner plate could be used. No attempt was made to duplicate the temperature and consistency conditions in the refining zone of a commercial refiner because of the experimental difficulties involved and the fact that these conditions are still not well understood. In spite of this limitation, the results gave some interesting insights into the effect that additives have in extending refiner plate life. Results showed that corrosion rates were lower when dissolved oxygen was high, bringing into question the belief that the role played by Na_2SO_3 in enhancing refiner plate life is via a mechanism of oxygen scavenging.

The potential for extending refiner plate life by corrosion control techniques is discussed. These include:

1. control of O_2 content,
2. alloying of plates,
3. anodic protection,
4. cathodic protection.

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NOTATION

E_{corr}	Open circuit corrosion potential
E_{pp}	The primary passive potential
I_{corr}	Corrosion current density
i_{cr}	Critical current density
i_{pass}	The passive current density
R_c	Rockwell hardness

CHAPTER 1

INTRODUCTION.

1. INTRODUCTION

1.1 Historical Development of Refiner Groundwood for Newsprint Manufacture

The term refining, as it pertains to the mechanical treatment of papermaking pulps, is of relatively recent origin and appears to have derived largely from the use of disk refiners. Before their introduction into the paper industry about a hundred years ago, disk refiners were extensively employed for flour milling and extraction of oils from vegetable seeds.

Disk refiners consist essentially of two counter-rotating concentric disks fitted with toothed abrading plates. After adjustment of the plate separation by a predetermined amount, feed material is fed from the center of one disk and is reduced in size as it passes through the refining zone to the peripheral gap. The surface of the abrading plates consist of a series of bars--breaker bars, intermediate bars and fine bar zones, with each performing a specific task in the refining process. The refiner plates are characterized by three basic variables: pattern, profile, and material.

It was just over fifty years ago that precision engineered disk-mills were successfully introduced into the paper and board industry. This led to serious consideration of their potential application in the whole field of stock preparation. The rapidity with which disk refiners have been adopted and continue to displace other types of stock preparation equipment is, as Steenberg (1) has noted, mainly attributable to the efforts of equipment manufacturers. Disk refiners were employed first as on-line stock preparation units ahead of paper machines, then, in quick succession, for the treatment of semichemical pulps and screen rejects in the pulp mill (2-7). It was probably inevitable that they would be modified eventually for use as primary units for mechanical pulp production using residual sawmill based materials which could not be pulped by conventional stone groundwood methods. Pioneering work in this field was carried out by Eberherdt (8-10), Textor (11), and de Montmorency (12).

Textor (11) started work on refiner mechanical pulp in the Bauer Brothers laboratory during the period of 1954-56. It involved short runs on a commercial size 36-inch (500 h.p.) refiner and consisted of all mechanical reduction of chips followed by classification and cleaning of the refined material. This basic work, reported by Eberherdt (8-10), resulted in patents by Textor and Eberherdt. The first commercial pilot-plant, capable of making 30-minute runs, was installed by Crown Zellerback in their Camas Research Division in 1958, using a 40-inch diameter 800 h.p. double disk refiner. The early work indicated that this refiner did not have enough capacity to be practical for large installations and a larger 48-inch disk refiner capable of using 3,000–4,000 h.p. was designed and installed at two locations--Crown Zellerbach Mill at West Linn, Oregon, and Publishers' Paper Mill at Oregon City, Oregon. Both these installations were single stage refining systems. A second large refiner was installed in the Oregon City Mill in 1962 giving rise to the first two-stage system.

In 1962, Holzer, Henderson, West and Byington (13) reported the advantages of refining wood chips at consistencies in excess of 15 per cent. Low consistency refining was characterized by very high power usage and feeding difficulties. Their studies were not only a precursor to the development of high consistency refining technique, but also a major evolutionary step in the development of refiner mechanical pulping.

During the same period, 1955-63, a number of other investigators were also working in this field. Fundamental studies were being carried out by Atack and May (14) at the Pulp and Paper Research Institute of Canada. Forgacs (15) was doing work on the characterization of mechanical pulps, while Beath and Neill (16) were working on a commercial system at Kenogami, Quebec, evaluating equipment and investigating pulp latency. Stewart (17) was working on a commercial plant pulping sawmill residuals at Powell River, B.C., while Dorland, Holder, Leask, and McKinney (18) were doing laboratory pilot plant studies in the central research division of Abitibi Paper Company. Jones, with Consolidated Bathurst Company, was also working on the consistency problems and did much preliminary plate design work (36). At Manstique, Michigan, Hoholik was studying grinding followed by refining.

1.2 Present Day Problem Areas

Although commercial experience has shown that refiner mechanical pulping of chips produces a substantially stronger pulp than stone groundwood and permits a reduction in the amount of chemical pulp used in newsprint, the process has not been optimized and considerable work and research remains to be done. Power requirements for refiner mechanical pulp are much higher than for stone groundwood, and the escalating price of energy is a cause of concern and must be overcome if the process is to develop further. Refiner plate costs are high and plate life must be increased without any serious adverse effect on pulp quality. Since there is pressure on newsprint producers to reduce energy requirements, a design of plate capable of maintaining pulp quality at reduced levels of power consumption will have a major impact on the economics of newsprint manufacture.

In response to the need to reduce energy requirements, improve pulp properties and increase plate life, development work by equipment suppliers and pulp and paper manufacturers is on-going. A large amount of detailed data, particularly on plate life, has been gathered, and there is also much data on specific energy consumption, effect of additives, and plate pattern. Unfortunately, much of the data which has been gathered has not been correlated with measured plate parameters, and, no systematic approach to the problem has been published in the literature (with the possible exception of work done by Holzer (13) and Atack (20) on plate taper).

Further improvements in plate design to reduce energy consumption and improve pulp properties would seem to hinge on solving the following problems:

1. How to characterize plates.
2. Development of methods to correlate energy consumption and pulp properties to measured plate parameters.
3. The maintaining of the desired plate characteristics over the life of the refiner plate.
4. The interrelationship between plate parameters and other refiner variables such as specific energy, consistency, power density and speed.

A systems analytical approach to the problems and data collected on the basis of statistically designed experimental techniques would help achieve the twin objectives of improved mechanical pulp at reduced energy cost. For this reason, a systems analytical approach was demonstrated in this thesis to analyze the refiner and refiner plate system with respect to wear.

The evaluation of plate life data is not a simple matter. For example, the data can be from two sources:

1. normal operation, one in which the plates have never been in physical contact; and
2. clashed operation, one in which the plates have been damaged either through plate to plate contact or because of the passage of some hard, usually metal, material through the refiner.

Since clashing will invalidate any design measurements made with respect to the plate geometry and surface characteristics, it is important to recognize when clashing has occurred and that clashed plate data not be confused with data from normal operation. It is difficult to distinguish between a normally run plate and a clashed plate and, in fact, as outlined in Section 3.5.3.1, this can only be done in many cases by microscopic metallurgical examination.

Plate design programs cannot be run in isolation from the production process since the type and condition of the refiner and auxiliary equipment, and such factors as tram, runout, condition of bearings, feed evenness, and steam and pulp removal arrangement, are important. Since pulp quality depends not only on refiner plate design, but also to a large extent on refining consistency, feed rate (production), stability of feed, type of refiner, type and quality of feed material when plates are being designed for a particular installation, all of these factors must be considered.

1.3 Objectives of Thesis

In summary, there is a need for a systematic approach to the design of refiner plates if progress is to be made toward improving pulp properties while decreasing costs. A systems analytical approach is needed. For these reasons the objectives of this thesis were set as follows:

1. To review the literature on the design and operation of the disk refiners, with particular emphasis on factors important in the design of refiner plates for extended plate life/power reduction/pulp quality improvement.
2. To monitor the wear of refiner plates run on a Sprout Waldron 42-1B refiner at Price (Nfld.) Pulp and Paper Company, Limited, Grand Falls, Newfoundland, using a systems analytical approach coupled with standard metallurgical techniques. From this study to elucidate the wear mechanisms involved and to propose solutions to the wear problems.

3. To study the corrosion characteristics of Ni-Hard refiner plates using potentiostatic polarization methods with particular emphasis on identifying the role played by sodium sulfite in the extension of refiner plate life. Knowing the role of sodium sulfite and the mechanism by which it extends plate life to propose measures to stop or inhibit more completely the corrosion process.

CHAPTER 2

FACTORS INFLUENCING PLATE LIFE: A LITERATURE SURVEY

2. FACTORS INFLUENCING PLATE LIFE: A LITERATURE SURVEY

2.1 Introduction

During the early stages of development of the refiner mechanical pulping process, circa 1960, the prime concerns were not with plate life, but with increasing the strength of the pulps produced whilst maintaining reasonable power consumption. Helleur and Jones (19) summarized the difficulties typically encountered. At low consistencies, in the range of 8%, very high strength pulps could be produced but at an energy consumption up to three times required for stone groundwood. Raising the consistency improved strength and reduced energy consumption but caused difficulties in feeding and maintaining motor loads. Holzer et al (13) and Atack and Wood (20) describe some of the work done during that period to overcome the problem. Eventually, it was recognized that the introduction of a small amount of taper between the plates resulted in sufficient self feeding which enabled consistencies to be increased to the 30% range and energy consumption to be reduced to 100-120 HPda/ODT.

The main factors identified in the literature as having an influence on plate life in addition to taper, were plate geometry, hardness, the addition of chemicals such as sodium sulphite and sodium carbonate to control pH and such operating variables as plate clearance, disk speed and whether or not the direction of rotation is reversed over the life of a set of plates. The effects of plate wear on pulp properties and on power consumption are well understood and have been commented upon by several investigators notably Dorland et al (18), Mihelich et al (21), Nystrom and Okell (22), and Beath et al (23). As the plates wear, at any given level of specific energy consumption strength properties deteriorate and debris content increases. Very little, however, appears in the literature about the causes of plate wear.

2.2. Plate Pattern

Refiners, of different size and power inputs used for different end results, need different refiner plate patterns. Each plate pattern is used for a specific purpose and the use of an alternate pattern invariably results in shorter plate life or clashing. The plate pattern involves length of each refining zone, width and height of bars and grooves, taper (Section 2.3), and the symmetry or asymmetry of bars.

Holzer, et al. (13) describe work done on two basic refiner plates illustrated in Figure 1. In general, their findings were that a plate which had a relatively fine radial bar, narrow grooves, and numerous intermediate dams, was the most satisfactory for their type of operation. The difference in the two plates studied was in the width of bars and grooves. Their work indicated that with wider bars and grooves, horsepower requirements were reduced; high consistency could be attained; and throughput was increased at the same freeness level. Holzer stated, "it is obvious that the field of plate pattern study offers good possibilities of significant improvements, and undoubtedly, investigations in this area will continue for some time."[1]

A few years after Holzer's work [1966], Mechanical Pulp Manufacture (24), reiterated the point that the ideal plate configuration would differ with wood species, chip pre-treatment, rate of feed, consistency, installed horsepower, and disk velocity. It also commented on the usual symmetry of plate patterns, so that the refining action would be the same irrespective of direction of rotation. The effect of the plate grooves which had been discussed by Holzer, et al. (13) and Atack and May (14) was also given in the report. Atack and May stated that,

> ... it appears that the grooves are rapidly plugged by a mass of shives, which becomes so hard that it can only be removed by manual cleaning with a suitable tool. Still, the plates thus plugged perform much better than plates with grooves as shallow as the remaining grooves in plugged plates. This is explained by the resilience of these "wood

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[1] Holzer, et al., "The Development and Production of Disk-Refined Groundwood Pulp", Tappi, 45, 3, March, 1962, p. 210.

fillings" in the grooves. The particles are evidently pressed down each time a bar of the other disk passes and therefore less damaged.[2]

It was also seen that for full utilization of the refining area, the radial velocity of the pulp particles should really decrease exponentially with the distance from the disk center, which is, of course, not so easy to arrange. Photographic studies by Atack (25) on a double disk refiner have indicated that in some cases as little as 20 per cent of the plate area was actively doing refining work at any one time. This is an important refining variable, which is controlled by plate design and which is manifested by non-uniform plate wear as well as inability to load a refiner to full capacity.

Three publications reflect the importance of plate pattern. Arnesjö and Dillén (26) [1975] state that at Hallsta paper Mill, Sweden in cooperation with Defibrator, they have run and are still running a substantial evaluation program to find the most suitable material and patterns for their purposes. Their aim is to use plates which allow a high energy input at high disk clearance. They believe that high energy input is achieved if the space between the plates

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[2] D. Atack and D. May, "Mechanical Reduction of Chips by Double Disk Refining", Pulp and Paper Mag. Can., 64, C: p. T-83 (Convention, 1963).

is well filled and the impact frequency exerted on the fibers is high.

Some work from Norway by Høydahl and Hauan (27) [1975] on comparison of results from small refiners in evaluating full scale systems pointed out the importance in comparing the smaller refiner results to a larger refiner of the plate pattern. For various reasons, they stated, that the plate pattern in the small and large refiner is not the same since each type of refiner has its own special designed pattern and taper. Although similar in principle, the operation of different refiners will be influenced by the total disk area, total power applied, feeding system, speed, and whether the refiner is a single disk or double disk machine.

The third, and perhaps the most important paper to date on plate pattern, is by Mannstrom (28) working with the Finnish Pulp and Paper Research Institute. Basing research work on May's (29) model of exponential chip breakdown, he states that

> "The influence of refiner plate design upon the quality of the pulp in a one-stage process is decisive. In the preliminary comparisons that were made with plates available on the market, stone-groundwood quality was attainable. In a one-stage RMP-process with cold chips, these plates were less suitable, and accordingly another plate was developed. As a starting point for this, there was taken an approach put forward by W.D. May in 1971 (29). Mathematically, it is assumed that chips-splitting is explicable by a exponential function, which would imply that the number of bars should

rise radially in agreement with the same function. However, with regard to the quality of the pulp, simultaneous consideration should be given to the bar width, the contemplated degree of filling in the refiner zone, the plate material, and the necessary taper. Fig. 2 illustrates a compromise between all of these factors. The refining plate is divided up into five sections. In section 5 the number of bars is 252, and that in section 1 is 792.
With this plate, it became an easy matter to obtain RMP pulp of high quality, and the shive content of the pulp also being low. Moreover, the strength properties were without exception 30 per cent superior to those of stone groundwood of standard quality. It is evident that a plate of this type operates with considerably less cutting than does a standard radial pattern.
However, a more interesting point was that the new plate behaves with respect to loading in a way different from that of standard plates available on the market. The loading curve for multi-sectioned plates is more linear. This could be taken to indicate that the refining energy released in a radial direction occurs more evenly. Consequently, May's model appears to be correct."[3]

The literature points out the importance of plate pattern but says little except that a different pattern is needed whenever any refiner variable changes. Careful study must be made of the relationship between changes in plate pattern and changes in refiner variables to lead to correct patterns for increased pulp quality, production economy, and maximum plate life. Mannstrom's (28) research may hold the key to much progress in the area of plate pattern.

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[3] Mannstrom, B., International Mechanical Pulping Conference Proceedings, Helsinki, 1977, p. 9:5, 9:6.

2.3 Running Clearance - Plate Taper (Profile)

Plate taper or profile has been found to be extremely important in plate pattern evaluations. It is one of the basic factors of plate design and is critical in regard to maintaining pulp quality and extending plate life.

Holzer, et al. (13) published some of the first data on plate taper at West Linn, Oregon. The initial plate sets (evaluated) were all ground with a standard plate taper of 0.005 inch per inch. These initial plate sets exhibited very short life (100 hours) largely due to deep tongue and groove scoring in the periphery--the apparent area of contact between the opposing new plates. Upon reducing the taper in stages to 0.002 inch per inch, the peripheral wear was reduced significantly. They surmised that the reduction in plate taper increased the amount of refining surface available for use on new plate start-up and caused the available power to be more evenly distributed over the entire plate surface and not concentrated at the periphery. This increased normal plate life to 500 to 600 hours. Kurdin (50) reiterated that for uniform pulp quality the power input per square inch of ground plate surface must remain constant.

Great Northern Paper Company, Millinocket, Maine (30) experimented with several types of plate designs in the late 1960's and found that a Bauer Pattern proved best for their use. This plate pattern had a relatively large taper which allowed the stock to distribute more uniformly towards the outer periphery, which had a flat area of approximately three inches. They found that plate clearances were at their closest in this area and it was there that they believed most of the refining action took place.

Extensive information on plate taper has appeared in papers from Sweden and Finland. Bergstrom's work (31) contains an evaluation of different plate tapers and different widths of the outer flat zone. They found that a poor quality pulp was obtained if too much work was put into the chips in the feed zone of the primary refiners (Table 1). This suggested that the wood particles have to be warm and susceptible to the intense treatment in the flat outer zone. Their results indicated that a large intermediate zone taper and a nearly flat outer zone produced the highest quality pulp.

Peterson and Dahlquist (32) dealt with single disk and double disk refiners in different arrangements, and the effect of the arrangement on pulp properties and energy consumption. Peterson notes that all sampling took place after "all plates were ground to the optimum taper, which was essential for a correct assessment of the performance of the refiners...."[4] Figures 3-5 show the effect which an

[4] V. Peterson, and G. Dahlquist, "Single Disk and Double Disk Refiners in Different Arrangements," I.M.P.C., 1973, Stockholm, p. 14:4.

the effect which an incorrectly chosen taper grinding had on the energy consumption; an increase in energy consumption, but no corresponding improvement in pulp quality.

Nurminen, et al. (33), Rauma-Repola Oy Paper Mill, Rauma, Finland, have experimented with refiner plates in their refiner installation. They have worked on plate tapers, and now have 0-1.5 per cent at the fine bar section and 1.5-5 per cent for the intermediate section (Table 2). They have also made comparisons between sawdust refiner groundwood made with different plate tapers and found tearing to increase, and breaking length to decrease with an increasing taper. At the same time as taper trials, plate wearing profiles were examined and no systematic information could be obtained.

Work on plate taper [1975] was done also by Beath and Mills (34) who initially reported they experienced the same wear as Holzer, et al. (13). Their plates had a uniform taper but "were found in the end to have developed parallel faces over the outer 2 to 4 inches of their radii. The refiner had told us that some parallel surface was wanted."[5] From there the extreme was tried, flat-ground plates--"a serious overshoot of a logical change."[6] Flat-ground plates

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[5] C. Mills, and L.R. Beath, "Single Stage Groundwood from a 12,000 h.p., 1,500 amd 1,800 r.p.m. Refiner." (Paper presented at I.M.P.C., San Francisco, 1975), p. 56.

[6] Ibid., p. 57.

would not permit feeding above 8,500 h.p. (on a 12,000 h.p. refiner). They found that their best combination was flat-ground plates running against plates having a taper of 0.005 inch per inch with the outer fine bar section flat.

In his work on disk misalignment, May (35) considers the running clearance between the surfaces of opposing plates as a critical parameter that determines the performance of disk refiners. For a given throughput of chips, he maintains, this clearance determines the amount of energy expended per unit weight of the material and in turn the "character" and "quality" of pulp produced. A variation of plate clearance from the inner section of the refining zone to the outer periphery is usually provided by a carefully designed taper that may have one or more steps to it. May states that this taper was thought to promote self-feeding in the refining zone and also to control the quality of stock.

Plate taper is necessary to enable maximum feeding of the refiner (34,35). Too much taper places excess wear on small areas--probably the outer edges--of the plates. An observation here is the feasibility of determining correct and optimum tapers through a study of the wear on the plates. A first approximation is that

$$\text{Wear} \equiv \text{h.p. days}/_{\text{BDT/in.}^2}.$$

If this were true then the numbers could be used to set correct plate tapers. If the plate taper is not optimum the flux of energy dissipation will vary over the plate. Early experiments by Consolidated Bathurst (36) on Sprout Waldron refiners with retaining rings should be reevaluated.

2.4 Plate Material

One of the earliest reports [1966] on plate material is contained in Mechanical Pulp Manufacture (24) which names the two most frequently used plate alloys in chip groundwood manufacture as Ni-Hard and M-alloy containing molybdenum and nickel but no chromium. With very corrosive pulps X-alloy, a stainless steel alloy, is used but is considered too soft for other applications. With the advent of more efficient methods for heat treatment of the plates for increased hardness and wear resistance, it is surmised that better pulp quality and process economy might result one day.

Bergstrom, et al. (31), at the Swedish Cellulose mill in Ortviken, Sweden, have evaluated plate alloys. In their studies they have developed two alloys (a martensitic stainless steel and a high chrome cast iron) which proved to be very suitable material for the 1,500 r.p.m. Sunds-Bauer 488 refiner with the stainless steel alloy showing very little wear after 1,600 hours of operation. They state that "a good plate material can almost eliminate quality variations and give a much longer plate life than standard Ni-hard type materials".[7] From personal correspondence they state (37) that plate material "is certainly one of the main factors in plate design".[8]

Nurminen and his group (33) describe various start-up problems associated with new refiner installations at Rauma, Finland, especially with the durability of the refiner plates in the beginning. Five plate materials were tried (Table 3), but none could exceed a 400 hour run due to heavy corrosion, which resulted in poor quality pulp and imbalance in the refiner causing vibration. The corrosion process was still unsolved at that time but believed to be a combination of steam cavitation, chemical corrosion and mechanical wearing.

They eventually found a material that is fairly resistant to cavitation and chemical corrosion and the age of the plates was subsequently doubled, and even tripled, depending on refiner position. The material was designated Uddeholm B; a summary of the plates is given in Table 4.

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[7] J. Bergstrom, G., Dahlquist, B. Fredriksson, and V. Peterson, "The Design of Refiner Plates", Pulp and Paper Mag. Can., 73, 6, June, 1972, p. 56.

[8] Personal correspondence from V. Peterson, May 27, 1977, Sundsvall, Sweden.

Specifications as to the chemical analyses, heat treatment, etc., are unavailable for the new material.

In the design of refiner plates, plate material is one of the extremely important factors to be considered. Conditions must be known or determined within the refiner and suitable materials selected to minimize corrosion and wear based on these conditions, i.e., pH, temperature, additives.

2.4.1 Hardness of Plate Material

The structure of the working surface of refiner plates is determined by the material. It is known from the work of Beath and Mills (34) that a good plate material can almost eliminate quality variations and give much longer plate life than standard Ni-Hard type materials.

Holzer, et al. (13), in 1962, evaluated three basic plate patterns, and three plate materials of varying hardnesses, 350, 450, and 600 Brinnel. They found that several basic factors of plate design were critical in regard to maintaining pulp quality and extending plate life. Plate alloys seemed to affect groundwood quality significantly in most cases. In general, better quality pulps had been produced using 350 Brinnel plates rather than the harder alloys, although the 600 Brinnel had shown some promise. The softer plates were readily conditioned (Section 2.4.2), i.e., the sharp edges were worn from the radial bars soon after start-up and were replaced by a rounded edge of small radius.

It was not known how the harder alloy plates conditioned, but if conditioning did not occur the quality was generally poor because of the excessive cutting action of sharp plates.

The use of softer alloy plates for refining was reiterated by Graham (38) of CIP Gatineau at a meeting [November, 1976] of the Mechanical Pulping Committee of the CPPA. He stated that CIP in their new TMP mill were using Japanese stainless ST alloy plates which are a soft stainless (Rc 48-50). They have used different alloys but found the softer ones to be the best; anything over Rc 50 was too hard. They found that the softer plates would, once they were ridged (from contact clashing), smooth out and still be very good but the harder plates, once ridged, deteriorated. No signs of erosion or corrosion were seen on the plates but they were worn down after 1,300-1,500 hours (even wear-down on bars).

Tyralski (39) suggests that to obtain a durable inclined surface the refiner plates should be made of materials of different hardness, to create a scale of wearability along their width. As a condition for uniform wear over the whole working surface area, the pressure should decrease radially in the direction from the axle to the periphery of the disks, since the peripheral speed increases in that direction. Usually, as wear sets in, the gap at the external diameter becomes larger than at the internal diameter of the disk, and this results in a higher pressure at the internal diameter and a reduction of pressure at the external diameter. This favors fiber shortening at the internal diameter and fibrillation at the external diameter, i.e., highly unfavorable conditions which become worse as the ratio of the internal to the external diameters decreases. At the same time there is reduction of efficiency because the working surface is utilized only partially. An increase of the ratio from the usual 0.45-0.5 to 0.6-0.65 can remedy this situation, but at the expense of reducing the width of the beating surface and in effect still reducing the efficiency. According to Tyralski (39) this drawback can be eliminated by constructing the disk's operating zone of at least three circular concentric zones of different hardness, e.g., 600-400 Brinell for the external zone, 300-220 for the middle zone, and 160-200 for the internal zone. This would maintain uniform wear and improve efficiency at a ratio of diameters of 0.45 or even 0.35-0.4.

The point to be stressed is that pulp quality and characteristics must be maintained over the life of the plate. Hence, soft plates subject to wear are considered more likely to change away from the shape designed in the plate and that present at start-up. Indications are that there is an optimum hardness necessary to prevent excess cutting of fibers and maintain pulp quality and characteristics.

2.4.2 Conditioning

Whether refiner plates condition or not may not be considered a very important factor in attempting to prolong plate life (with associated good pulp quality). Holzer et al (13) state that softer plates are readily "conditioned', i.e., the sharp edges are worn from the radial bars soon after start-up and are replaced by a rounded edge of small radius. The harder alloy plates may or may not condition in the same manner (Section 2.4.1). A set of plates, however, which conditions will continue to show an increase in the wear radius of the radial bars and if this wear becomes excessive, refining power will rise and throughput will drop, leading to early plate removal. All plates, however, produce inferior pulp during a wearing in period caused by the cutting action of the sharp edges on pulp fibers (24).

Beath, et al. (21) made an interesting observation regarding plate wear under high consistency operation (25-30%). They stated that it "is unnecessary, and may even be undesirable, to 'condition' new plates just after installation."[9] They do not, however, elaborate on the

[9] W.G. Mihelich, D.J. Wild, S.B. Beaulieu, and L.R. Beath, "Single-Stage Chip Refining – Some Major Operating Parameters and Their Effects on Pulp Quality", Pulp and Paper Mag. Can., 73, 5, May, 1972, p. 81.

observation. The factor of plate conditioning may therefore be important if it were able to be quantified with respect to rate of wear and decline of pulp quality.

2.5 Different Plate Patterns on Rotor and Stator Disks

A factor which may be very important in refining and may lead to improved plate life is that of the use of different plate patterns on the rotor and stator disks of a refiner. This technique is mentioned by Arnesjö and Dillén (26) and by Beath and Mills (34). A concept of the refining action in a double disk refiner has arisen that the wood particles are mainly stationary in the refining zone but spinning around their axis under the action of the two counterrotating disks. In normal commercial refining, however, the particles tend more to follow one or the other disk around, preferentially the one with the central entry ports, the rotor, while being pounded by the other one.

Mills and Beath (34) have described single stage groundwood production from a 12,000 h.p., 1,500 and 1,800 r.p.m. double disk refiner. They commented after various plate design trials that "over a span of time, the best combination has proven to be flat ground plates running against plates having a taper of 0.005 inch per inch with the outer fine bar section flat."[10]

Arnesjö and Dillén (26), in describing thermomechanical pulping at Hallsta Paper Mill in Sweden essentially extend on the idea above of particles following a disk. Their aim was to use plates which allowed a high energy input at high disk clearance. They believed that high energy input was achieved if the space between the plates was well filled and the impact frequency exerted on the fibers was high. Their idea resulted in the use of patterns with rather narrow-spaced and thin bars especially in the stator plates, "the main task of which is believed to be to 'hold' the material in the refining zone."[11] On the rotor plates a somewhat more open pattern with some cross bars, which prevent a too rapid radial transport of the materials, might be used.

2.6 Consistency

In 1962, Holzer, et al. (13) showed that newsgrade mechanical pulps produced by refining hemlock chips were definitely stronger than hemlock stone groundwoods of equivalent freenesses provided that the refining was

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[10] C. Mills, and L.R. Beath, "Single Stage Groundwood from a 12,000 h.p., 1,500 and 1,800 r.p.m. Refiner." (Paper presented at I.M.P.C., San Francisco, 1975), p. 58.

[11] B. Arnesjö and S. Dillén, "Thermo-Medhanical Pulping at Hallsta Paper Mills." (Paper presented at I.M.P.C., San Francisco, 1975), p. 101.

conducted at a consistency in excess of 15 per cent. Low consistency refining requires relatively large volume throughput at a given tonnage rate; this means a reduced retention time for chips and a low shear force allowing random positioning of chips. On the other hand, in high density refining, a pulp pad of significant thickness is established between the plates making the shearing force between the plates more effective for defibering and developing the groundwood fiber.

Chip refining installations in the late 1960's operated at 20 to 25 per cent consistency, which appeared to be the practical optimum, although energy consumption dropped up to 30 per cent consistency, which was the maximum feasible consistency. The difficulty above 20 per cent consistency was in maintaining constant consistency and stable flow. Beath and Mills (34) have conducted refining trials at discharge consistencies ranging from the low 20's to over 60 per cent. They found, in general, that pulp quality improved steadily with increasing consistency up to 50 per cent or a little higher. Above the 55 to 60 per cent discharge consistency range pulp quality diminishes. Consistency fluctuations result in nonuniform flow, fluctuating load, lower pulp quality and may contribute directly to plate clashing. Stothert and Crotogino (40) showed from the work of Snow and Goosney (41) that low consistency refining, where the grooves of the plate are not filled with stock, has a detrimental effect resulting in a considerable amount of fiber cutting.

Refining consistencies in the range from 3 to 35 per cent were investigated on a rejects refiner by Wild (42). He found that the refining operation was improved when refining at the highest consistency where load swings were least, ± 5 per cent of load, and also the refiner could be brought to full load faster than at low consistency. Wild also found that the high consistency refining resulted in much longer plate life on Ni-hard plates; at 30 per cent, plate life was averaging 900 hours as opposed to 400 hours at 15 per cent, and only 150 hours at 6 per cent. He contributed most of the decline in plate life to extreme water-erosion at lower consistencies.

It appears that higher consistencies contributing to thicker pads and less water erosion lead to much longer plate life. There is also the possibility that thicker pads reduce the risk of clashing, again contributing to longer plate life.

2.7 Additives and pH Control

The major portion of reported data on the use of additives and pH control is from Beath, et al. (23,43). They have reported (43) that in the manufacture of refiner groundwood at high refining consistencies, Ni-Hard refiner plates "wear" largely as a result of corrosive attack by wood acids. By the addition of about four pounds of soda ash per ton of chips, which raised the pH from a normal 4.8-5.2 range to about 6.4-6.8, they showed that plate life could be almost doubled.

In their original work, Beath, et al. (23) report that the use of soda ash with Ni-Hard plates gave a very substantial cost reduction (Figure 6). In part, this reduction resulted from an extension of economic plate life, but the more important benefit of the soda ash treatment came by way of slower loss of refining efficiency and consequent savings in specific energy and production capacity. The best results were obtained by increasing the pH from 4.8-5.2 to the range 6.2-6.6.

Beath, et al. (43) also compare sodium sulfite used in one refiner with soda ash used in another. Sodium sulfite is a readily available chemical which can also be used to adjust pH. Additionally, it is known to react with wood and the literature (44,45) reports that effects other than those resulting from the pH change are obtained. Tables 5 and 6 give the results of their work and the figures shown in Table 5 were used to compare plate life associated costs for three conditions: (1) no treatment; (2) sodium carbonate; (3) sodium sulfite. Results are shown in Figure 7. Some related data from Figure 6 is summarized in Table 6 which shows that plate life costs are lowered by $1.20 per ton by the use of sodium carbonate and by $3.55 per ton by the sodium sulfite. The sodium sulfite also has a substantial pulp brightening effect. Good plate protection and balance of other factors suggest 20 to 25 pounds per ton as a good rate of addition. At that rate a brightness increase of 4 to 5 units is obtained.

Sodium carbonate is a fairly strong base so only four pounds per ton is required to increase the pulp from pH 5 to pH 6.5 where substantial protection against plate corrosion is obtained. However, small increases above that level raise pulp pH to the point where the well known yellowing effect of caustic occurs strongly and substantial loss of brightness results. Nurminen, et al. (33) found, however, that the addition of sodium carbonate to keep pH between 6 and 6.5 did not reduce chemical corrosion and no prolonging in the life of the plates could be established.

2.8 Reversal of Plates

In conducting early laboratory tests, Dorland, et al. (18) in 1961 reversed the rotation of plates every 500 passes (10 to 12 pounds of chips per pass) to insure uniform wear and thus obtain comparable pulps. Holzer, et al. (13) found from semicommercial tests run in the early 1960's that periodic reversal of motor direction helped maintain a relatively high throughput during the first half life of the plate. Beyond this point they found that reversal did not appear to help to any great extent. This reversal was helpful on plates which conditioned (Section 2.4.2) and showed increases in wear radii of the radial bars, since if the wear became excessive, due to nonreversal, refining power would rise and throughput would drop.

Plate patterns were usually symmetrical at first (24) so that the refining action would be the same irrespective of the direction of rotation and motors were often reversed once a week to avoid a one-sided blunting of the plate pattern. As stated, however, this practice was being questioned since all plates produced inferior pulp during a wearing in period, and a similar pulp quality could be expected at each reversion of rotation.

Great Northern Paper Company, Millinocket, Maine, started up a modified rejects refining system in 1963 (45) and found it necessary to reverse refiner motors weekly to even out plate wear and to improve refiner efficiency and quality. Upon initial start-up of their new refiner plant in 1969, Price (Nfld.) Pulp and Paper Company, Limited, Grand Falls, Newfoundland, initiated plate reversal on a trial basis but apart from the detrimental fact, that ammeters and other instruments on the refiners were not reversible, there were not enough benefits indicated to continue the practice of plate reversal.

R.J. Scott (46) of Carter Oji Kokusaku Pan Pacific Limited, New Zealand, stated that they found it essential to reverse the direction of the disks at least every 200 megawatt hours of operation or the plate life was drastically reduced and the feeding ability of the refiner deteriorated rapidly. Based on their reversal of direction of disks at approximately every two days, they were able to get a plate life of somewhere near 1,000 hours or 3,500 megawatt hours, at a production rate of 140 A.D.M.T. per day. In their opinion, also, blow black conditions in refiners were closely associated with the reversability of the refiner and the ability to feed evenly into the refining zone.

This facet of extending plate life via periodic plate direction reversal seems today to have become a much neglected practice. Some very serious study and experimentation is quite evidently needed to validate claims of benefits from the practice and to determine parameters to decide the optimum times of reversal if indeed reversal is beneficial.

2.9 Refiner Speed

The peripheral velocity of refiner disks lies in the range 12,500-20,000 f.p.m. and for double disk refiners, the relative disk velocity is probably what counts, with the top velocity being 30,000 f.p.m. The exact effect of velocity changes on refining and pulp quality has not yet been determined.

Ludhe (47) reported 50 per cent decrease in energy consumption but also lower strength when going from 1,200 to 1,800 r.p.m., but these experiments were made at an early stage [1962] in the history of chip refining. Henderson (48), by increasing the velocity from 1,200 to 1,800 r.p.m., got a much lower freeness and a correspondingly higher strength at a given energy consumption. The early opinion [1966] seems to be that the pulp quality increases with the velocity but that the effect is small compared to other variables, which have to be controlled. If, however, a higher velocity makes it possible to put more horsepower into a given refiner, this will have a major effect on the capital cost.

Bergstrom, et al. (31) report the replacement of Sund-Bauer 480 Refiners (1,000 r.p.m.) with Sund-Bauer 488 Refiners (1,500 r.p.m.) in 1968 with the increased rotational speed changing refining conditions considerably. The new refiners had a much higher capacity than the previous model and could refine first-stage pulp to a lower freeness level, even at higher production rates. They discovered, however, that the refiner-plate material and plate design, which had given satisfactory results at 1,000 r.p.m., were not suitable at the higher speed. A study of pulp quality in relation to plate wear revealed that the plates were breaking down much faster than in the 1,000 r.p.m. refiners, and that pulp quality was deteriorating at a correspondingly high rate. As a result, a program to develop entirely new refiner plates was started.

An interesting analysis of the effects of an increase in speed has come from Beath and Mills (34) on the operation of a Twin-50 inch double disk refiner at both 50 Hz (1,500 r.p.m.) and 60 Hz (1,800 r.p.m.). After solving start-up problems on 60 Hz operations,

> ... the refiner was started on 50 Hz power using the plate pattern which had worked well at 60 Hz. Abnormal vibration occurred and the machine shut itself down due to overload on a load sensing conveyor. On opening the refiner the breaker bar section of the plates, and the ribbon conveyors, were found solidly filled with chips. This end result was reproducible.
> The problem was clearly due to the speed reduction from the prior 1,800 r.p.m. to 1,500 r.p.m. While only 16% in speed, the change was 30% in terms of the maximum breaker bar impact on chips. The breaker bars at the lower speed would not reduce chips to the small sizes needed to leave the breaker bar space at the rate of chip feed; that space then filled and the plug built back along the ribbon conveyors. The process ended, when the load sensing conveyors, having no free volume into which to discharge chips, filled and stopped on overload.[12]

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[12] C. Mills, and L.R. Beath, "Single Stage Groundwood from a 12,000 h.p., 1,500 and 1,800 r.p.m. Refiner." (Paper presented at I.M.P.C., San Francisco, 1975), p. 59.

The solution was "to restore the loss of breaker bar impact, the plates were changed with the new plates having a longer breaker bar section ....".[13] It is not known whether Beath and Mills predicted trouble in changing from 60 Hz to 50 Hz, but it can be readily seen that as the refiner speed changes so does the necessary plate pattern to accommodate changes in throughput.

2.10 Steam Generation and Removal

Dana et al (49) have given a detailed description of steam generation in the refining zone of disk refiners. They also state that:

> The direction of flow of steam in the refining zone and the pressure gradient developed there .... become critical factors in both the stability of operation and the quality of pulp produced in the refiner. They are themselves determined by the geometry and speed of the refiner, the plate pattern and plate taper, and the operating conditions of throughput, motor load, and the inlet consistency and temperature of the feed material.[14]

In their description of single stage groundwood from a 12,000 h.p., 1,500 and 1,800 r.p.m. refiner, Beath and Mills (34) discussed the egress of steam from various plate

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[13] Ibid, p. 59.

[14] H.R. Dana, W.D. May, K.B. Miles, and B.G. Newman, "A Study of Steam Flow and Self-Pressurization in Chip Refiners." (Paper presented at I.M.P.C., San Francisco, 1975), p. 143.

patterns. Plates (S.W. D20A031) which have relatively wide, deep grooves which extend to the outer periphery made steam egress easy, and the pressure build-up needed to force its removal, small. Steam escape with those plates was so easy that all steam left by the periphery for loads up to 10,000 h.p. The same plate pattern, but with a complete peripheral dam, gave only 65 per cent as large a power increase per unit hydraulic pressure increase; they considered that this was due to more difficult steam escape resulting in a higher proportion of the hydraulic pressure increments being used to balance increasing steam pressure. Another plate pattern (S.W. D20A001) used by Beath and Mills had a band of fine, shallow grooves at the periphery which were a restraint to steam outflow. Those plates normally had a back flow of steam at loads of 7,000 h.p. and up.

In their study of steam flow and self-pressurization in chip refiners, Dana et al. (49) used a standard refiner (conditions listed in Table 7) to investigate the effect of the operating and design parameters on the distribution of pressure and the flow of steam (ignoring presence of wood) by progressively changing each variable in turn while the other remained fixed. Both operating parameters and design parameters were studied; motor load, consistency, feed inlet temperature, inlet and outlet pressure, plate gap, plate taper, disk rotational speed, disk diameter, roughness of plate surface.

From their work they predicted that the pressure in the refining zone of a chip refiner was likely to be sensitive to plate clearance, plate taper, plate roughness, inlet consistency, inlet pressure, disk diameter and motor load, and insensitive to changes in inlet temperature, disk speed, and reduction of outlet pressure below atmospheric. The back flow of steam was likely to be very sensitive to disk diameter, inlet tempeature and inlet pressure, and insensitive to plate taper, plate roughness, disk speed, inlet consistency and reduction of outlet pressure below atmospheric. This work demonstrates that correct plate design is necessary (disk diameter, etc.) to insure proper steam egress and alleviate problems caused by back flow of steam which could lead to blowback and clashing.

Conventional refiners assume uniform taper from entrance to exit preventing steam from exceeding supersonic velocities which, according to Dana et al (49) may cause the occurrence of shock waves. This may also prevent refiners from clearing--the net result of which is self-pressurization, increased retention time, excess pressure on fine bar sections, excess wear and reduced plate life. In addition, power requirements are increased. A proposed solution is the use of converging-diverging plates (nozzle effect--Figure 8) to enable steam to clear. The results should be closer plate clearances without excessive pressures, lower shive content and less energy for the same pulp properties. Earlier waveline plates investigated by such companies as Consolidated Bathurst in the early 1960's should perhaps be reviewed.

2.11 Optimum Timing of Refiner Plate Replacement

Longer plate life is not necessarily optimum plate life. In the pulp and paper industry, as in all others, costs associated with production must always be optimized to maximize profit. Therefore, it is imperative to remove refiner plates when they have surpassed their optimum plate life based on costs. This section is a discussion of the method of arriving at this optimum time. It is also worthwhile to note here that if for some reason the plates give excellent quality pulp with no increased energy consumption, then it would be senseless to remove them purely on the basis of statistical data.

One of the earliest books dealing with refiner mechanical pulping (24) noted that the timing of refiner plate replacement was chiefly determined by the increasing difficulty of feeding the refiners. As the plates got worn, the screw feeder would consume more power and eventually an increase of the feeder speed would have no effect on tha refiner load. At the same time, the shive content would rise and general quality of the pulp would drop--partly due to plate wear, partly due to fluctuating feed rate (also dependent on wear of the plates). This meant, therefore, that the output of pulp at a given freeness and probably the quality would start dropping while the specific energy consumption would increase. At some point, they concluded, there would be a minimum total cost of refiner plates and refining energy per ton of pulp. Of course, requirements of production or quality might necessitate plate replacement before this point was reached.

A paper by Freeman (30) at the 6th International Mechanical Pulping Conference described the Great Northern Refining System at Millinocket, Maine. In describing their experimentation with refiner plates he noted that "plate life is generally a result of pulp quality and refiner efficiency, when both drop off, the plates are changed."[15]

Beath, Mihelich and Wild (23) present a very complete and extensive paper on the optimum plate replacement time. They state, "that refiner plates are a substantial cost item in making refiner groundwood. It is often thought desirable to minimize the cost of plates, per ton of

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[15] C.W. Freeman, Great Northern Refining System (paper presented at 6th International Mechanical Pulping Conference, Atlanta, 1968), p. 427.

groundwood, by keeping them in service as long as possible. This is a naive viewpoint. Plates should be kept in service only until the sum of all costs associated with plate life has reached a minimum."[16] As Beath has said, "an optimum program for frequency of refiner plate changes requires that the sum of all costs (per ton of pulp) which are affected by plate life is minimized. The essential point is not the amount of such costs, but that the amount be minimized."[17] Among the costs considered by Beath were power costs which, while affected by plate wear, were largely independent of it. Thus, they noted that the figures obtained for total plate life associated costs had no absolute validity such as would have permitted them to have been used in comparing costs between two refiner groundwood plants. However, within a given refiner groundwood plant, they provided a realistic basis, he maintained, for: (1) establishing optimum plate change intervals; (2) selecting the most economical type of refiner plates; (3) selecting the most economical refining conditions.

Beath, et al. (23) arrived at the total plate life associated costs by considering many factors. They derived

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16 L.R. Beath, W.G. Mihelich, and D.V. Wild, "Refiner Groundwood Costs Associated with Plate Life", Pulp and Paper Mag. Can., 71, 8, April 17, 1970, p. 73.

17 Ibid, p. 74

from these factors the total tons, Q_T, produced to T hours of plate service and subsequently the plate life associated costs, S_T, to T hours of plate service. The average plate life associated cost per ton of 92 B.V. (Beater Value) pulp over the period to T hours of plate service would then be:

$$\frac{S_T}{Q_T} = W_T \tag{1}$$

Equation (1) can be used to calculate plate life associated costs (W_T) for various plate service life times, T. Values of W_T can then be plotted against plate service time (as in Figure 6); the optimum time of plate change is that corresponding to the cost minimum of the curve.

Beath, <u>et al</u>. (23) provided several case histories and showed the variation in plate life associated with service life. The curves (Figure 6) showed that, typically, costs decreased to a minimum from which they slowly, but steadily increased. The curves were usually fairly flat near their minima and the optimum time for plate change was therefore not critical. From Figure 6, Beath showed that the long potential life of stainless steel plates, with its promise of low plate costs per ton of pulp, was misleading and that the minimum value of all costs associated with plate life was somewhat higher than it was for the less durable Ni-Hard. The use of soda ash with Ni-Hard plates also gave a very substantial further cost reduction. In part, this reduction resulted from an extension of economic plate life, but the more important benefit of the soda ash treatment came by way of slower loss of refining efficiency and the consequent savings in specific energy and production capacity.

Arnesjö and Dillén (26) in a paper on TMP at Hallstå Paper Mill in Hallstavik, Sweden, explains when and why they change their refiner plates. They state that, "equally important as the selection of proper plate design (in TMP production) is a careful control of the condition of the plates in the refiners."[18] They have found that damaged or too much worn plates in only one of the refiners was sufficient to cause a severe quality drop in the entire production from the plant. Therefore, an intensive control of the plates was essential. It was, however, they noted, also important to let the plant run as stable as possible and frequent shut-downs of the refiners were highly undesirable. Thus, they concluded that plate condition control could not be based on visual inspection of the plates but rather on quality evaluation of the pulp from each individual refiner.

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[18] B. Arnesjö, and S. Dillén, "Thermo-Mechanical Pulping at Hallsta Paper Mill." (Paper presented at I.M.P.C., San Francisco, 1975), p. 101.

In their plant they used a graph of Long Fiber Content (i.e., Bauer McNett + 30 mesh fraction) versus Freeness for this purpose. As indicated in Figure 9, the effect of closing the disks could be generalized into two straight lines in such a graph. At high disk clearance a long fiber reduction of 0.6-0.7 per cent was obtained for each 10 ml freeness drop, indicating that fibrillation was the main reason for the freeness drop. At very narrow refiner gaps, however, the long fiber was reduced by 2-3 percent from each 10 ml freeness drop, which was an indication of severe fiber cutting. Their aim was to operate close to the point where the slope was changed. Therefore, they have divided the graph into different areas as indicated in Figure 10. When the plates go into the "area indicating bad plate condition or other operational disturbances"[19] they must be removed.

This section points out the extreme importance of removing the plates, not necessarily only when the quality starts to drop or the life is long, but when the total plate life associated costs have reached a minimum, as demonstrated by Beath et. al (23). Beath's method of determining plate life at minimum plate life associated cost seems to be very neglected and little is said elsewhere in the literature

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[19] Ibid., p. 101.

concerning it. Most refiner plates are removed when the "blue glass" shows excess shives and the refiners will not load up to their maximum production rates. Beath's and Arnesjö's methods need to be studied more fully and put to use to prove or disprove their validity.

2.12 Plate Wear

A considerable number of papers comment on the wear of refiner plates and associated problems caused by it. This section deals with and summarizes the available literature while Chapter III of this thesis deals with an actual case study of refiner plate wear.

An early attempt to characterize wear came in a book entitled Mechanical Pulp Manufacture (24). It stated that plate wear was of three types: a pitting of the surface, which resembled cavitation; abrasion, which often resulted in deep circular grooves; and metal to metal wear, mostly close to the periphery, where the plates would just meet. Both pitting and metallic wear could be avoided by operating with proper plate clearance. This meant maintaining an adequate rate of flow, since the refiners were in practice set according to the motor loads not according to plate clearance. It was assumed that the pitting was caused by steam trapped between the plates. The book stated that the circular grooves were the result of nonuniform distribution of the refining work done by the plates (see Chapters III and IV). The solution was to taper and shape the plates so that the stock was more uniformly distributed and each part of the refining area did about the same amount of work.

An important comment made was that, "there has been no evidence of any effect of a normal, gradual plate wear on power consumption and plate quality."[20] All plates produce inferior pulp during a wearing-in period. In the future, they assumed that more efficient methods for heat treatment of the plates for increased hardness and wear resistance, might result in better pulp quality and process economy. Wear of the plates seemed to be directly related to plate clearance (i.e., feed rate) and the ease of steam escape.

The first recorded attempt to determine the effect of normal plate wear on the pulp quality and power relationship was conducted by Nystrom and Okell (22) at Crofton Pulp and Paper Limited, British Columbia. The study commenced with new Ni-Hard plates in all refiners. The effect of normal plate wear on power consumption and freeness relationship (Figure 11) showed that at any given plate age the freeness decreased as the power consumption increased. As the plate wore, however, the power consumption versus

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[20] Mechanical Pulp Manufacture, Chapter 14, p. 197.

freeness curves shifted upward. Therefore, in order to maintain a constant freeness, the power consumption increased as the plates wore.

Similarly (Figures 12,13) at any given plate age, the tear factor and per cent mullen increased as the power increased. These curves shifted downward as the plates wore. Therefore, to maintain a constant per cent mullen or tear factor, the power requirements increased with plate wear. This investigation emphasized the importance of plate condition on quality, power efficiency and production rate, and provided an incentive for the development of longer-lasting refiner plates.

It is widely accepted, as noted by Kurdin (50), that the refiner plate serves a screening function at the transition between breaker bars and the intermediate refiner bars. The clearance of the plates determines the size of wood particles passing between the refiner bar sections. If the particle size is not reduced sufficiently, permitting materials to pass on to the next bar zone, excessive wear normally results at this transition point. Therefore, it is necessary if uniform pulp quality is essential, to maintain constant power input per square inch of ground plate surface. Refiner plates, therefore, with a high ground taper naturally result in wear causing a flat section at the outer diameter of the plate requiring an increase in the total power to maintain this pulp quality.

The wear of refiner plates has been dealt with in much detail by Beath, et al. (23) who stated in their paper on costs associated with plate life that progressive wear of refiner plates during their service life resulted in one, or more of: decreasing pulp quality, decreasing production rate and increasing specific energy. The direct effects of plate wear, by erosion and corrosion, on various pulp qualities was shown by Mihelich, Wild, Beaulieu, and Beath (21). The differences between new plates (16 hours) and worn plates (227 hours with no pH adjustment) and the effects obtained by them are seen in Figures 14-19. Figures 20-22 show typical results obtained at varying specific energy inputs, when operating continuously at approximately 27 per cent discharge consistency and no pH adjustment in the refining zone. Figure 20 showed that, for given specific energy inputs, new plates tend to produce higher freeness pulps than worn plates. They noted that most of their other data showed this trend, but "there were instances where worn plates produced pulps of equal or higher freeness than when they were new. We attribute these exceptions to wood quality changes and/or plate damage."[21]

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[21] W.G. Mihelich, D.J. Wild, S.B. Beaulieu, and L.R. Beath, "Single-Stage Ch[illegible] Refining", Pulp and Paper Mag. Can., 73, 5, May, 1972, p[illegible] 81.

Figures 21 and 22 from Mihelich's work (21) showed that there was a continuous deterioration in pulp strength as the plates wore. When the plates became extremely worn, short-term motor load variations increased and it became increasingly difficult to fully load the refiner, which was then producing a short-fibered, choppy pulp. Figure 23 shows that shive production was very sensitive to plate condition. As is now widely accepted, they advocated that quality deterioration with plate age could be reduced considerably by increasing refining zone pH.

Actual case histories of plate life were discussed by Nurminen, et al. (33) from their new refiner installations at Rauma, Finland. They found that the durability of the refiner plates was a big problem in the beginning. Over a two year period they tried five plate materials (Table 3) but none of them could exceed a 400-hour run. The cause of this was determined to be heavy corrosion, which resulted in poor quality pulp and an imbalance in the refiner causing vibration. They have been unable to solve the corrosion process, but believe it is a combination of steam cavitation, chemical corrosion, and mechanical wearing. Examples of this mechanical wearing are seen in Figures 24 and 25. In Figure 25, the plates have been touching each other, whereas in Figure 24 there have been hard particles between the plates.

In their opinion, the particles loosened from the wearing plates (Figure 26) were causing this kind of corrosion.

Arnesjö and Dillén (26) stresses the point that as important as selection of proper plate design is, equally important is a careful control of the condition of the plates in the refiner. They have found that damaged or too much worn plates in only one of seven of the refiners in their plant is sufficient to cause a severe quality drop in the entire production from the plant. Therefore, they stated, that an intensive control of the plates was essential. It is, however, also important to let the plant run as stable as possible and frequent shut-downs of the refiners are highly undesirable. Thus, plate condition control cannot be based on visual inspection of the plates, but rather on quality evaluation of the pulp from each individual refiner.

Laliberte (51), in discussing corrosion problems in the pulp and paper industry, states that the wearing of steel refiner plates in chip-refining constitutes the most visible problem in the mechanical pulping section of the mill. He notes that "the abrasive action of the chips, high temperature, and localized boiling of the water in the refining zone rapidly attack the refiner plates."[22]

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[22] Laliberte, L.H., Corrosion Problems in the Pulp and Paper Industry, International Symposium on Pulp & Paper Industry Corrosion Problems, NACE, Houston, 1977, p. 9.

The literature on the wear of refiner plates is quite extensive, yet without much detail. The mode of wear, its causes and probable cures, have not been expounded on at all and thus there is a very urgent need for research work on the wear of refiner plates. Some recent investigations have been conducted and these are reviewed in Chapter III.

2.13 Corrosion

Corrosion has as great an effect upon plate life as wear. Many times these two factors are considered identical and at times it is very difficult to distinguish between them. Each is a separate entity but may contribute so extensively to the other that they are inseparable. Heidemeyer (52) notes that mechanical work on a surface (i.e., due to contact between rotating refiner plates) may actually increase rates of corrosion considerably. His theory is illustrated in Figure 27. The introduction of some mechanical energy (via contact rubbing) reduces the activation energy necessary for chemical reaction and thus increases corrosion rates. Therefore, in the case of refiner plates, the wear process, although it may seem very insignificant when no serious contacts occur (clashing), may be contributing significantly to the rate of corrosion. This area presents itself for research and may provide some excellent insights into the relationship between wear and corrosion.

Corrosion is, as we have stated, an important contributor to the decline in the life of refiner plates. Minimizing the fact of its importance is the lack of published literature on causes and cures, especially with respect to refiner plates themselves. Research has been conducted on the corrosion of refiner plates by such groups as Bergstrom et. al. (31), but is unpublished.

Laliberte (51), while discussing corrosion problems in the mechanical pulping section of a mill, said regarding refiner plate corrosion that "the corrosion problem involves the action of erosion accelerated by the corrosive environment, as well as cavitation caused by localized flashing of water to steam."[23]

Some paper companies have stated that they have corrosion problems and are working for solutions or else have overcome their problems but give no details. Two papers [1973] have given information on work in an effort to combat corrosion. Nurminen, et al (33), in describing their new refiner installations at Rauma, Finland, have stated that the durability of refiner plates was a big problem in the beginning. Five plate materials had been tried (Table 3)

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[23] Ibid, p. 9

during two years but none of them could exceed a 400-hour run. The reason was heavy corrosion which resulted in poor quality pulp and an imbalance in the refiner causing vibration. Their corrosion process is still unsolved, but they believe it is a combination of steam cavitation, chemical corrosion, and mechanical wearing. Steam cavitation can be seen from their photographs (Figures 24 and 26) and they also stated its influence was partly the reason for the defects they have pictured in Figure 28.

Chemical corrosion--which they stated resulted from organic acids released from wood--has probably caused the damage shown in Figures 25 and 28. They attempted to reduce chemical corrosion by adding sodium carbonate in order to keep the pH between 6 and 6.5. However, they could establish no increase in the life of the plates. They eventually found a material fairly resistant to cavitation and chemical corrosion. The age of the plates were doubled, and even tripled, depending on refiner position. This material was Uddeholm B; no details of its composition or formation are provided.

Beath, _et al_. (43) also concluded that in the manufacture of refiner groundwood at high refining consistencies, Ni-Hard refiner plates wear largely as a result of corrosive attack by wood acids. Beath (23) earlier reported on this phenomenon and showed that plate life could be almost doubled by the addition of about four pounds of soda ash per ton of chips, which raised the pH from a normal 4.8-5.2 range to about 6.4-6.8. Figure 29, however, shows the detrimental effect of sodium carbonate when being used to extend plate life.

Because sodium carbonate is a fairly strong base, Beath, et al. (43) found that only four pounds per ton was required to increase the pulp from pH 5 to pH 6.5 where substantial protection against plate corrosion was obtained. It was found, however, that small increases above that level raise pulp pH to the point where the well known yellowing effect of caustic occurs strongly and substantial loss of brightness occurs (Figure 29). Beath also found that the use of sodium sulfite had a substantial pulp brightening effect. They found that good plate protection, and balance of other factors, suggests 20 to 25 pounds per ton as a good rate of addition. The use of Na_2SO_3 and sodium carbonate additives and their effect on plate life is discussed more fully in Section 2.7 and Chapter IV of this thesis.

2.14 Summary

This literature survey shows that many factors are important in refiner plate design. External refiner factors (variables) such as disk parallelism, vibrations and refiner feed rate although not reviewed are extremely important.

Each of these must be adjusted before the refiner is started and must be kept under control for the life of the set of plates. Two internal refiner variables considered are consistency and additives (pH control). The literature indicated that consistencies in excess of 25 per cent produced much stronger pulps than low consistency pulps at equivalent freeness. Throughput was also higher at higher consistencies and the amount of fiber cutting was decreased considerably. It is also significant to note that high consistency refining results in much longer plate life on Ni-Hard plates.

The literature on additives and pH control used to prolong plate life attests to the extreme importance of reducing chemical corrosion. None of the reports attempt, however, to determine the types or modes of corrosion involved and indeed no experimental work directly related to the corrosion and wear of refiner plates has been reported. Also, no specific details on the role of the additive sodium sulfite is known, making it an area of necessary research.

Two other factors directly related to the actual refiner operation are the reversal of plates and refiner speed. Extension of plate life by means of periodic plate direction reversal seems to be a much neglected practice. Some very serious study and experimentation is evidently needed to validate claims of benefits from the practice and to determine parameters to decide the optimum times of reversal if indeed reversal is beneficial. The exact effect of velocity on refining and pulp quality is not known either with certainty; the early opinion [1966] seems to be that the pulp quality increases with the velocity but that the effect is small compared to other variables, which have to be controlled. The only valid aspect known is that as the refiner speed changes so does the necessary plate pattern to accommodate changes in throughput.

Running clearance or taper, plate pattern, different plate patterns on rotor and stator disks, and steam generation and removal are all factors contributing to a correct refiner plate geometry. The running clearance between the surfaces of opposing plates is a critical parameter that determines the performance of disk refiners and is necessary to enable maximum feeding of the refiner. A carefully designed tapered plate clearance is thought to promote self-feeding in the refining zone and also to control the quality of the stock. Each plate pattern is used for a specific purpose and the use of a different pattern invariably results in shorter plate life or clashing. Careful study must be made of the relationship between changes in plate pattern and changes in refiner variables to lead to correct patterns for increased pulp quality, production economy, and maximum plate life. A factor which may be extremely important in plate design and may lead to improved plate life is that of the use of different plate patterns on the rotor and stator disks of refiners. This concept is only mentioned twice in the literature but suggests itself to some much needed research.

The direction of flow of steam in the refining zone and the pressure gradient developed there, are critical factors in both the stability of operation and the quality of pulp produced in the refiner. They are themselves determined by the geometry and speed of the refiner, the plate pattern and taper, and the operating conditions of throughput, motor load, and the inlet consistency and temperature of the feed material. To insure proper steam egress and alleviate problems caused by backflow of steam which could lead to blow-back, and clashing, correct plate design is necessary.

Refiner plate material factors such as composition, hardness, and conditioning, are all inherent properties of the actual plate production, the casting techniques and heat treatment. Plate conditioning is not considered an important factor in attempting to prolong plate life, but could be extremely important if it were able to be quantified with respect to rate of wear and decline of pulp quality. The actual conditioning process appears dependent on plate hardness which in turn must be optimized to prevent excess cutting of fibers and maintain pulp quality and characteristics. Plate hardness is in turn dependent on the material composition which is one of the very important factors to be considered in the design of refiner plates. Conditions have to be known or determined within the refiner and materials selected to minimize corrosion and wear based on these conditions, i.e., pH, temperature, additives, etc.

One of the most important considerations in discussing factors influencing plate life is that longer plate life is not necessarily optimum plate life. The importance of removing the plates, not only when the quality starts to drop or the life is long, but when the total plate life associated costs have reached a minimum must be re-emphasized. Various methods of determining the end of useful plate life have developed in the industry--blue glass showing excess shives or inability to load up refiners to their maximum production rates--but a much more scientific approach, such as that of Arnesjö and Dillén (26) using graphs of long fiber content, or Beath's (23,43) graph of minimum total plate life associated costs must be re-introduced and given serious consideration in the timing of refiner plate replacements.

CHAPTER 3

THE APPLICATION OF SYSTEMS TECHNIQUES TO THE STUDY OF THE WEAR OF REFINER PLATES

3. THE APPLICATION OF SYSTEMS TECHNQIUES TO THE STUDY OF THE WEAR OF REFINER PLATES

A literature study on the wear of refiner plates has been presented in Section 2.12. As was stated there, a shortage of information concerning the wear of refiner plates exists. There is no literature indicating any experimental research performed to determine modes and rates of wear of refiner plates in different environments. The author has conducted some testing using new refiner plates supplied by Price (Nfld.) Pulp and Paper Company, Limited, Grand Falls, Newfoundland. These plates were examined and measured before use, put in use in the refiner plant at Price (Nfld.), and removed and re-examined after use. This chapter presents an analysis of the wear of these refiner plates during the production of mechanical pulp from chips, based on this actual case history.

The study was undertaken using the systems approach of Czichos and Mølgaard (53). A tribological systems data sheet (Figure 30) developed by Czichos (53,54,55) was used to analyze completely the refiner plate/pulp/refiner plate system. The principles of system analysis and their application to tribology and also the systemanalytical data sheet are explained fully in two papers by Czichos (54,55). A further paper on the application of systems techniques to the study of wear by Mølgaard and Czichos (53) was the guideline followed to conduct this case study on refiner plates.

Each section of the systems data sheet (Figure 30) will be considered separately with detailed information, where available, being included as part of this chapter. The section numbers relative to each portion of the data sheet are indicated on Figure 31.

3.1 General Problem Statement

The tribological data sheet is intended to serve as a guide in the analysis of wear problems to insure that all relevant data is taken into account. It was used here to determine if it can indeed serve this purpose in the severe wear problem encountered on refiner plates. The actual problem statement is to characterize a 42-inch single rotating disk Sprout Waldron refiner in operation.

3.2 I. Technical Function of the Tribo-System

Stated simply, the technical function of the tribo-system being characterized was to convert wood chips into refiner mechanical pulp.

3.3 II. Operating Variables

3.3.1 Type of Motion

We have considered the case of a 42-inch single rotating disk refiner. One disk is moving (1,800 r.p.m.) while the other remains stationary. In the macro system of the two sets of 42-inch diameter disks with attached plates the motion is that of rotation. On a micro scale, however, where we consider part of one bar on the rotating disk moving past a part of another bar on the stationary disk the motion is designated sliding.

3.3.2 Duration of Operation

In the case considered here the duration of operation was in the order of hundreds of hours (in some cases up to 1,500 hours or more) and might well be considered continuous.

3.3.3 Load $F_n(t)$

The only data available on the applied loads on the refiner disks are the charts of the applied horsepower over the life of the set of refiner plates. The charts for the complete life are available but only a representative printout is shown here (Figure 32). As can be seen, there is some fluctuations of applied horsepower with time.

The power consumption of a disk refiner may be separated into three principle components: the power required to revolve the disk in a fluid medium -- disk friction; the power imparted to the stock - effective work; and the power required to accelerate the stock to exit velocity from the plates - pumping losses. According to Herbert and Marsh (56) an expression for the total power consumption, which has been verified, to some extent, by experimental laboratory work with a commercial-size disk refiner, is:

$$hp_t = K_d N^3 (D_o^5 - 2/3\ D_i^5) + K_e N\ D_i (D_o^2 - D_i^2) + K_p\ Q\ N^2 D_o^2 \qquad (2)$$

where

hp_t = total brake horsepower applied;

K_d = disk friction constant, which is directly proportional to the density of the fluid handled and varies with plate geometry;

N = rate of revolution, rpm;

D_o = outside diameter of refiner plates, ft;

D_i = inside diameter of bar and groove circle of the refiner plates, ft;

K_e = a constant which includes the coefficient of friction between fibers and plate and fiber and fiber as well as average separating pressure between plate "contacting" surface;

K_p = a constant which includes the gravity constant and the density of the fluid;

Q = quantity of fluid pumped out between plates.

Herbert and Marsh (56) then present an expression for torque, T, based on the coefficient of friction (f),

$$T = \pi n f p_{max} r_i (r_o^2 - r_i^2) \qquad (3)$$

where f = coefficient of friction (fiber to fiber and fiber-to-plate)

n = number of friction areas

p_{max} = maximum pressure between plates, lb/in^2 (at r_i)

r_i = inside diameter of plates, in.

r_o = outside diameter of plates, in.

T = torque, in.-lb.

Letting

N = speed of rotation, r.p.m.

$\frac{NT}{12}$ = ft.-lb./min.

and $\frac{NT}{12}/500$ = h.p. $\frac{NT}{6600}$

$$\therefore \quad T = \frac{6600 \times h.p.}{N} \text{ (ft.lb./min.)} \qquad (4)$$

Therefore, knowing the applied horsepower and speed developed by the refiner for this applied horsepower, the thrust developed between the tribo-elements [1] and [2] are determined. Some tables of the thrust (Tables 8,9,10) developed by the refiner and steam produced are reproduced here from the work of Atack and Stationwala (57).

3.3.4 Velocity v(t) (fpm)

The velocity of the rotating (sliding) refiner disks is shown in Figure 33. This shows that the velocity of the rotating disks is not time dependent but distance (from center of disk) dependent, i.e., V(x) where X is the distance from the center of the refiner disk.

3.3.5 Temperature T(t) (°C)

The temperature dependence of the disks during their life is seen in Figure 34. This is reproduced from the work of C. Mills (58) in determining if an open discharge refiner was self-pressurizing. The figure shows that the temperature increases from 100°C at the refiner disk's inner periphery to a maximum of 138°C near its center and back to 100°C again at the outer periphery of the refiner disk.

3.3.6 Other Operating Variables

There are three primary control variables in most types of refiner mechanical pulping operation. They are dilution water flow rate, throughput and refiner plate gap setting. In turn, these variables, or some combination of them, control discharge consistency, specific energy and motor load. The latter variables may be termed secondary control variables and are the ones invariably used by the operator to control pulp quality.

Another variable which may be considered as an operating variable and of direct effect on the tribological system is the pressure developed between the refiner plates. Pressure is directly related to the temperatures developed by the saturated steam (Figure 34) and is shown in Figure 35. This figure shows that as much as 36 psig pressure is developed near the center of the refiner plates.

3.4 III. Structure of the Tribo-System

Some of the information on the structure of the tribo-system such as designation of element and material, chemical compositions, topography descriptors and surface layer data are included on the tribological systems data sheet (Figure 31). The tribological system under consideration is composed of three elements: (1) the stationary refiner plate; (2) the rotating refiner plate; and (3) the pulp solution. Figure 36 is a photograph showing tribo-elements [1] and [2].

3.4.1 Volume Properties (Geometry/Dimensions/Volume) of Tribo-Element [1] and [2]

Table 11 shows the dimensions of tribo-element [1] and [2]. This refiner plate is actually one-twelfth of tribo-element [1] and [2]. The total system consists of a circular 42-inch disk of twelve plates which rotates against another stationary disk of 12 plates, with tribo-element [3] between them.

3.4.2 Volume Properties (Geometry/Dimensions/Volume) of Tribo-Element [3], the Lubricant

As can be seen from Figure 31 tribo-element [3], which in other systems is a lubricant, consists in this system of water, steam, Na_2SO_3 and wood chips. The wood chips and water enter between tribo-elements [1] and [2] and exit as pulp and steam. Table 12 gives the volume properties (Volume) while Figure 37 gives the actual profile dimensions of tribo-elements [1] and [2] and thus the volume properties (dimensions) of element [3], the "lubricant". Figure 38 also gives a graph of effective cross sectional area through the tribo-elements based on circumference and separation between plates at that circumference.

The wood chips which constitute an integral part of the lubricant [3] are of different sizes. A typical classification of chips entering between tribo-elements [1] and [2] is as follows:

> 1 in.	15%
3/4 in.	20%
1/2 in.	35%
1/4 in.	24%
1/8 in.	3%
< 1/8 in.	3%

3.4.3 Volume Properties--Chemical Composition of Tribo-Element [3], the Lubricant

The "lubricant" is a mixture (Figure 31) of water, Na_2SO_3, and wood chips being converted to pulp and steam. The data in Table 13 is typical for the "lubricant" used at Price (Nfld.) Pulp and Paper Company, Limited, Grand Falls, Newfoundland.

3.4.4 Volume Properties--Phys.--Mech. Data--Tribo-Elements [1] and [2]

Tribo-elements [1] and [2], the refiner plates, were cast at 2,600°F using the green sand casting (no resins, etc.) technique. After casting they were cooled to ambient temperature either outdoors or to room temperature. The plates were then shaken out of their moulds and could have been left for a week or more before further treatment.

A stress relieving operation was next performed on the plates; heating for two hours at 500°F and then air quenching. This caused a mechanical change in the grain structure-austenite to martensite. The purpose of this treatment was to give a Rockwell hardness, Rc, of 54-58. The chemical composition of the Ni-hard plates was as follows:

3.40-3.65 C, 0.35-0.50 Mn, 0.55-0.70 Si, 2.40-2.70 Cr, 4.20-4.50 Ni, 0.20-0.30 Mo, < 0.05 P, < 0.120 S (usually 0.15-0.20), balance Fe.

3.4.5 Volume Properties--Phys.-Mech. Data--Tribo-Element [3], Lubricant

This section deals with the breakdown of the wood chips (a component of the lubricant) as they advance between tribo-elements [1] and [2] and also with steam production and removal. The generation and removal of steam from between the refiner plates was discussed in Section 2.10.

The process of chip breakdown through tribo-elements [1] and [2] was discussed quite extensively by Atack and May (14). They demonstrated that the chips changed into match-stick-like material, to slender pin chips, to large fiber bundles, to smaller bundles, and finally separated fibers. The refiner used was a commercial-sized double disk refiner (Bauer Model-400) with plates of the type shown in Figure 39. Table 14 gives the experimental conditions for first stage refining using the C-906 plates (Figure 39) while Table 15 shows the classifications of material through the refiner plates. These conditions, refiner and refiner pattern are not the same as the refiner used in our study, but the breakdown of chips is probably in the same sequence although not necessarily dependent time wise. Figures 40-47 reproduced from the work of Atack and May (14) picture the breakdown that occurs between the refiner plates and shows the size and type of particles through the plates. These pictures show the changing physical aspect of the wood chip component of the lubricant.

3.4.6 Surface Properties--Other Data

The surface properties (topography descriptors and surface layer data) of tribo-elements [1] and [2] are included on Figure 31. CLA (centre line average) values (surface roughness) were measured along the bars before use and it was found that the breaker bars had an average value > 400, the intermediate bars, 80, and the fine bars, 120 (micro-inches).

3.4.7 Contact Area A(t)

Opposing disks do not normally contact each other directly but interact through the pulp between them. Due to the motion of one disk relative to the other, the bars on one set of plates move pass the bars on the other set.

The details of "contact", i.e., the alignment of the bar surfaces on two opposing plates, was investigated by placing two transparent photographic prints of a plate on top of each other and moving one print relative to the other. Assuming that the refiner is moving at a maximum speed of 1,800 r.p.m., the fraction of maximum possible contact can be related to time and distance travelled. From this the contact area has been determined as one plate moves completely over another plate. From these figures we can also determine the stress field over a complete refiner plate. The graph of contact area over a full plate from our case study using Sprout Waldron Ni-hard plates, type D13A001, is given in Figure 48.

The contact pattern essentially repeats itself over each one-quarter of the plate pattern--the first quarter repeats itself but in reverse for the second quarter. The second half is the same as the first half. The heights of the sawtooths are not quite as high near the center of the plate due to the interference caused by the bolt holes. After the first 0.6 inch of circumference (less than 1/10 of plate), from 0.60 inch to 4.90 inches the pattern oscillates to give an average contact area of about 0.5. The exact nature of this oscillation is not established precisely but is assumed to be sawtooth. From the tracing of the refiner plate being contacted by successive plates the pattern in Figure 48 was obtained.

3.4.8 Element [3] ("Lubricant")--App. Lubrication Mode

Element [3] consists of dilution water, Na_2SO_3 and wood chips. Both the dilution water and Na_2SO_3 are metered into the eye (entry) of the refiner and then mixed with the wood chips. The chips are metered in via a belt and from there by a screw conveyor into the center of the disks (i.e., gravity feed).

3.4.8.1 Residence Time (Retention Time)

A very important physical property of element [3] (the "lubricant") is its residence time between the refiner plates. How long does it take a chip to pass through the entire refining zone and exit as pulp fibers? Yan (59) in his work on the kinetic theory of mechanical pulping has derived a retention time, τ, in a refiner based on the fiber length reduction (on a weight basis). The result was:

$$\tau = \ln \frac{\langle x \rangle_1 - 0.263}{\langle x \rangle_2 - 0.263} \qquad (5)$$

where $\langle x \rangle_1$ and $\langle x \rangle_2$ were the weight-average lengths of fiber samples entering and emerging from the refiner. He found that the specific energy (in h.p. day/ton) was a linear function of log τ (similar linearity can be found in collision theory and the Arrhenius equation).

When pulp was refined at given plate age, pattern, and separation at constant consistency, Yan noted that the log of the feed rate R (in ton/day) of pulp was inversely proportional to specific energy (h.p. day/ton) (Figure 49). Yan also related specific energy to retention time (also known as residence time). Extrapolating his data (Figure 50) to a value of 90-100 h.p.d./ton (similar to case study refining conditions) we get a residence time of 0.25-0.47 second.

Gavelin (60) noted that the residence time of the fibers in the refining zone was an important variable, which was determined by the centrifugal force, the screening process (of chips and fibers between the plates) and the speed with which the particles were broken down. It was normally 0.3 to 3 seconds with the indication being that the pulp quality increased with shorter residence time.

Assuming, therefore, a residence time of 0.50 second and the appropriate inlet and outlet conditions, the amount of fiber between the plates (tribo-elements [1] and [2]) at any instant can be determined. From the calculations there is 3.50 pounds of fiber between the plates at any instant.

3.4.9 Tribological Transactions

The possible interactions between the three elements of the system can be broadly classified in the form of a matrix as in Figure 51. The fields in the matrix are numbered in the order in which they are dealt with in the following sections. An analysis of the transactions represented by the matrix is an iterative process involving both a consideration of all possible processes and the evidence obtained from examining the elements of the system, particularly the surfaces of the solid elements and the composition of element [3]. The diagonal fields, 1, 2 and 3 relate to processes solely within elements [1], [2], and [3], respectively, typically those, such as deformation, which alter the physical nature of parts of the elements and those such as corrosion, which transform the material of part of the element to a material of a different chemical composition. The off-diagonal fields numbered 4, 5 and 6 relate to transactions between elements. Our primary concern is with transactions of fields 4 and 5 which remove material from elements [1] and [2], respectively, and transfer this material to [3], the volume between these plates. We are also concerned with transactions in field 6 which relate to the transfer of metal or corrosion products from one plate to an opposing plate, i.e., between elements [1] and [2].

In the case study under consideration two possible routes must be considered and therefore two separate sets of interactions. Tribo-elements [1] and [2] may not clash (CONDITION A) or else may clash (CONDITION B) during their useful life.

3.4.9.1 Field 1. Tribo-Element [1]--Stationary Refiner Plate (Condition A - No Clashing)

A detailed photographic and metallurgical analysis of the used plates is given in Section 3.5.3.1. The only change in tribo-element [1] will be one of transformation since corrosion and wear of the refiner plates are known to occur. The actual mechanisms of corrosion and the contributing factors have been investigated (Chapter IV).

The corrosion process is believed to be due to stress corrosion cracking (Sections 4.5 and 4.6).

3.4.9.2 Field 2. Tribo-Element [2]--Rotating Refiner Plate (Condition A - No Clashing)

Tribo-element [2] may be considered in essentially the same way as [1] except for one dissimilarity. The plates on the rotor disk (tribo-element [2]) lost approximately 65 per cent more material than those on the stator disk (tribo-element [1]) (Table 16). The modes of wear do not, however, seem to differ. This loss may indeed be due to the mechanics of the disk refiner but for all purposes the two sets of plates should be similar. One possible reason for a difference may be different rates of heat loss from each set of plates due to structural differences in their mounting. The backing arrangements for rotor and stator plates are different. These backing arrangements may also cause different vibrations in rotor and stator plates which in turn could cause different amounts of wear. There is also the possibility of differences in electrical potential due to stray or induced currents passing through the rotor arm and not the stator, contributing to more wear on the rotor plates. Finally, the work done on the chips in converting them to pulp is through the rotor and not the stator. It would be beneficial to check the wear on plates removed from Twin 50's or other double rotating refiners to see if there is any significant difference in amount of wear on the plate sets.

3.4.9.3 Field 3. Tribo-Element [3]-- "Lubricant" (Condition A - No Clashing)

The different components of the "lubricant", water, steam, Na_2SO_3 and wood chips, are transformed as they progress through tribo-elements [1] and [2].

When wood is impregnated with sodium sulfite (Na_2SO_3) it will react with the lignin and with the organic acids present and thereafter proceed with the reactive carboxyl groups, a process of saponification resulting mainly in the formation of sodium acetate and sodium hydrogen sulfite. If the reaction is allowed to continue, the acidity of the pulp will drop to about pH 4.5, the acidity of sodium hydrogen sulfite. When all sodium sulfite is consumed, the pH will drop further to the acidity of the predominant organic acid present, acetic acid. The pH may then stabilize in the region 3.2 to 3.4. The Na_2SO_3 is also known to remove dissolved oxygen from the system.

The energy requirement to reduce chips to single fibers has been determined by May (61) and indicated that approximately 0.2 h.p. days per ton of energy was used. This would produce a temperature gradient of only about 1°C over the whole disintegration (i.e., from chips to single fibers, Section 3.4.5). The discrepancy between these figures and the much larger energy consumption and temperature gradient observed in chip refining has led to the postulation of a refining parameter which has been called the ineffectiveness factor (Section 3.4.9.3.1). May (61) has assumed a model of chip breakdown where disintegration occurs in discrete steps through the refining zone (making it readily amenable to mathematical treatment). Figures 52 and 53 show his model breakdown (see Section 3.4.5).

The primary tribological function in field system "3" is one of alteration. The destruction of chips may be treated as an alteration process, to change wood chips to wood fibers. In a disk refiner, chips are broken down by fracture along the grain in fairly well defined stages. They are first split into matchstick-like material, and then, as they move toward the periphery of the refining zone, into more slender pin chips, then large fiber fundles, smaller bundles, and finally into separated fibers.

It is apparent that a radial temperature gradient exists through the refining zone of a refiner (Figure 34) because chips, entering the machine cool, emerge as hot pulp, accompanied by a copious quantity of steam. The heat has originated from a conversion of the mechanical energy provided by the rotating disk into thermal energy in the refined material. One possible source of this conversion is the disintegration process itself, for disintegration cannot be achieved without a certain minimum dissipation of mechanical energy as heat. Thus, when a fragment breaks, energy necessary to strain the material to the breaking point is present as stored strain energy in the specimen. After it breaks, the deformed fragments spring back to their unstrained shape and most of the stored energy is converted into heat within the material. The fragments are thus hotter than the parent material, and as disintegration proceeds, the radial flow of the material results in an increasing temperature outwards through the refining zone. The temperature gradient is also enhanced by energy dissipated by viscous mechanisms in the wood during the deformation leading to failure. Additional data on chip breakdown is contained in Section 3.4.5.

3.4.9.3.1 The Ineffectiveness Factor

Of the 90 horsepower days per ton of energy consumed in a normal refiner groundwood operation, a reasonable guess might be that about 20 to 40 horsepower days per ton are used to achieve separation of the fibres, and 50 to 70 horsepower days per ton to produce fines and internal surface area. The figure 20 to 40 horsepower days per ton is one to two hundred times as great as the energy loss calculated above as unavoidable for the complete separation of the fibres. This ratio has been called the "ineffectiveness factor".

The rapid passage of the projections on the refiner plates, about 15,000 per second in the centre of the plates, 1,000 per second at the breaker bars, and the repeated collisions and interactions between particles that must take place, suggests that for every deformation of a fragment that results in disintegration, the fragment is subjected to many unsuccessful deformations. While these may fail to produce disintegration, they nevertheless must consume energy. The energy dissipated over all unsuccessful attempts at disintegration could account for the total energy needed in practice to separate the fibres. The number and magnitude of these per disintegration could vary widely from moment to moment. From the point of view of consumption of energy-of-rupture, however, they can be considered equivalent to a specified number of deformations of equal magnitude, each of which dissipates the same energy as a successful deformation, but which fails to produce disintegration. The number of these is then equal to the ineffectivensss factor. This constitutes a physically real definition of the ineffectiveness factor, from which its mathematical definition as the ratio of two energy values automatically follows.

The ineffectiveness factor is therefore a measure of the lack of efficacy of the refiner plate pattern, and will of course vary between different plate designs and different refiners. The greater the ineffectivehess factor, the more heat is dissipated in unsuccessful deformations and the greater the temperature difference between successive disintegrations. It follows that the number of fibres broken at each disintegration, and consequently the number in the final pulp, will be a function of the ineffectiveness factor.

The ineffectivenss factor defines the mechanical energy pumped into the fragments between successive disintegrations, and therefore the increase in heat content. The temperature rise in the material produced by this will depend on the consistency of refining, for the amount of water accompanying the material must also be heated. Hence the temperature at each disintegration becomes a function of the consistency, so that the number of broken fibres also depends on the refining consistency. It is also apparent that it will depend on the original temperature of the chip feed, which determines the starting point of the temperature gradient.[24]

3.4.9.4 Field 4. Tribo-Element [1] - Tribo-Element [3]; Stationary Refiner Plate - "Lubricant" (Condition A - No Clashing)

The only possible action here is one of transmission or transfer. There is the transfer of

[24] W.D. May, "A Theory of Chip Refining - The Origin of Fibre Length," Pulp and Paper Mag. Can., 74, 1, January, 1973, p. 72.

mechanical work and also of corrosion products and metal in the attrition process from [1] to [3]. The transfer from element [3] to element [1] involves heat (entropy), "chemicals", e.g. water in corrosion process, and wood in grooves. Atack and May (14) demonstrated that the wood remains in the grooves after they fill up. The same processes occur in Field 5 which involves interaction between Tribo-Element [2] and [3], the rotating refiner plate and the "lubricant".

3.4.9.5 <u>Field 6. Tribo-Element [1] - Tribo-Element [2]; Stationary Refiner Plate - Rotating Refiner Plate (Condition A - No Clashing)</u>

In this system where there is no clashing (i.e., direct contact), the "lubricant" is a transmission or dissipative medium. The system has mechanical energy entering through elements [1] and [2] in the form of work and has heat coming off. The dissipative mechanism (in the lubricant) transforms work to heat as rotational energy of the plates is imparted to break up the chips. By all external appearances, no work is done by the stationary plate (Figure 54).

Figure 55 demonstrates an instance of kinetic friction of the lubricant since all the dissipative processes, producing entropy from work, occur in the lubricant. The main cause for the production of entropy from mechanical work seems to be in the mechanism of viscous deformation of the lubricant, under the action of shear forces (based on the work of J. Mølgaard (62)). In our case study there is little difference between the two surfaces (I) and (II), tribo-elements [1] and [2]. The transformation of work, D(W+S) may take place on the stationary plane; the work would then be transmitted (Figure 56). The force may pass into the stationary plate, return again and be dissipated in the lubricant (Figure 56), in which case both the plates and the lubricant heat up.

3.4.9.6 <u>Condition B--Clashing</u>

When tribo-elements [1] and [2] come into contact with each other or "clash" the resulting interactions are the same for Fields 1 and 2 as when there was no clashing (see Sections 3.4.9.1 and 3.4.9.2). Field 3, tribo-element [3] (the "lubricant"), however, is different. With contact of plates during refining the refining process is invariably going to be rougher or more severe (compare Section 3.4.9.3). There will be more cutting of fibers due to plate to plate contact and less fibrillation (production of intact fibers). There will also be more turbulence between plates since the volume will be decreased for the same throughput (when no clashing occurs)--and more steam cavitation.

Fields 4 and 5, the interactions between tribo-elements [1] and [3] and between [2] and [3] respectively, are also the same as for the no clashing condition (see Sections 3.4.9.4 and 3.4.9.5).

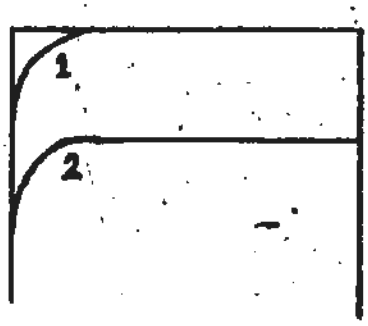
3.4.9.7 Field 6. Tribo-Element [1] - Tribo-Element [2]; Stationary Refiner Plate - Rotating Refiner Plate

Section 3.4.9.6 considers tribological interactions when there is some evidence of clashing between the plates (CONDITION B). Clashing means that the two refiner plates or tribo-elements touch (Figure 57) with no pad of lubricant between them (refer to Sections 3.4.9.1 to 3.4.9.5 for the case of no clashing). Clashing could lead to plastic deformation of the surface (W-6) but since the bars on the refiner plates are in actual fact asperities on a macro scale the result is seen in Figure 58 if one plate were flat. If surface I (tribo-element [1]) were flat the asperity would move as shown by the dotted line in Figure 58 but since surface II also contains macro-asperities the result is as shown in Figure 59.

Therefore, each bar could be experiencing a cycle of events in which the asperity (macro scale-bar) is initially deformed elastically during a short period in which F_H (Figure 59) moves to the left at a greater rate than F_A moves to the left. If there is no movement of A_1A_2 then the net work done on the bar is stored in the bar (macro asperity). If the work is stored this may lead to oscillation of the asperity, in turn to vibration and finally transmission of the work into the plate itself. The total process may therefore be a sum of all the individual cycles of deformation and vibration at each of the asperities on both surfaces.

This analysis is quite interesting and needs to be considered in much greater detail. Indeed, all of the friction mechanisms listed in Table 2 of Molgaard's paper (62) (on which this previous analysis is based), (1) viscous deformation of fluid between two solids, (2) plastic deformation of solid surface layers, (3) alternating elastic deformation and oscillation, and (4) alternating union and separation, may be present between the refiner plates as the plates invariably touch and retouch during their life.

In considering the wear patterns of the plates the previous analysis may be very important and may indeed explain the wearing-in mechanism of new plates and subsequent wear. For example, it may explain which of the wearing paths 1 or 2 below is involved in the wearing-in process. Is only the corner removed (1)? Or is the corner plus the top of the bar removed (2)?



Do plates wear 1 or 2?

Also, it is quite likely that there will be increased corrosion in this situation due to contact of plates making surface layers more susceptible to corrosion as noted by Heidemeyer (52). The corrosion products, oxides, etc., which constitute the surface layers are removed much quicker than in the case of no contact, facilitating increased corrosion again. At points of contact the temperature increases, often quite considerably, leading to a weakening of the bars.

From the observation of the used plates there appears to be some wedge formation which may involve transmission of material from [1] to [3] and the reverse. Detailed wear data is contained in Section 3.5.3.

3.5 IV. Tribological Characteristics

Some of the information pertaining to part IV of the systems data sheet is given in Figure 31.

3.5.1 Changes in Properties of the Elements

An important change in property is the change in hardness of the plates after use. No hardness tests were conducted before use but some micro-hardness measurements were made after use. A sample was removed from the top of an intermediate bar (positions chosen for study were selected using a random number process). The sample removal site is shown on Figure 60. Figures 61 and 62 also show the sample at 80 X and 300 X magnification with no etching. Etching with mixed acids in glycerol and using the Normanski interference on the Reichert Metallograph (a microscope with camera attachment) revealed four layers near the surface. This is seen in Figures 63-65. A series of micro-hardness tests were performed across the sample and revealed a harder surface layer (Figure 63) with no visible structure, possibly suggesting a white layer. This is a layer altered by considerable and rapid temperature changes, possibly along with some mechanical deformation (usually featureless in microscopy). Figures 66 and 67 also show martensitic and austenitic areas.

Property changes in tribo-element [3] are described in Section 3.4.5.

3.5.2. Friction Data

Some of the ideas concerning friction between the elements is discussed in Sections 3.4.9.5 and 3.4.9.7. The only available data is a graph of horsepower days consumed per oven dry ton of pulp produced (Figure 32) for the life of the set of plates used in this case study.

3.5.3 Wear Data - Analysis of Worn Refiner Plates

The only wear data of value that is available is that from an examination of the plates after use. All of the plates were weighed before use and again after use to determine weight loss. By a random process (area divided and random numbers used to determine areas to be studied) ten

(10) areas on the fine bar section and ten (10) areas on the intermediate bar section were chosen to be examined. These areas were analyzed and photographed.

As shown in Section 1.2 data with respect to plate life may come from either of two sources,

(1) normal operation, one in which the plates have never been in physical contact, and

(2) clashed operation, one in which the plates have been damaged either through plate to plate contact or because of the passage of some hard, usually metal, material through the refiner.

Clashing will invalidate any design measurements made with respect to the plate geometry and surface characteristics of the plates and will invariably destroy much wear data from normal operation.

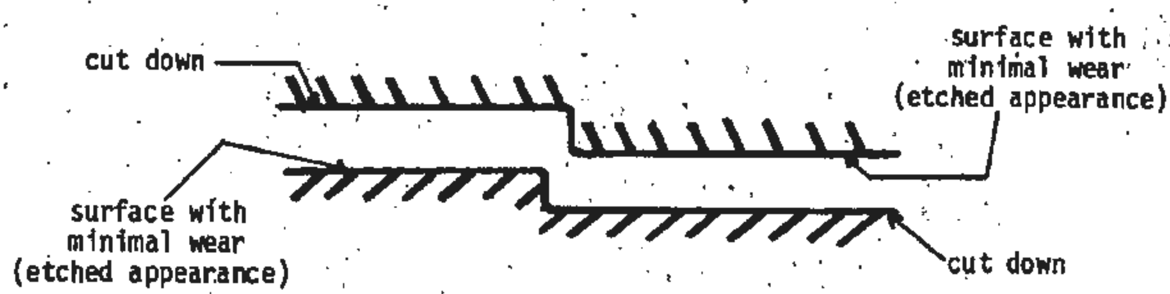
The refiner plates after use were found to have worn in sharply defined annular zones at randomly defined radii. In each zone the wear was asymmetrical, with one of the opposing plates wearing more than the other. The location of the wear zone and the disk experiencing wear (rotor or stator, element [1] or [2]) were both found to be different for other sets of plates. Figure 36 shows a typical unused refiner plate while Figure 68 shows tribo-element [1] (the stator plate) after it is worn, and Figure 69 shows tribo-element [2] (the rotor plate) after it is worn. As seen from these photographs elements [1] and [2] interlock, i.e., the unworn part of [1] fits perfectly into the worn part of [2] and vice versa.

At first, it was believed that this wear patten was the result of plate clashing and/or damage due to foreign material. The typical appearance of tongue and groove scoring had always signified clashing to refiner operators. There was evidence of the transfer of metal from element [1] to element [2], smearing of surface layers, and some wedge formation. These again seemed to indicate clashing. Metallurgical studies of the plates and the metal removal patterns, however, clearly showed that this was not the case.

3.5.3.1 Metallurgical Investigations

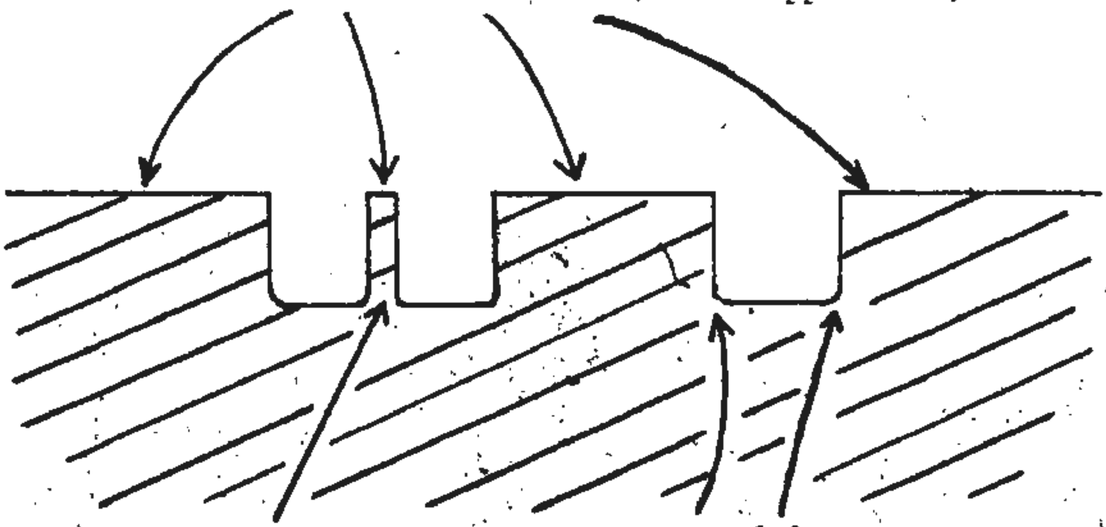
To help refrain from analyzing portions of the worn plates that looked interesting but not representative, the intermediate bar section (Figure 36) of the plates were divided into three hundred (300) blocks of one square centimeter (1 cm^2). Ten (10) of these blocks were then chosen for study using a system of random numbers with each of these areas being photographed and studied using a Reichert Metallograph (a microscope with camera attachment) capable of a magnification of 2000X. Figures 70-75 show typical sites that were studied. Figure 70 (stator) shows a surface layer of deposited metal while Figure 71 (rotor) reveals a surface with very little damage apart from some radial cracks and blunting of the edges of the bars. On the right side of Figure 73 (rotor) are seen cut down areas with cracks at the bottom of the cut down pieces but most of the bars still have little wear - the surface appears as if it were only etched by an alkaline or acid medium (see Figures 71,73,75). Matching or interlocking with this are the bars from the stator plate seen in Figure 72. On the left side of this picture are the cut down areas corresponding to the almost unworn surface of Figure 73. In a side view we have the following:

STATOR PLATE



ROTOR PLATE

The last two photographs, Figures 74 and 75 showed many cut down areas with a side view as seen below.



It was found from these that narrow bands of metal were left between some cut down areas and that all the cut down areas had rounded edges. These facts did not indicate clashing or momentary harsh mechanical contact.

To study this further cut down areas from used plates were mounted, polished, etched and studied using the Reichert Metallograph. The results of this are seen in Figures 76 (30X) and 77 (120X). Both pictures show the rounded and smooth surface of the cut down area and also the unchanged Ni-Hard grain structure near the surface. These facts again attest to the wear as resulting from a nonclashing or normal operation. It is also interesting to note in Figure 77 the presence of a crack at the base of the worn down area. This may have been an original surface crack that progressed, causing or aiding the wear process, or it may have resulted either directly from the wear or from stress corrosion cracking (s.c.c.). Of the cut down areas studied more than 75% had cracks at their base and it is possible that the other 25 per cent had cracks also that were removed as the wear progressed.

Further microscopic examination of the intermediate bars, after polishing and etching with 5% Nital, revealed that a majority of the corners of the cut-down areas were made of a grey structureless material as seen in Figure 78 parts (a) and (d). Some of the areas that were not cut down or worn also had a complete or partial covering of this grey material; none, however, was found on the bottom of any of the cut down areas. Microhardness tests performed on this grey material revealed hardnesses of Rc 62-65 whilst the base metal had hardnesses of Rc 52-56. None of the layers underneath this grey material show any different microstructures from the parent material. It is possible that these areas such as are seen in Figure 78(d) came about because of momentary contact between higher macro-asperities on rotor and stator bars. The covering, such as is seen in Figure 78(c) near microhardness mark 7 could also have resulted from transfer of metal and/or the same type of momentary contact. The dark area with microhardness marks 5 and 6 (Figure 78(c)), however, appears to be part of the original material and may have been formed during the casting process.

This analysis clearly shows that the plates were not clashed and that the metal removal patterns observed were indicative of that produced by a process similar to electrochemical machining.

3.5.3.2 Electrochemical Machining

Electrochemical machining (E.C.M.) is a process in which metal is removed without the use of mechanical or thermal energy when an electric current is combined with a chemical to form a reaction of reverse plating. A schematic arrangement for electrochemical machining is seen in Figure 79 and Appendix A contains details of the machining process. It is postulated that an E.C.M. process is occurring between the opposing refiner plates and it is this process which is responsible for the relatively short plate life and the unusual wear patterns observed. On an industrial macro-scale a direct current of relatively high amperage and low voltage is continuously passed between the anodic workpiece and cathodic tool (electrode) through a conductive electrolyte removing metal at rates in the range of 1.64 to 2.29 cm^3/1000 amp. min. In the refining process it is believed the electrochemical machining is on a micro-scale since removal rates are in range of $4.59\text{–}7.37 \times 10^{-3}$ cm^3/min. (based on weight losses from Table 16 and plate life data). Because the operation is continuous over a 600-1,000 hour time scale the total amount of material removed, 3-5 kilograms per set of plates, which is equivalent to 25-40 per cent of all the intermediate and fine bars, is large and contributes significantly to loss of refining area, thereby decreasing plate life.

With reference to Appendix A we find various points concerning E.C.M. to be verified from our microscopic metallurgical examination. The worn surface of the tribo-elements contained no burrs or striation marks and as seen in Figure 77 did not reveal any metallurgical damage. We also found that the surface causing the wear (the tool, Figure 73) did not experience any wear. Also, the refiner plates used were made from Ni-Hard which is a white cast iron containing about 4 per cent nickel and 2 per cent chromium. Ni-Hard has been used in refiner plate manufacture because of its erosion-corrosion resistance in near neutral solutions such as pulp slurries. This resistance of most nickel alloys, however, to chemical attack does not seem to retard electrochemical solution during electrochemical machining and indicates that it is quite possibly occurring.

From Appendix A we note that a current is necessary for electrochemical machining. Where does this current originate between the plates? Some possible sources are local potential differences with much of the current going through the opposing metal plates, thus yielding a very low resistance. There are possible potential differences due to differences in temperature, ion concentration, and dissolved oxygen. All of these factors may relate to the manner in which the wood chips move, at times perhaps, more or less stationary relative to one surface while sliding at high speed upon the other.

CHAPTER 4

CORROSION TESTING OF REFINER PLATES

4. CORROSION TESTING OF REFINER PLATES

4.1 Production of Refiner Plates - A History

Commercial refiner plates are bulky, difficult to handle, and not easily broken or cut into manageable test samples. Therefore, a non-destructive testing procedure was developed so that a plate after testing could be used in commercial operation. Prior to describing the test procedure developed for use in this study, the following is provided as background information on the manufacture of refiner plates.

The Ni-Hard[25] refiner plates used in this study were cast at 2600°F using a green sand casting technique which uses no resins. After casting, the refiner plates were cooled to ambient temperature, shaken out of their moulds and may have been left for a week or more before further treatment. Since each plate was shaken out at a different time and temperature each of the twelve plates in a set could have slightly different metallurgical properties. A stress relieving operation was next performed on the plates; heating for two hours at 500° F followed by air quenching. This

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[25]Ni-Hard is a white cast iron with a Brinell hardness of 550 to 725 containing about 4% nickel and 2% chromium. Ni-Hard has found wide application where erosion-corrosion resistance is needed in near-neutral and alkaline solutions or slurries. White cast irons such as Ni-Hard have practically all of the carbon in the form of iron carbide. To guard against graphitization, which is related to the rate of chilling from the melt, the silicon content is kept low.

caused a mechanical change in the grain structure-austenite to martensite. The purpose of this treatment was to give a Rockwell hardness, Rc, of 54-58.

The fine and intermediate bar sections of the plate surfaces were then wet ground and all edges were dry ground. On plates with fine bars there was 100% clean up of surfaces, that is the grinding stone went over 100% of the surface. A degree of flatness of 60 thousandths of an inch was a quality control standard during the production of the plates. Also, an integral part of the quality control standards was a stress relieving process which was automatically programmed and controlled.

The final process on the plates was that of balancing. A Micropoise Balancing Machine similar to ones used on airplane impellors and jet engines was used to dynamically balance a complete set of plates. The machine, which was progammable, indicated where, and how much, molten lead had to be poured into holes on the back of the plates to balance them.

This history indicates that each refiner plate may be different metallurgically. Because of this it is extremely desirable that a plate be tested before use and then examined metallurgically after use. The testing includes:

1) photographing and weighing (before and after use);

ii) Magnaflux testing for determination of cracks and checks from casting and surface grinding (before use);

iii) Reichert Metallograph inspection for high magnification photography (2000X) of surface characteristics (before and after use); and

iv) electron probe microanalyzer inspection for verification of chemical composition and metallurgy as compared to material specifications.

4.2 <u>Experimental Procedure and Apparatus</u>

A set of unused refiner plates were obtained from the Price-Newfoundland Ltd. mill at Grand Falls for preliminary examination. Each segment of the set was weighed, photographed and specific areas, selected by a random process, were subjected to microscopic examination using a Reichert Metallograph capable of a magnification of 2000X. Magnaflux testing was also conducted to detect flaws in structure such as cracks. The plates were then returned to the mill for use in a 2500 HP 42 1B Sprout Waldron refiner. When removed from the refiner, the plates were cleaned of pulp, reweighed and rephotographed.

The corrosion characteristics of the plate material were determined using a modified version of ASTM G5-72 as described in Appendix B. A detailed analysis of the wear characteristics of the plates is given in Chapter 3.

Since the ASTM Designation G5-72 polarization cell (Fig. 80) could not be used in the experimental set-up a cell had to be designed. The following were criteria considered in the design: (1) cell volume; (2) electrode arrangement within the cell; (3) the nature of the electrodes used; (4) the proposed application of the cell; (5) the facility for addition/removal of electrolytes, gases and electrodes from the cell; and (6) the power output of the potentiostat.

The cell volume could not be too large since very large resistances would result when poorly conducting electrolytes were being tested. Small volumes were also to be avoided since rapid depletion of reagants or accumulation of reaction products could occur. It was decided the cell would be an open four (4) litre beaker containing 900 ml. of electrolyte. Addition or removal of the electrolyte from the cell was necessary to prevent undue dismantling of the system and therefore a suction side arm was added to the beaker. Temperature control of the electrolyte was made possible by the use of a suitable immersion heater. Aeration of the electrolyte was made possible by bubbling in air or oxygen directly through a sintered glass-ended tube and de-aeraction by the addition of nitrogen as opposed to hydrogen.

The ratio of electrode area to solution volume (A/V Ratio) must be as large as possible (2.54 cm. dia. electrode used). The cell capacity or volume of electrolyte in the cell is also important according to Greene (63) since the decay rate of the initial current is exponentially related to the ratio of electrode area to the electrolyte volume.

4.3 Comparison of Standard Potentiostatic Analysis Techniques (ASTM G5) and Experimental Research Techniques

The method used in this experimental research differed significantly in several aspects from the method outlined in the standard reference method for making potentiostatic anodic polarization measurements, ASTM Method G5 (Appendix B). The testing method developed for use on Ni-Hard plates, however, has given results which are equivalent to the standard method results and are also reproducible (Section 4.3.1).

Use of the ASTM method requires standard samples made to fit standard equipment. The hard and brittle nature of the Ni-Hard refining plates, however, made the fabrication of such samples extremely difficult without alternation of the physical and chemical properties of the Ni-Hard itself. It was also beneficial to have a non-destructive testing method for several reasons:

i) ASTM methods limited testing to plates that were unfit for further use;

ii) It is very advantageous to be able to test corrosion characteristics before and after the plates are used in commercial operation.

The most significant difference in our experimental method from ASTM method G5 was that the specimen or working electrode was still an integral part of a whole refiner plate isolated via a teflon disc and epoxy resin as seen in Figure 81. Also the standard polarization cell was replaced, as described in Section 4.2, with an ordinary four litre open neck beaker. A 2.54 cm. diameter hole was cut through the base of this beaker which fit, with the aid of epoxy resin and a teflon disc, directly onto the refiner plate. The area of the refiner plate thus exposed as a working electrode surface was not prepared with SiC paper (although grease and surface dirt was removed by scrubbing with both acetone and ethyl ether), but left as it would be under working conditions in a refiner. It should be noted that the standard procedure of preparing surfaces with 240/600 - grit SiC paper was not necessary since each refiner plate would be different in both surface characteristics and chemical and physical composition (this is inherent in the manufacture of the plates described in Section 4.1).

All tests were conducted at room temperature, 22-25°C, since the setup disallowed immersion in a controlled-temperature bath. It would be possible, however, to use an immersion type heater in the cell itself. The top of the experimental corrosion cell, the four litre beaker, was not closed nor was the test solution purged with oxygen-free hydrogen gas, but these and previously described variations did not appear to alter results (Section 4.3.1).

The working electrode (refiner plate) was connected to the reference electrode (Ag/AgCl or Calomel) via an ammonium nitrate (NH_4NO_3) salt bridge. Since the three electrode system (auxiliary or counter/working/reference) was being used the auxiliary electrode (a platinum wire electrode) was centered directly above the working electrode as seen in Figures 81, 82. The appropriate test solution was then placed in the polarization cell and the experimental procedure of the standard reference method (ASTM G5) was used to perform all experimentation.

4.3.1 Derivation of Standard Curve and Reproducibility of Results

Using a standard sample of 430 S.S. obtained from the American Society for Testing and Materials (A.S.T.M.), a standard reference plot for type 430 S.S. (Figure 83) was reproduced using our experimental set-up. The experimental data, as seen in Figure 83, coincides with the standard although the temperature was lower and there was no purging of the solution in the cell. This reproduction of the standard potentiostatic anodic polarization plot confirms that our setup is precise enough to give reproducible standard results and thus results on refiner plate specimens in situ that are also reproducible. This leads to the desirable position of testing plates before and after their use in commercial operation.

4.4 Analysis of Experimental Results

Potentiostatic testing was carried out to check the effects of pH, Na_2SO_3 addition and dissolved O_2 content on the corrosion of Ni-Hard plates. This was done to gain insight into corrosion behaviour of plates spurred by metallographic analysis which showed clearly that corrosion processes were at least as important, if not more important, than clashing and wear. The objectives of the testing were to see if there was any justification for the belief that Ni-Hard is an active-passive metal, and approximately what corrosion rates could be expected.

To pursue these objectives, potentiostatic tests were run on Ni-Hard refiner plates under different conditions. The tests were conducted at varying pH and with the addition of Na_2SO_3. In each case the test solution was set at the desired pH by the addition of H_2SO_4 and/or NaOH. The anodic polarization curves obtained were compared with the potentiostatic anodic polarization curve of pure iron (Figure 84)[26] in $\underline{N}H_2SO_4$ given by Fontana and Greene (64) and

[26] Fontana, M.G. and Greene, N.D., Corrosion Engineering, McGraw-Hill, New York, 1967, p. 336.

for many of the test runs were found to be quite similar (Tables 17 - 21). The resulting curves exhibited a distorted "S" shape. An explanation could be that only the iron in the Ni-Hard material is actually corroding. The curves are actually inverted mirror images of the typical "S" type curve displayed by stainless steel.

The curves obtained had corrosion potentials in the range of -0.43 to -0.53 volts (versus the Saturated Calomel Electrode, S.C.E.) and the corrosion current densities were in the range of 30-250 mA/cm^2. The Tafel slopes (the volts per decade slope of the anodic and cathodic polarization curves, Figure 85), βa and βc, are generally in agreement for all runs with Stern and Weisert (65) who state that for a large majority of metal-electrolyte systems βa varies from 0.06 to 0.12 V/decade and βc is greater than 0.06V/decade.

4.4.1 <u>pH Test Results</u>

One of the main objectives of the potentiostatic testing was to determine the effect of pH on the corrosion behaviour of the Ni-Hard refiner plates. These tests were conducted under controlled pH conditions and Table 22 shows the progression of pH from 2.0 to 7.0. The values of Epp, i_{cr} and i_{pass} (See Figure 85) indicate that the corrosion resistance of the plates is high at low pH (2.0 - 3.0), decreases quite considerably in the range, 3.0 -5.0, and then increases significantly as it approaches neutral conditions.

This is shown in Figure 86 which indicates that there is an optimum pH for maximum corrosion resistance of the Ni-Hard plates. The data collected was incomplete in this respect and therefore no actual value for this optimum pH/maximum resistance was obtained. A pH of 6.5 - 6.8 is used at Price (Nfld.) Pulp and Paper Co. Ltd., Grand Falls, Newfoundland, based on experience. It would be very beneficial if the actual optimum value (if it existed) could be determined with consideration being given to mill conditions with respect to piping materials, paper brightness and foaming problems.

From Table 19 a comparison of the dissolved oxygen content during tests numbered 16-19 seems to show that the larger amount of dissolved oxygen in test 17 (compared to 18) and test 16 (compared to 19), at equivalent pH, aids passivation. This may be extremely important when Na_2SO_3 addition (Section 4.4.2) is considered since this additive, used to extend plate life, is also an oxygen scavenger.

4.4.2 Addition of Na_2SO_3 Test Results

The major objective of the potentiostatic testing was to determine the mechanism by which Na_2SO_3 extends plate life and to determine the amount necessary for optimum protection. From Tables 19 - 21 it can be seen that the sodium sulfite had a stabilizing effect on the pH during each test run. In most of the other tests, with no Na_2SO_3 addition, the pH increased during the run (except under very acidic conditions, i.e. pH 2.0) indicating the loss (disappearance or transformation) of H^+ ions.

The results may indicate a complete lack of passivity and corrosion control when a small amount of Na_2SO_3 is added (i.e. ~ 0.6910 g/900 ml ≡ 1.68 lbs/oven dry ton of wood pulp). It is noted, however, that i_{corr} at this level is extremely low (5.2 μA/cm^2) and the ability to passivate is not essential at this low value. As the amount of Na_2SO_3 is increased (Tables 19, 20), E_{corr}, i_{cr}, E_{pp} and i_{pass} (see Figure 85) decrease. This indicates that the addition of further Na_2SO_3 increases the corrosion resistance and passivation characteristics of the Ni-Hard samples. More anodic and cathodic combinations need to be run, however, to evaluate i_{corr}. As more Na_2SO_3 is added (Tables 19 - 21) the passive potential range decreases indicating a lower anodic protectibility region. Again the question of an optimum amount of Na_2SO_3 giving maximum corrosion resistance is raised (Figure 87). More detailed tests need to be run to determine this optimum value if it exists. We must also note that for moderate amounts of Na_2SO_3 (i.e. > 6.0 g/900 ml of sample) the dissolved oxygen level fell to zero; the effect of this is detailed in Section 4.6.

As in actual mill operations, the use of sodium sulfite in polarization experiments reduced refiner plate corrosion and extended plate life. The addition of sodium sulfite to the refiner changes the rate of the cathode reaction, probably by oxygen reduction, which in turn, reduces the rate of metal dissolution. Results showed that corrosion rates were lower when dissolved oxygen content was high, bringing into question the belief that the role played by Na_2SO_3 in enhancing refiner plate life is via a mechanism of oxygen scavenging.

The test results indicate that very small amounts of Na_2SO_3 (0.84 kg/oven dry metric tonne) could reduce plate life and increased amounts (> 8.0 kg/o.d.m.t. of pulp) could extend plate life. From industrial experience it is known that amounts in excess of this were costly and could cause foaming problems. The actual role of the Na_2SO_3 re dissolved oxygen is, therefore, still unclear, as is also its intermittent use. More experimentation is needed to define more precisely the role of Na_2SO_3 in reducing refiner plate corrosion. If it were found that the removal of dissolved oxygen decreased passivation, it might be possible to use an oxidizer or an additive that was not an oxygen scavenger.

Removal of oxygen by Na_2SO_3 inside an actual refiner is in all probability incomplete. Oxygen is likely to be left in crevices, surface cracks and under pulp and chip particles in grooves between bars. This incomplete removal of the oxygen by the Na_2SO_3 will result in oxygen differential cells being formed. These will lead to loss of material by corrosion resulting in the patterns observed in Section 3.5.3 - wear at sharply defined annular zones at randomly defined radii (Figures 68,69). Complete oxygen removal, on the other hand, would result in even wear on all bars - this is not seen. This partial de-aeration with insufficient quantities of Na_2SO_3 possibly interferes with passivation in pits and cracks. The Na_2SO_3 seeps into pits, raising the pH within the pit and producing the HSO_3^- ion. This in turn could lead to the production of polythionic acids under the right conditions of temperature and pressure. Polythionic acids in turn promote stress corrosion cracking (S.C.C.) (66).

4.5. Metallurgical Investigation of Plates

Metallurgical investigations of wear experienced by refiner plates have been presented in Section 3.5.3.1. It was found that both rotor and stator plates experienced large amounts of metal removal (Table 16) on the intermediate bars (25-40% material removed - see Section 3.5.3.2) forming an interlocking wear pattern. These cut-down areas (see Figures 68,69), which were believed to have been caused by electrochemical machining (E.C.M.), were examined for evidences of corrosion.

Microscopic examination revealed many radial cracks in the intermediate bars (see Figure 88; also seen on Figures

60, 71-75); as many as 20 cracks per 10 cm. length of bar on the rotor plates. There were less cracks on the stator plates and most of the cracks were found to be transgranular. Many of these cracks were also visible without the aid of a microscope (see Figures 68,69). These cracks are thought to be due to stress corrosion cracking (S.C.C.), some of which may have originated at surface cracks and checks present on the new plates. Residual stresses in the new plates are also believed to have aided the crack propagation.

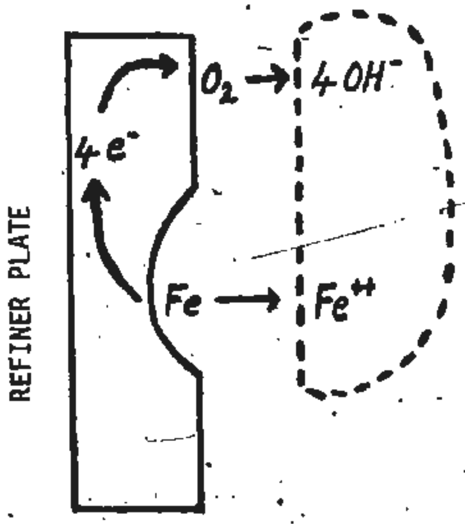
4.6 Corrosion Mechanisms

The tests performed indicate that the iron in the Ni-Hard refiner plates is undergoing corrosion. A possible set of reactions are

$$2Fe = 2Fe^{++} + 4e^{-} \tag{6}$$

$$O_2 + 2H_2O + 4e^{-} = 4OH^{-} \tag{7}$$

These reactions account for the increase in the pH of solutions around corroding specimens from the production of OH^{-} ions. We have



$Fe(OH_2)$ + rust

(Fe) (OH) some oxide compound(s)

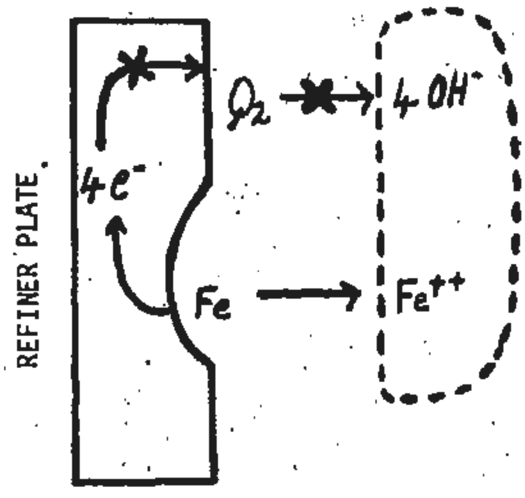
FeO

Fe_3O_4

Fe_2O_3

The addition of Na_2SO_3 must be considered next. If Na_2SO_3 is used the reaction is

$$2Na_2SO_3 + O_2 = 2Na_2SO_4 \qquad (8)$$



Na_2SO_3

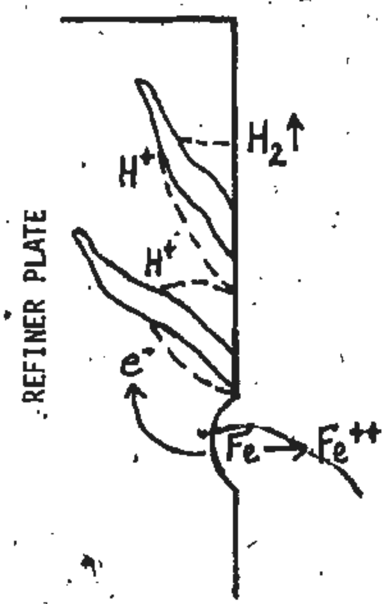
(oxygen scavenging inhibitor)

Note: X's on the previous reactions - these do not occur with Na_2SO_3 present

This removes O_2 and blocks the move of electrons and thus effectively blocks the corrosion reactions. If this is the dominant use of the Na_2SO_3, to use up oxygen, it will inhibit corrosion and indeed evidence seems to indicate that this is the dominant mechanism. There is one problem, however, the refiner plates continue to corrode in Na_2SO_3 solution, albeit at a slower rate. Other reactions must therefore be occurring. In aqueous media the following reactions also occur

$$2Fe = 2Fe^{++} + 2e^- \quad (9)$$

$$2H^+ + 2e^- = H_2 \uparrow \quad (10)$$



Dotted lines represent increasing size of cracks

If H^+ forms in surface cracks on the refiner plates the cracks could open up as H_2 is formed, extend further and pieces could be removed from the plates. Surface cracks and checks present due to surface grinding and manufacture may lead, due to increased pressures in single stage operation of refiners, to increased clashing via the route of cracks as anodic sites for electrochemical machining (Section 3.5.3.2). The increased pressures may result in loss of more material, which in turn yields larger cracks and may end in clashing.

The exact role of the Na_2SO_3 is not clear here. Na_2SO_3 as it takes up (scavenges) O_2 raises the pH by reducing the H^+ ion concentration - a known effect. However, if too much oxygen is taken out of solution, reaction 7,

$$O_2 + 2H_2O + 4e^- = 4OH^- \tag{7}$$

is inhibited and reaction 10,

$$2H^+ + 2e^- = H_2\uparrow \tag{10}$$

is consequently enhanced.

This reaction is one of the dominant mechanisms for electrochemical machining (Section 3.5.3.2, Appendix A). It therefore appears that Na_2SO_3 inhibits the rate of iron dissolution from the Ni-Hard plates but because of its scavenging property also removes dissolved oxygen from the solution. This in turn leads to the enhancing of a mechanism that is necessary for electrochemical machining. It is therefore possible that Na_2SO_3 extends the life of the Ni-Hard refiner plates but also eventually causes their destruction. Since dissolved oxygen appears to be necessary for effective plate protection the use of an alternate additive may be necessary. This alternative would be selected through potentiostatic testing and could be equally as effective as Na_2SO_3 without the detrimental oxygen scavenging property. This chemical may then lead to even longer plate life than that with Na_2SO_3.

4.6.1 Formation of Ridge Groove Pattern

Metal loss from the plates has been attributed to corrosion by a process similar to electrochemical machining (sections 3.5.3.1 and 3.5.3.2). In electrochemical machining, the part to be machined is made an anode by passing a controlled current between it and the "cutting" tool which serves as a cathode. Electrolyte pumped between the tool and the work piece serves to promote the corrosion reaction and remove corrosion products. A similar situation is believed to have occurred here which explains why the removal of metal was in a ridge/groove pattern as illustrated in Figs. 68 and 69. If the grooves are created by corrosion, these areas must be anodic with respect to the ridges. That is, the corrosion cell consists of an "active" groove which serves as an anode, and a passive ridge which serves as a cathode. The electrolyte is of course the pulp. Figure 89 shows schematically the mechanisms which are believed to govern the process. The sequence of events are considered to be as follows:

1. A groove is initiated on the plate as a result of such factors as clashing, passage of grit, stones or tramp

metal through the refiner, or localized wear due to entrapment of chips in the spaces between the bars. Alternately, surface cracks may become localized anodes due to crevice corrosion.

2. The groove, with less access to dissolved oxygen, becomes an active site and undergoes corrosion according to the reaction

$$M \rightarrow M^{2+} + 2e^- \qquad \text{anodic reaction}$$

3. The electron sink for the electrons can be either

$$1/2\ O_2 + H_2O + 2e^- \rightarrow 2OH^-$$

cathodic reaction (at areas adjacent to the groove) or

$$2H^+ + 2e^- \rightarrow H_2 \uparrow$$

cathodic reaction (within a groove or in a crack)

The oxygen reduction reaction tends to passivate the areas adjacent to the grooves making these areas potential ridges. The hydrogen ion discharge within the grooves tends to promote such processes as stress corrosion cracking thereby making the groove more prone to attack through crevice corrosion. It is possible that the former cathodic reaction predominates when a bar lines up with a bar and the latter predominates when a bar lines up with a space between the bars of the refiner plate. It should be noted that a bar alternates very rapidly indeed from facing a bar on the opposite disk to facing a space between bars. Thus, the effective state of the bar surface will be an average of the two situations, so that grooves on a bar surface are exposed to relatively less agitated conditions than is the case for corresponding ridges. Thus, it is believed that the ridges, being more exposed to the pulp, have greater access to buffering solutions such as sodium sulphite and dissolved oxygen which would tend to make such areas cathodic.

Data obtained from the potentiostatic tests carried out on the Ni-Hard refiner plate material can be interpreted to support the above hypothesis. Figures 90 and 91 show that the lowest susceptibility to corrosion as indicated by the anodic polarization curve being on the left, occur under conditions of high agitation, high pH and high levels of dissolved oxygen. This is the situation most likely to approximate that at the ridge areas. Anodic polarization curves on the right indicating, higher susceptibility to corrosion, occur with stagnant solutions with low oxygen content analysis, and with stagnant solutions with high oxygen content along with high acidity. Even higher corrosion rates are indicated for conditions of depleted oxygen in agitated solutions. The situation which may be postulated as existing in the grooves is either less agitation, or a depletion of oxygen, or indeed both factors together.

Once local electrochemical cells are established, the associated reactions and current flow and the pattern of active and passive sites on the surface could be self-perpetuating. The above results can not be taken as proof that a process similar to electrochemical machining is the governing mechanism controlling the wear and corrosion of refiner plates since it is highly unlikely that the data obtained under laboratory conditions reflects the situation in a refiner. However, the fact that a groove/ridge pattern was observed on the plates, that this was not a result of clashing, and that Ni-hard plate material can have greatly different corrosion characteristics depending upon pH, dissolved oxygen and degree of stagnation between plate and electrolyte lends support to the hypothesis.

Indications from the potentiostatic studies are that use of sodium sulphite can have beneficial effects in reducing corrosion in that it increases pH. On the other hand, there is evidence that sodium sulphite, because of its ability to scavenge oxygen, plays a role in making Ni-Hard prone to crevice corrosion thereby promoting the ridge/groove pattern on plates frequently misinterpreted as clashing.

4.7 Conclusions and Recommendations

It is noted here that the experimental testing conducted did not simulate actual refining conditions but was done to gain some insight into the effects of pH and the role of Na_2SO_3. Experience has shown that the use of Na_2SO_3 at controlled pH conditions does aid plate life extension. The test procedure used did not duplicate what happened in a commercial refiner, but it does cast doubt on the use of sodium sulphite, and suggests that commercial trials should be made without sodium sulphite in order to test the conclusions arrived at. Therefore the following conclusions have been drawn from the wear study and the corrosion testing and analyses:

1. All effects attributed to clashing are not from clashing. Clashing does occur but it is not the predominant mechanism in loss of plate life, nor can it always be visually determined. Extensive metallurgical and microphotographic examination are necessary to determine the mechanism of wear and corrosion.
2. The predominant mechanism of wear and corrosion is that of electrochemical machining (E.C.M). Stress corrosion cracking (S.C.C) is also very much in evidence.
3. The quality of new refiner plates with respect to surface grinding checks and cracks is very poor. These cracks make excellent corrosion sites.
4. The role of Na_2SO_3 is not completely understood. It is known to extend plate life but a more beneficial additive may exist.

Considering these conclusions the following recommendations to the paper mills are proposed:

1. Trials with stainless steel refiner plates should be conducted. These plates should have the pattern, taper and geometry of Ni-Hard plates that give reasonable life and good pulp.
2. The quality of present plates with respect to surface checks and cracks (corrosion sites) must be considered. The surface grinding process must be under strict control and to a much cleaner surface finish.
3. Mills should have more say, not only in plate pattern but also in metallurgy - both composition and treatment of plates.
4. More potentiostatic testing must be conducted to determine the pH and amount of Na_2SO_3 to give optimum corrosion resistance (Figures 86,87), separately and in combination.
5. Again through potentiostatic testing the role of Na_2SO_3 must be defined more fully especially with respect to dissolved oxygen. It must be determined if the Na_2SO_3 does actually lead to plate failure (via E.C.M.) while at the same time giving extended plate life.
6. Finally, potentiostatic testing must be conducted to ascertain if another additive would be as effective as

Na_2SO_3 without its detrimental oxygen scavenging property.

If these changes and recommendations do not considerably extend refiner plate life a study of anodic or cathodic protection (possibly in conjunotion with the recommendations) should be undertaken.

TABLES AND FIGURES

TABLE 1 : Effect of plate profile on pulp quality and furnish cost. Sund-Bauer BDA 488 refiner (48 in. 1,500 r.p.m., 2,500 h.p. double disk). Average over 400 hr. period (Reference 31, p. 56).

Plate No.	Material	Width of Flat Outer Zone	Taper of Intermediate Zone	(b) Q-value	Furnish Cost (HPD/Ton) Energy	(a) Chem Pulp	Total
1	A	large	large	0.36	89	18	107
2	A	large	small	0.34	90	26	116
3	A	small	large	0.29	92	59	151
4	A	small	small	0.32	88	52	140
5	B	large	large	0.35	93	12	105
	Groundwood			0.33	70	80	150

(a) Cost of chemical pulp added to increase tear factor to 66. Every % sulfite added to the finish increases the cost by an amount equivalent to about 5HPD/ton.

(b) $Q = \left(\frac{\text{Tear factor}}{90}\right)^{2/3} \times \left(\frac{\text{Breaking length}}{8000}\right)^{1/3} \times \left(\frac{\text{Scatt. Coeff.}}{800}\right)^{4/3}$

A - Ni-hard type matl. with increased contents of chromium and nickel
B - Martensitic S. steel

TABLE 2 : Used Tapers

Refiner	Taper 2%	Taper 3%	Taper 5%
Sawdust I Refiner	X	XX	
Sawdust II	XX	X	
Chip I			XX
Chip II	X	XX	
Reject I	XX		
Reject II	XX		

XX Main Taper X Sometimes used Ref. 33, p. 10

TABLE 3

First plate material experiments

PLATE MATERIAL	NUMBER OF TRIALS	AVERAGE PLATE AGE (h)
HI MOLY	18	250 - 400
HI CROM	9	250 - 400
HI CLEWA	5	150 - 400
X - METAL	8	300 - 400
MARSITE	1	400

TABLE 4

Uddeholms B-material

	REFINER POSITION (1) S_1	S_2	$C_1^{(2)}$	$C_2^{(2)}$	R_1	$R_2^{(2)}$
NUMBER OF PLATES USED	5	7	3	3	10	6
AVERAGE PLATE AGE (h)	760	766	900	1020	560	800
ENERGY INPUT (MILL. kWh)	3.1	2.5	2.5	2.3	2.4	1.5

1) S - SAWDUST-, C - CHIP-AND R - REJECT REFINERS

2) NEW REFINERS

TABLE 5: Data Used to Compare Plate Life Associated Costs

Refiner	Conditions	No. of Sets of Plates	Initial HPD/ODT for 92 B.V.	Energy Increase Per Service Hour
Bauer	No Treatment	15	87.5	0.0500
Sprout	4 lbs. per ton, Na_2CO_3	7	87.5	0.0231
Bauer	20 lb. per ton, Na_2SO_3	2	81.1	0.0040

TABLE 6

Effects of chemical treatment

	NO TREATMENT	4LB/TON Na_2CO_3	20LB/TON Na_2SO_3
Plate Life Associated Costs at Optimum $/Ton	19.42	18.22	15.87
Optimum Plate Service, Hours	280	424	923
Plant Average Capacity, Ton/Day	212	218	243
Cost Decrease, $1/Ton	---	1.20	3.55

TABLE 7: Standard Refining Conditions

Inlet diameter	558 mm (22in.)
Outlet diameter	1016 mm (40in.)
Peripheral gap	.25 mm (.010in.)
Plate taper	.0075 mm/mm (.0075 in/in.)
Rev/min	1200 (each disk, double disk refiner)
	1800 (single disk refiner)
Power	1500 kW (2000 h.p.)
Specific energy	6.4 MJ/kg (90 h.p.d./o.d.t.
Inlet consistency	17%
Feed inlet temperature	38°C (100°F)
Inlet pressure	101 kPa (14.7 psi)
Outlet pressure	101 kPa (14.7 psi)
Skin friction coefficient	0.1
Slip factor	0.3

TABLE 8: Temperature and pressure at different motor loads and throughputs

Throughput odt/t	t/d	Motor Load h.p.	kW	Consistency Inlet %	Outlet %	Specific Energy hpd/odt	kWh/t	Temperature °C	Pressure psig	kPa
21.5	19.5	2000	1492	19.6	29.2	93.0	1835	132	19-27	131 -189
21.5	19.5	1600	1194	19.6	26.3	74.4	1468	123	15-20	110.3-137.9
28.8	26.1	2000	1492	23.5	35.0	69.4	1370	120	15-18	103.4-124.1

TABLE 9: Temperature vs. distance at different consistencies

Test	Consistency Inlet %	Consistency Outlet %	Differential pressure across hydraulic cylinder psi	Differential pressure across hydraulic cylinder kPa	Specific energy hpd/odt	Specific energy kWh/t	Temperature (°C) at given distances from outer periphery of refining zone 2.54cm 1.00	5.39cm 2.12	8.26cm 3.25	10.80cm 4.25	13.97cm 5.50
1	22.4	43.0	480	3310	91	1795	121	129	134	128	125
2	19.7	32.7	530	3650	91	1795	125	132	136	130	129
3	17.1	26.3	560	3860	91	1795	128	134	137	132	130
4	26.0	40.2	390	2690	60.5	1195	113	121	127	121	122
5	22.9	33.7	410	2830	60.5	1195	118	124	129	123	122
6	19.7	25.8	460	3170	60.5	1195	123	129	133	128	125
7	24.2	42.6	480	3310	74	1460	121	128	132	126	126
8	20.3	30.0	510	3520	74	1460	124	131	135	130	128
9	17.7	23.8	540	3720	74	1460	127	134	136	132	128
10	23.8	50.9	530	3650	91	1795	120	131	135	130	129
11	19.3	27.6	560	3860	63	1243	129	138	142	135	124
12	19.3	23.9	390	2690	45	888	119	124	128	122	114
13	19.3	21.9	280	1930	30	592	109	110	105	102	102
14	24.4	[illegible]	360	2480	91	1795	114	122	121	123	123
15	22.6	39.9	430	2960	91	1795	117	127	126	128	128
16	20.4	31.0	480	3310	91	1795	123	131	130	131	130
17	18.6	27.6	570	3930	91	1795	130	136	136	136	134

TABLE 10: Calculated thrust for different hydraulic pressures

Test	Hydraulic Pressure Opening psig	kPa	Closing psig	kPa	Difference psi	kPa	Hydraulic Thrust lb.	kg	Calculated Thrust lb.	kg	Difference lb.	kg
1	730	5033	250	1724	480	3309	22560	10233	13320	6042	9240	4191
2	760	5240	230	1586	530	3654	24910	11299	15410	6990	9500	4309
3	770	5309	210	1448	560	3861	26320	11938	16730	7589	9590	4349
4	680	4689	290	1999	390	2690	18330	8314	9160	4155	9170	4159
5	690	4757	280	1931	410	2826	19270	8772	10620	4817	8650	3924
6	710	4895	250	1724	460	3172	21620	9807	13410	6083	8210	3724
7	720	4964	240	1655	480	3309	22560	10233	12700	5761	9860	4472
8	740	5102	230	1586	510	3516	23970	10873	14780	6704	9190	4169
9	750	5171	210	1448	540	3723	25380	11512	16140	7321	9240	4191
10	750	5171	220	1517	530	3654	24910	11299	14420	6541	10490	4758
11	770	5309	210	1448	560	3861	26320	11938	18210	8260	8110	3673
12	620	4275	230	1586	390	2689	18330	8314	9650	4377	8680	3937
13	520	3585	240	1655	280	1930	13160	5969	2100	953	11060	5016
14	650	4482	290	1999	360	2483	16920	7675	10230	4640	6690	3035
15	900	4826	270	2862	430	2969	20210	9167	12750	5783	7460	3384
16	720	4964	240	1655	480	3309	22560	10233	15350	6963	7210	3270
17	770	5309	200	1376	570	3933	26790	12152	19050	8641	7740	3511

TABLE 11: Dimensions of Tribo-Elements [1] and [2]

Section	Projected Area/Plate	Total Projected Area/ Circle of Plates
Fine Bar*	16.26 in.^{2}	195.14 in.^{2}
Intermediate Bar*	40.48 in.^{2}	485.7 in.^{2}
Breaker Bar*	36.46 in.^{2}	437.6 in.^{2}
TOTAL	93.20 in.^{2}	1118.4 in.^{2}

*Refer to Figure 36

TABLE 12: Volume Properties (Volume) of Lubricant (element [3])

Section	Volume/Plate (through bars of plate)	Volume Between 2 Disks (0.010 in. Clearance)
Fine Bar	0:5163 in.^{3}	14.3792 in.^{3}
Intermediate Bar	3.2096 in.^{3}	86.4504 in.^{3}
Breaker Bar	6.9856 in.^{3}	380.597 in.^{3}
TOTAL	10.7115 in.^{3}	481.427 in.^{3}

TABLE 13: Typical Data for Components of Element [3] ("Lubricant")

Water (Dilution)	Volume - 24% (Avg. 10 gal./min.) pH - 6.4 - 6.6 Temp. - 2°C - 15°C (depending on season of year) D.O. - 7.0 - 8.0 ppm Conductivity - 25 - 40 μmhos ppmFe - 0.20 ppm ppm Chlorine - 1.4 ppm ppm Chloride - 3.37 ppm
Na_2SO_3 (Additive)	Volume - 0.50 u.s.g.p.m. pH - 8.50 - 12.0 Temp. - 30°C - 40°C
Wood Chips	Moisture Content - 50 - 60% Throughput - 26 o.d.t./day
Steam (product)	Saturated

Inlet Conditions	Outlet Conditions
Temperature 2 - 15°C	100°C
Pressure 1 atm	1 atm
Consistency* 22%	40% (*weight of wood fibers to total weight of slurry)

TABLE 14: Experimental Conditions for First-Stage Refining

Refiner Shaft Speed	1,200 r.p.m.
Refiner Plate Pattern	C-906
Refiner Plate Material	Modified Ni-hard
Plate Taper (Measured)	0.0046 in. per inch
Rate of Feed	6 O.D. ton/day
Refining Consistency	15%
Nominal Plate Separation	0.005 in.
Dilution Water Temperature	170°F
Batch Operation using 5 lb. O.D. black spruce chips per run.	

TABLE 15:- Bauer-McNett Classification of Accepted Stock Produced at Various Points Through the Refining Zone

Radial Length Along Refining Zone (in.)	1.0	2.5	4.0	5.5	7.0
R28	41.2	37.0	30.9	31.0	31.2
28/48	23.3	23.5	23.6	24.0	23.9
48/100	14.4	15.3	16.0	15.3	14.5
100/200	5.4	5.4	8.5	8.1	7.2
P.200	15.7	18.8	21.6	21.6	23.2
% Accepts (by weight)	19.0	30.3	32.8	45.0	82.5

TABLE 16: Segment Weight Loss After 518 Hours

Segment number	Rotor weight loss (g)	Stator weight loss (g)
1	27	65
2	98	73
3	99	78
4	109	78
5	107	70
6	101	71
7	124	71
8	111	69
9	106	49
10	180	45
11	112	20
12	102	91
$\bar{x}$	106	65
δ	33	19

TABLE 17: Experimental Potentiostatic Results

RUN	Direction	Curve Shape	TEMP (°C)	D.O. / pH	Agitation Level	Na_2SO_3 Added (g)	E_{CORR} volt	i_{CORR} (μA/cm²)	i_D (μA/cm²)	i_{cr} (μA/cm²)	E_{pp} volt	i_{pass} (μA/cm²)	β_a (mV/dec.)	β_c (mV/dec.)
1	Anodic		23	N.R.* / N.R.(5.6)	0	0	-.437	250	N.A.	**1.7^4	-0.008	115	190	N.A.+
2	Cathodic		N.R.	N.R. / N.R.	0	0	-.499	250	1.9^4	N.A.	N.A.	N.A.	N.A.	290
3	Anodic		N.R.	N.R. / N.R.	0	0	-.522		N.A.	1.5^4	0	2000	85	N.A.
4	Anodic		N.R.	N.R. / 6-3.5-8.5-7.8	0	0	-.527		N.A.	2.0^4	.300	475	80	N.A.
5	Anodic		N.R.	N.R. / 7-4.6-8.6	0	0	-.465	33	N.A.	1.5^4	0	495	80	N.A.
6	Cathodic		N.R.	N.R. / 7-4.6-3.9-7.0-4.4	0	0	-.452	33	4.0^3	N.A.	N.A.	N.A.	N.A.	115
7	Cathodic		N.R.	N.R. / N.R.	0	0	-.434	25	6.5^3	N.A.	N.A.	N.A.	N.A.	60

* Not Recorded ** $1.7^4 = 1.7 \times 10^4$ + Not Applicable

TABLE 18: Experimental Potentiostatic Results (Cont.)

RUN	Direction	Curve Shape	TEMP (°C)	D.O (ppm) / pH	Agitation Level	Na_2SO_3 Added (g)	E_{CORR} (volts)	i_{CORR} ($\mu A/cm^2$)	i_D ($\mu A/cm^2$)	i_{cr} ($\mu A/cm^2$)	E_{pp} volts	i_{pass} ($\mu A/cm^2$)	β_a (mV/dec)	β_c (mV/dec)
8	Anodic		N.R.	N.R. / 6.0-5.1 -8.7	0	0	-.527	-	N.A.	1.5^{4}	0	4000	100	N.A.
9	Anodic		N.R.	N.R. / 6.0-3.1 -8.4	0	0	-.475		N.A.	$[illegible].3^{4}$	.250	160	85	N.A.
10	Anodic		N.R.	N.R. / 6.0-4.9 -8.6	0	0	-.404		N.A.	1.1^{4}	-.100	3300	70	N.A.
11	Anodic		N.R.	N.R. / 5.0-4.6 -8.6	0	0	-.517		N.A.	1.4^{4}	.150	4000	95	N.A.
12	Anodic		N.R.	N.R. / 5.0-4.3 -8.5	0	0	-.482		N.A.	1.1^{4}	.500	4000	125	N.A.
13	Anodic		N.R.	N.R. / 5.0-5.5 -8.6	0	0	-.470		N.A.	8.0^{3}	.050	2400	100	N.A.
14	Anodic		N.R.	N.R. / 6.5-5.8 -9.0	0	0	-.481		N.A.	6.0^{3}	.100	2600	120	N.A.

TABLE 19: Experimental Potentiostatic Results (Cont.)

RUN	Direction	Curve Shape	TEMP. (oC)	D.O (ppm) / pH	Agitation Level	Na_2SO_3 Added (g)	E_{CORR} volts	i_{CORR} ($\mu A/cm^2$)	i_D ($\mu A/cm^2$)	i_{cr} ($\mu A/cm^2$)	E_{pp} volts	i_{pass} ($\mu A/cm^2$)	β_a (mV/dec.)	β_c (mV/dec.)
15	Anodic		N.R.	N.R. / 4.0-6.8 -8.4	0	0	-.338		N.A.	4.3^{3}	0	335	90	N.A.
16	Anodic		22.5	6.0-5.7 -4.5 / 4.0-5.0 -8.2	0	0	-.338		N.A.	7.0^{3}	0	1500	150	N.A.
17	Anodic		23.8 - 21.8	9.1-8.7 -5.8 / 3.0-5.0 -3.4	0	0	-.444		N.A.	8.4^{3}	0	150	85	N.A.
18	Anodic		21.5 - 21.0	6.3-6.0 -6.3 / 2.5-2.1	0	0	-.440		N.A.	9.9^{3}	0	200	70	N.A.
19	Anodic		24.0 - 23.0	7-4.6 -2.2 / 7-4.7 -7.0	0	0	-.477	27	0 N.A.	8.0^{3}	.200	590	90	N.A.
20	Anodic		23.5 - 22.0	3.3-0.5 -0 / 4.0-3.9	0	6.8724* (16.8lb/ o.d.t.)	-.454		N.A.	3.0^{3}	.200	1500	70	N.A.
21	Anodic		23.0 - 20.7	3.1-0.2 -0 / 6.3-6.2 -5.8	0	7.4732 (18.3lb/ o.d.t.)	-.507		N.A.	3.5^{3}	.100	1200	170	N.A.

* Equivalent to 16.8 pounds per oven dry ton of wood pulp

TABLE 20: Experimental Potentiostatic Results (Cont.)

RUN	Direction	Curve Shape	TEMP (°C)	D.O (ppm) / pH	Agitation Level	Na_2SO_3 Added (g)	E_{CORR} volts	i_{CORR} ($\mu A/cm^2$)	i_D ($\mu A/cm^2$)	i_{cr} ($\mu A/cm^2$)	E_{pp} volts	i_{pass} ($\mu A/cm^2$)	β_a (mV/dec.)	β_c (mV/dec.)
22	Anodic		22.8 / 21.9	2.1-0.1 -0.0 / 6.5-6.4 -6.1	0	7.7157 (18.9lb/o.d.t)	-.533		N.A.	3.3^3	.050	1100	125	N.A.
23	Anodic		23.9 / 23.1	2.7-0.2 -0.0 / 7.6-7.6 -7.4	0	15.36 (37.6lb/o.d.t)	-.532		N.A.	2.5^3	.050	860	110	N.A.
24	Anodic		23.5 / 22.4	7-0.4 -0.0 / 7.4-7.1 -7.8	0	0.6910 (1.68lb/o.d.t)	-.552	5.2	N.A.	not able to read			115	N.A.
25	Cathodic		24.1 / 22.1	7-0.4 -0.0 / 7.4-7.4 -7.21	0	0.6910	-.552	5.2	3.3^3	N.A.	N.A.	N.A.	N.A.	275
26	Anodic		22.0 / 21.4	1.8-1.0 -5.0 / 6.3-3.0 -5.7	3	.5714	-.497	88	N.A.	not able to obtain from graph			135	N.A.
27	Cathodic		22.7 / 21.8	7-4.7 -4.1 / 6.4-3.6 -3.7	3	.0684	-.312	88	1.1^3	N.A.	N.A.	N.A.	N.A.	85

TABLE 21: Experimental Potentiostatic Results (Cont.)

RUN	Direction	Curve Shape	TEMP (°C)	D.O (ppm) / pH	Agitation Level	Na_2SO_3 Added (g)	E_{CORR} volts	i_{CORR} ($\mu A/cm^2$)	i_D ($\mu A/cm^2$)	i_{cr} ($\mu A/cm^2$)	E_{pp} volts	i_{pass} ($\mu A/cm^2$)	β_a (mV/dec.)	β_c (mV/dec.)
29	Anodic		23.1 / 22.3	4.6-4.7-5.3 / 6.9-6.0-6.8	3	0.0058	-.177	0.8	N.A.	not able to obtain from graph			105	N.A.
30	Cathodic		23.8 / 22.8	5.8-5.9-4.7 / 6.9-6.4-6.5	3	0.0053	-.202	0.8	530	N.A.	N.A.	N.A.	N.A.	150
31	Anodic		22.0 / 21.5	7.9-6.5-6.0 / 7.0-6.8-6.0	0	0.0041	-.233		N.A.	not able to obtain from graph			80	N.A.
32	Anodic		22.5	0.25-0.0 / 6.6-6.6-4.2	3	8.18	-.569	82	N.A.	1.7^4	0.650	3.6^3	65	N.A.
33	Cathodic		23.8 / 23.0	1.6-2.0-0.0 / 6.5-6.0-3.7	3	8.18	-.568	82	3.0^4	N.A.	N.A.	N.A.	N.A.	125
34	Anodic		23.8 / 22.0	2.9-2.0-0 / 6.5-6.3-4.4	3	12.2	-.548		N.A.	2.14	0.350	5.6^3	135	N.A.

TABLE 22: Variation of Corrosion Characteristics with pH.

RUN	pH after 55 min	i_{cr} ($\mu A/cm^2$)	E_{pp} (volts)	i_{pass} ($\mu A/cm^2$)	β_a (mV/dec)	D.O. (ppm)
18	2.12	9.9^{3}*	-.050	200	70	6.3
17	2.8	8.4^{3}	0.0	150	85	9.1
12	4.26	1.1^{4}	-.100	4000	95	N.R.+
11	4.56	1.4^{4}	0.0	4000	125	N.R.
19	4.68	8.0^{3}	-.300	590	90	4.6
16	5.0	7.0^{3}	-.050	1500	150	6.0
13	5.5	8.0^{3}	-.150	2400	100	N.R.
14	5.8	6.0^{3}	-.200	2600	120	N.R.
15	6.8	4.3^{3}	-.250	335	90	N.R.

* $9.9^{3} = 9.9 \times 10^{3}$ + N.R. = Not Recorded

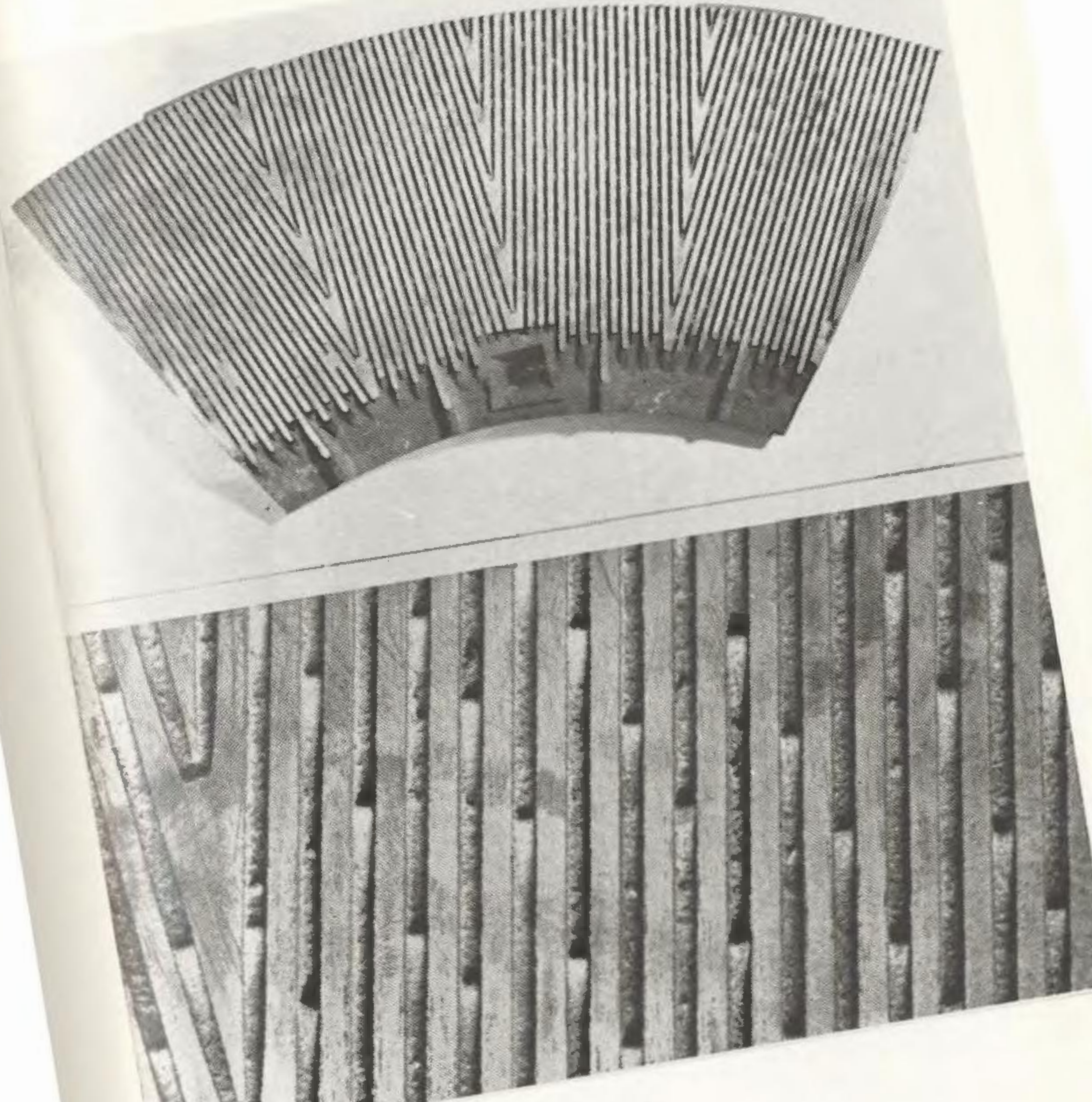


Fig. 1. Basic Plate Pattern

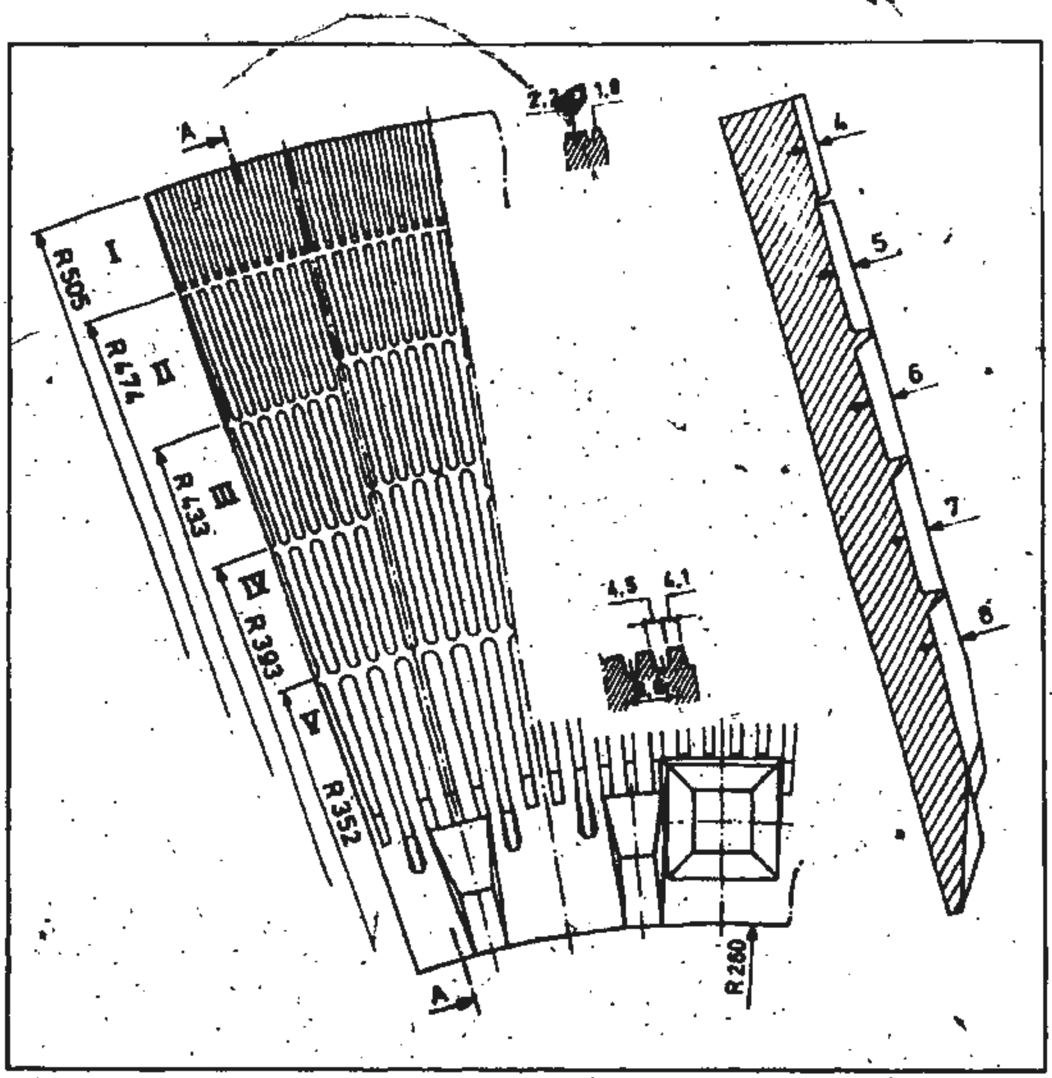


Fig. 2. New Exponential Refiner Plate, Model FPPRI

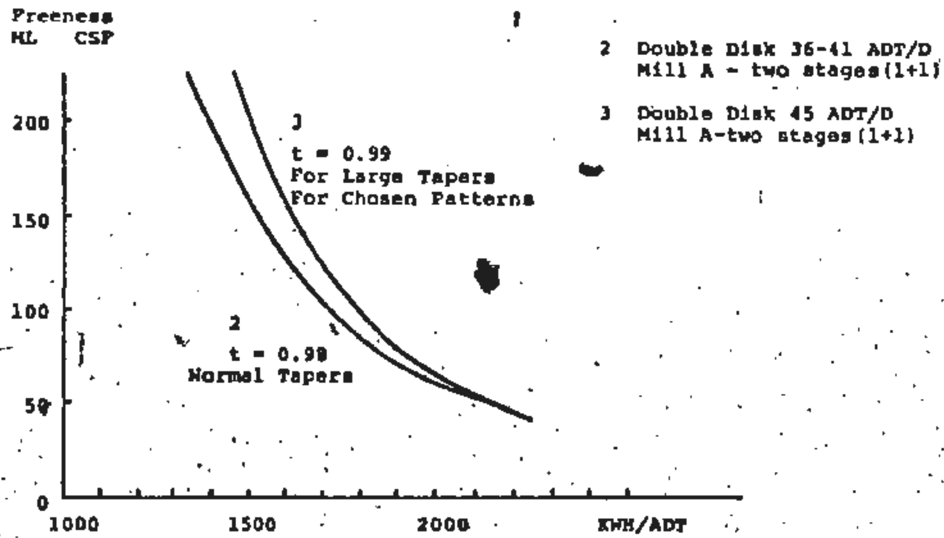


Fig. 3. Freeness vs. energy consumption (KWh per air-dry metric ton) with different plate tapers.

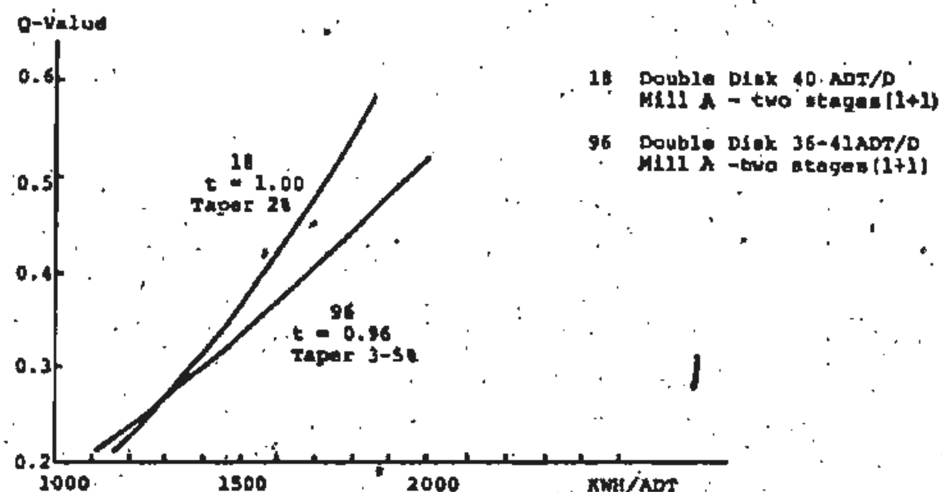


Fig. 4. Q-value vs. energy consumption (KWh per air-dry metric ton) with different plate tapers.

7

Double Disk two stages (1+1)
Different plate tapers

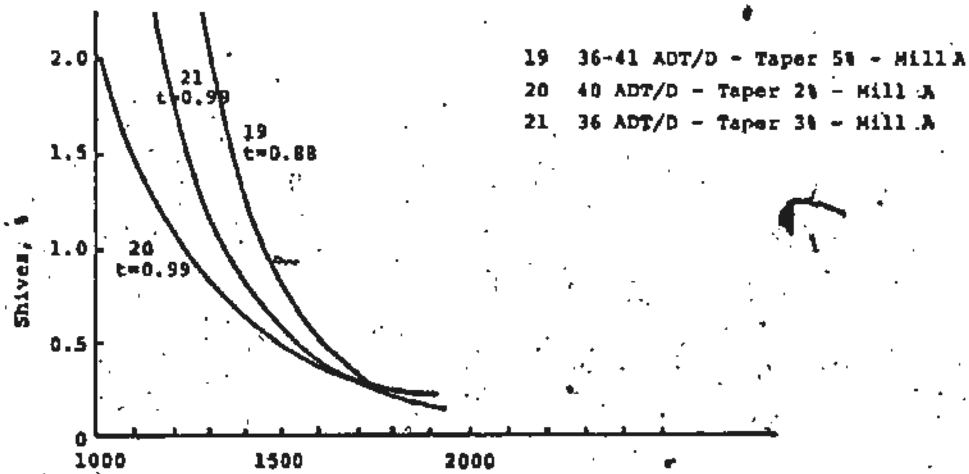


Fig. 5. Shives content vs. energy consumption (KWh per air-dry metric ton) with different plate tapers.

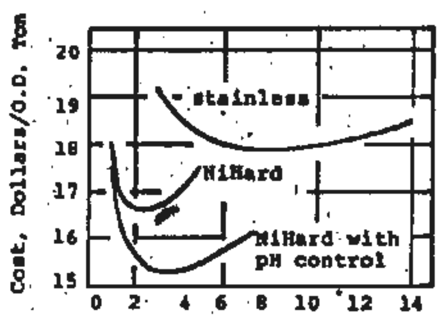


Fig. 6. Plate life associated cost vs. plate life; stainless steel plates; Nihard plates; Nihard with pH control.

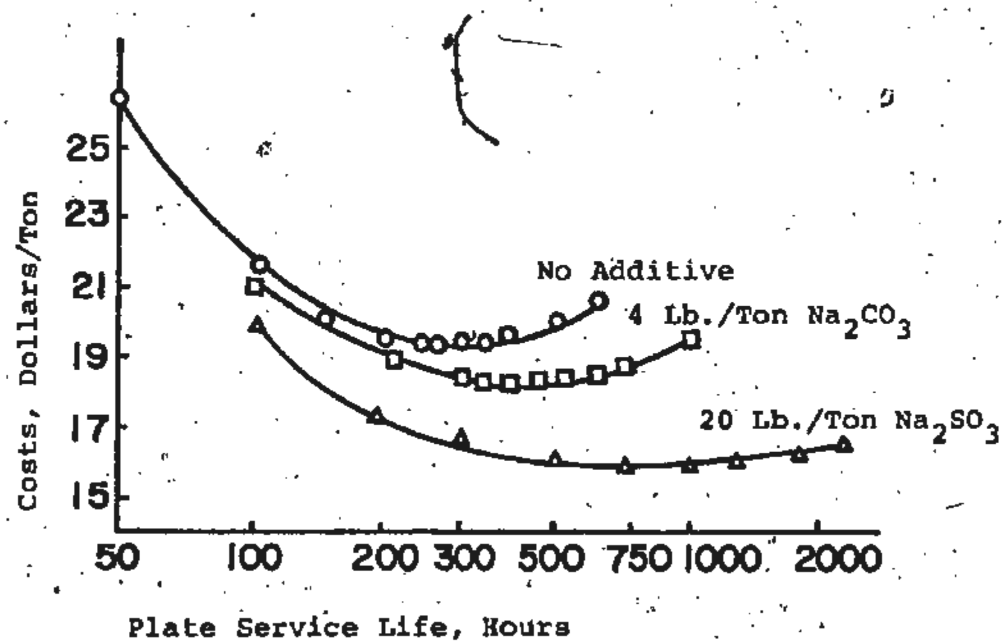


Fig. 7. Plate life associated costs - effect of additives.

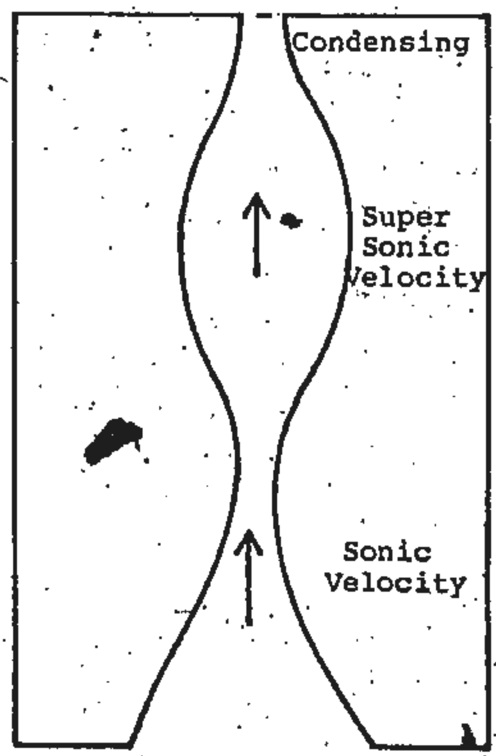


Fig. 8. Converging-Diverging plate design to permit super sonic escape of steam (not to scale).

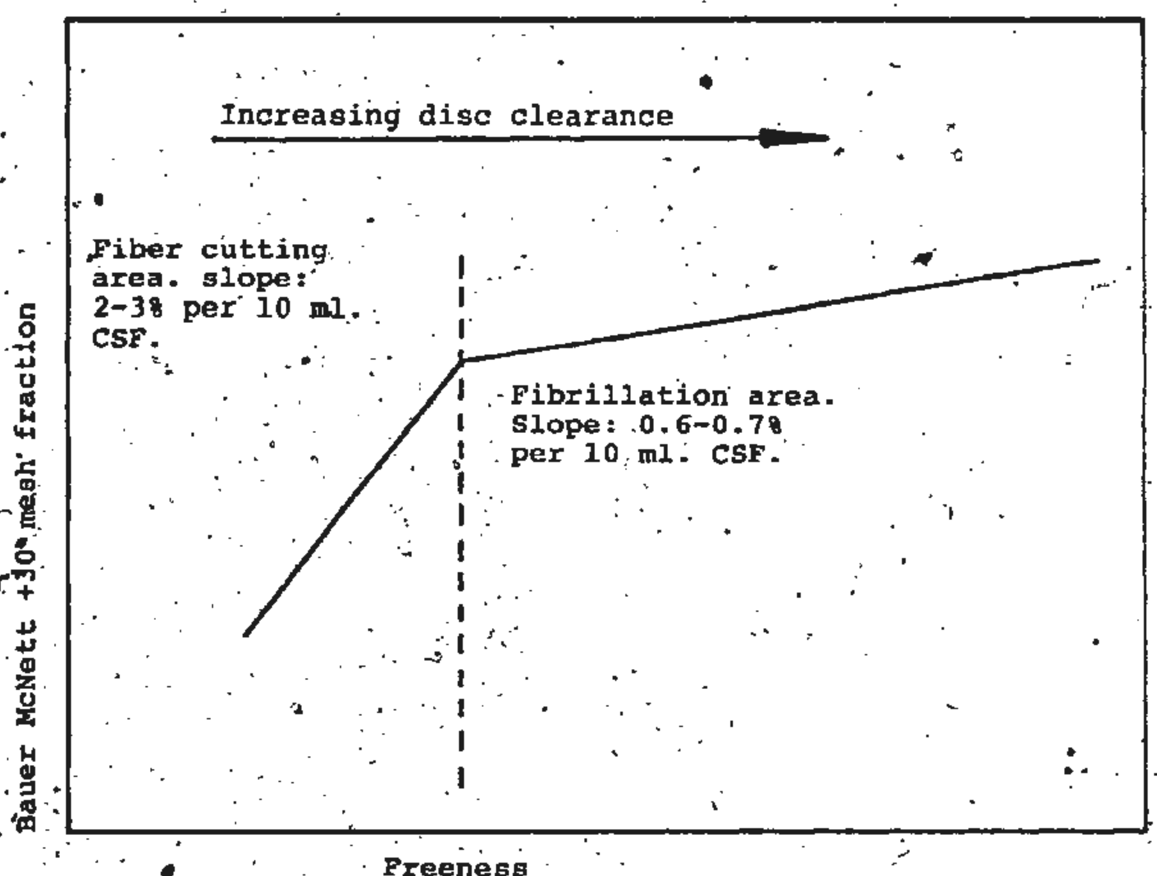


Fig. 9. Long fiber content versus freeness. Principal effect of changed disc clearance.

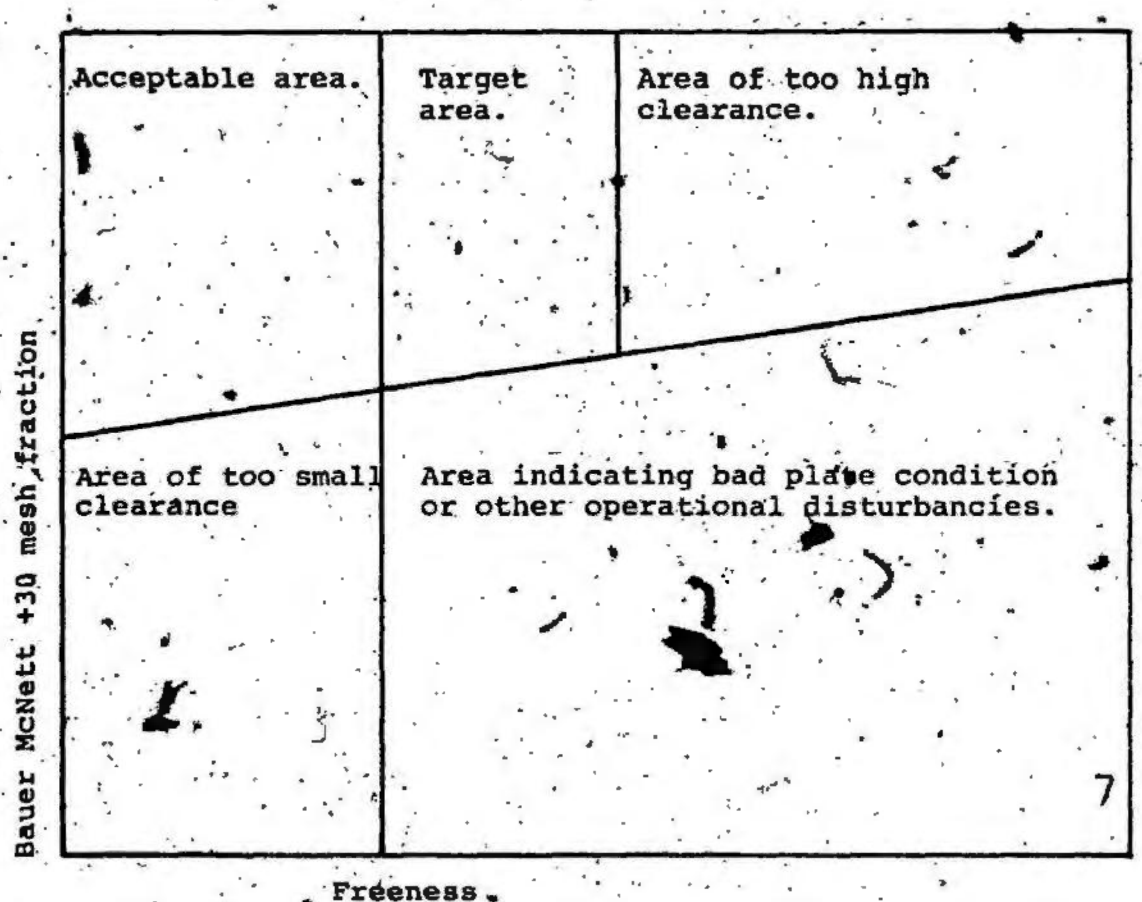


Fig. 10. Principal design of refiner operation and plate condition control graph.

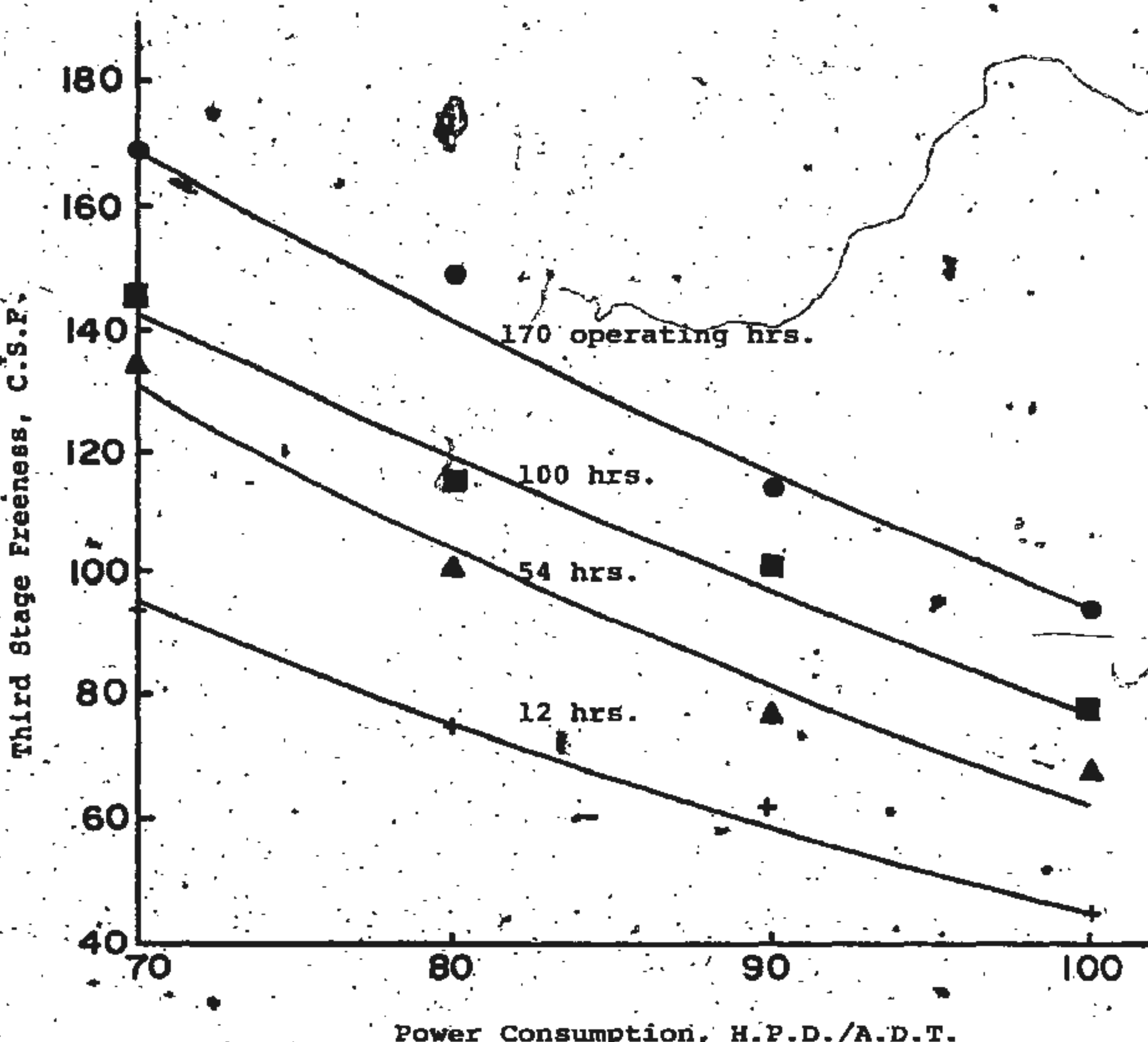


Fig. 11. The effect of normal plate wear on freeness and power: three-stage refining.

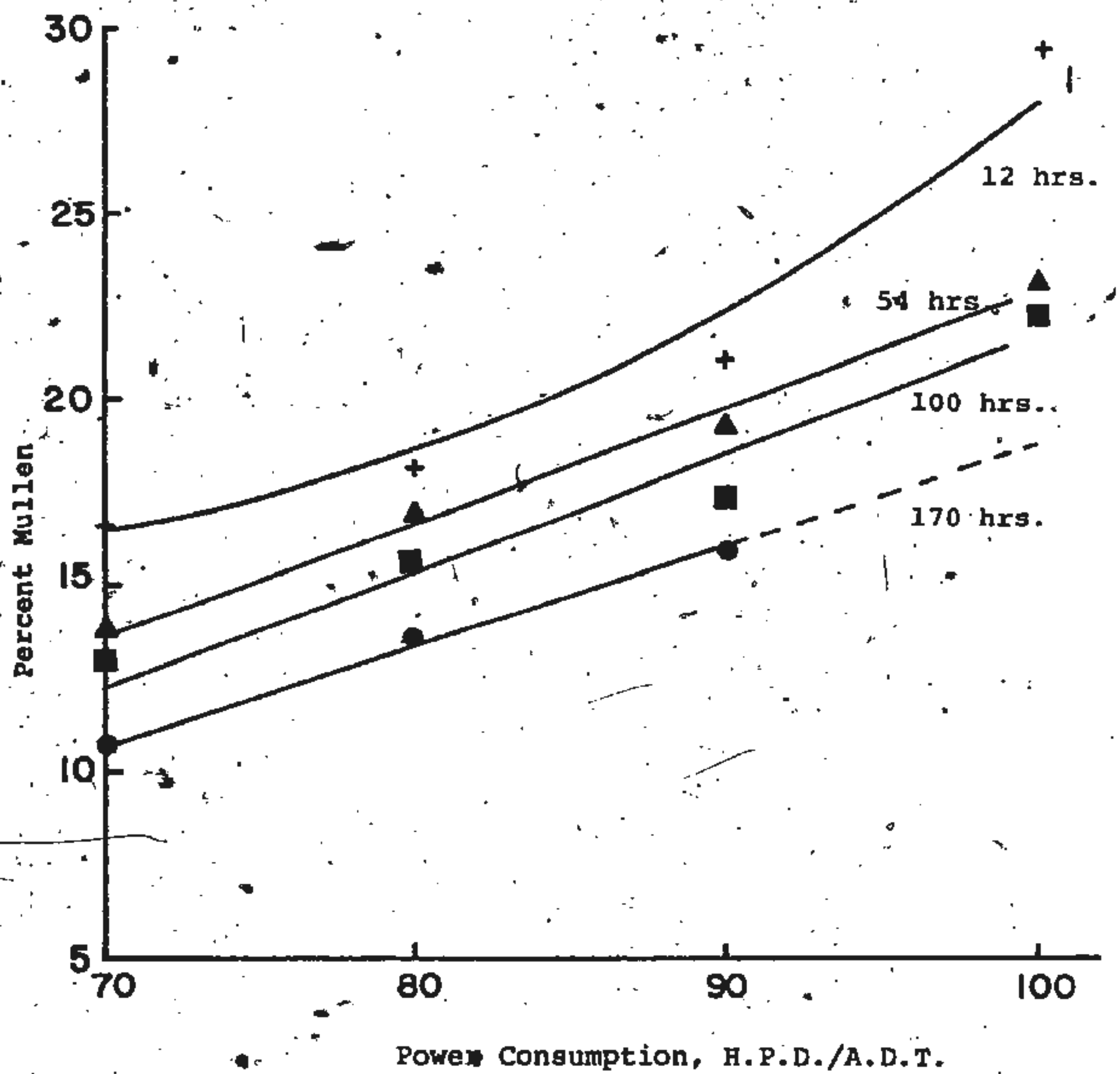


Fig. 12. Effect of normal plate wear on percentage mullen and power: three-stage refining.

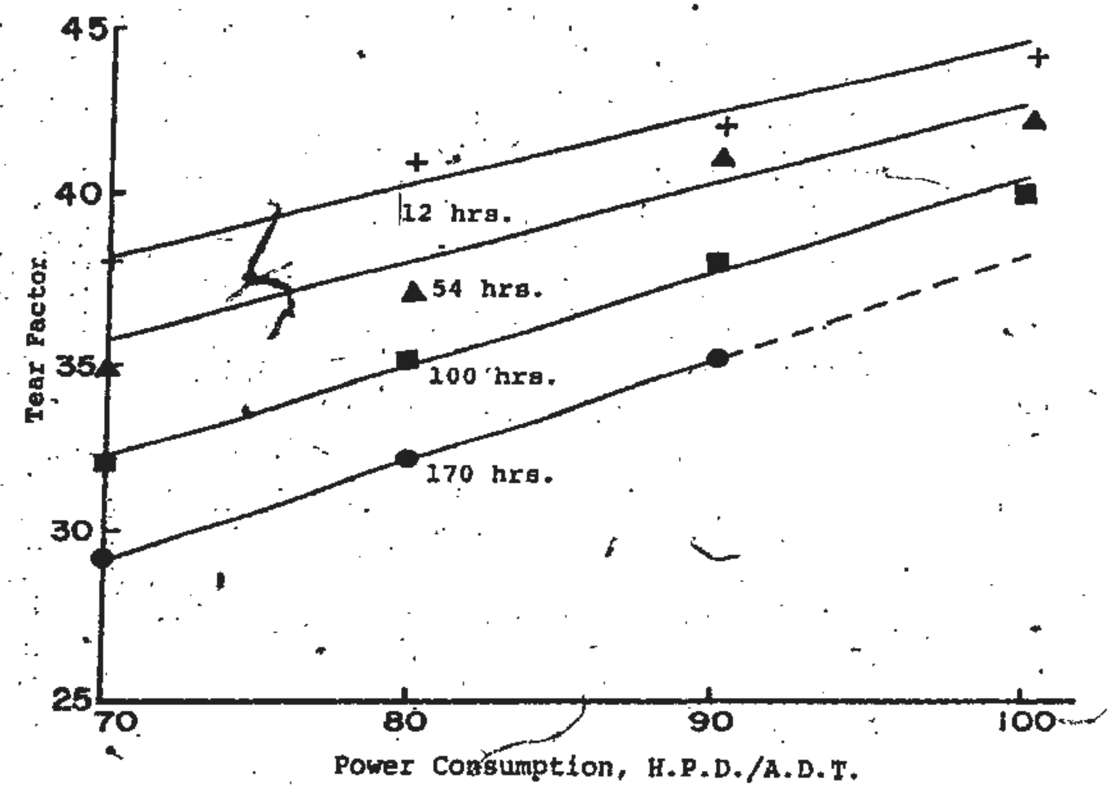


Fig. 13. Effect of normal plate wear on tear factor and power: three-stage refining.

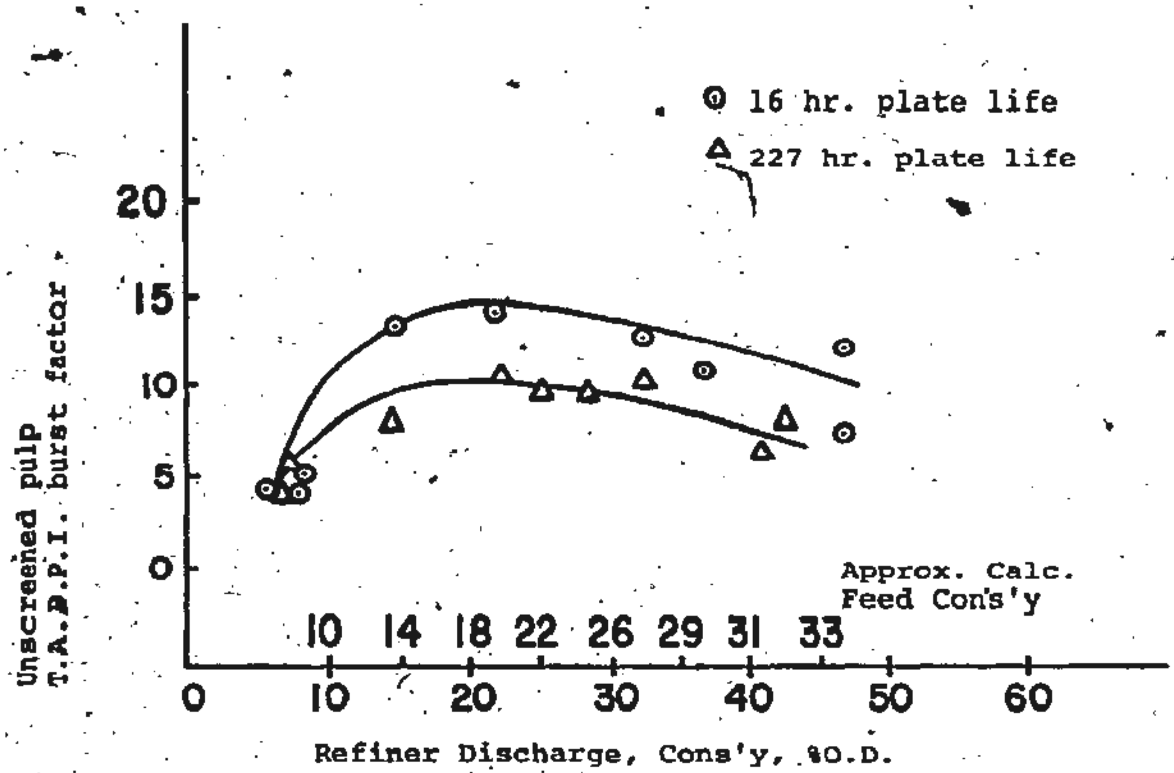


Fig. 14. Effect of refining consistency on burst factor.

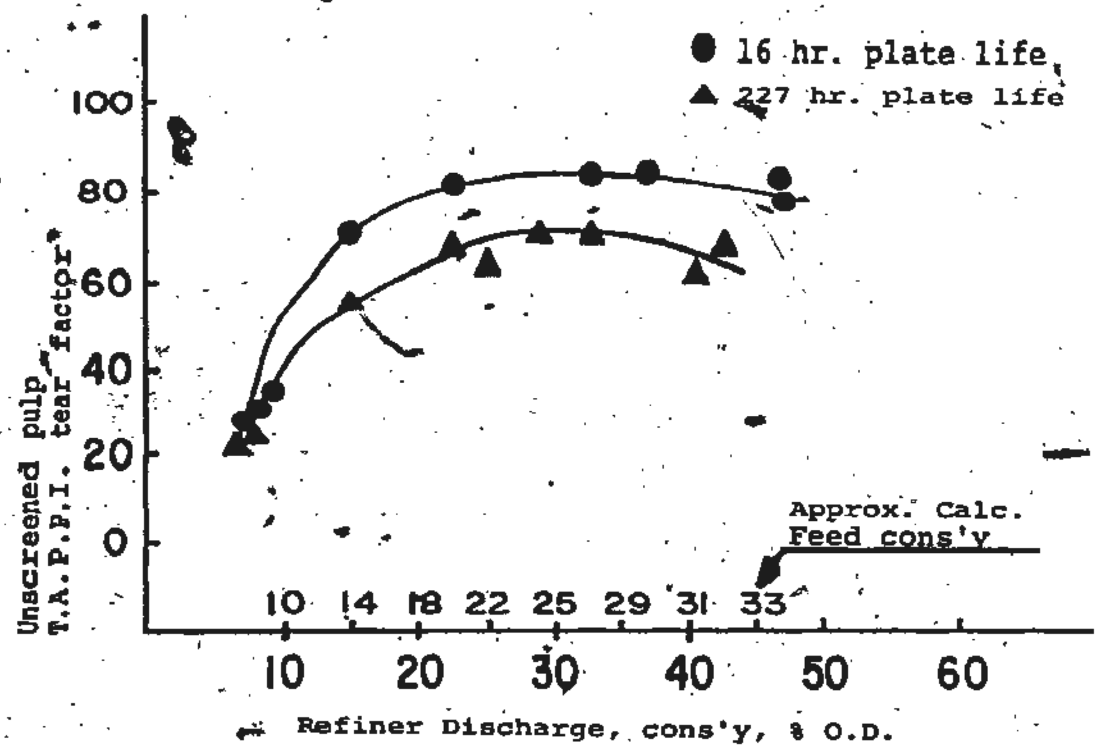


Fig. 15. Effect of refining consistency of tear factor.

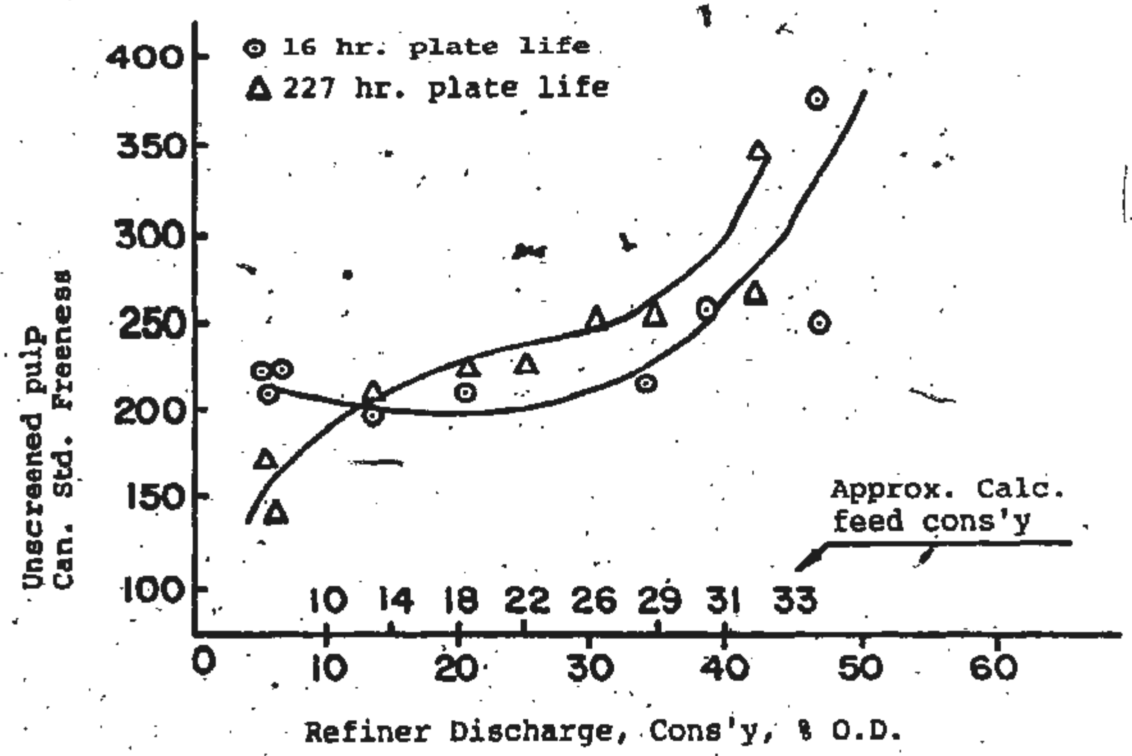


Fig. 16. Effect of refining consistency of freeness.

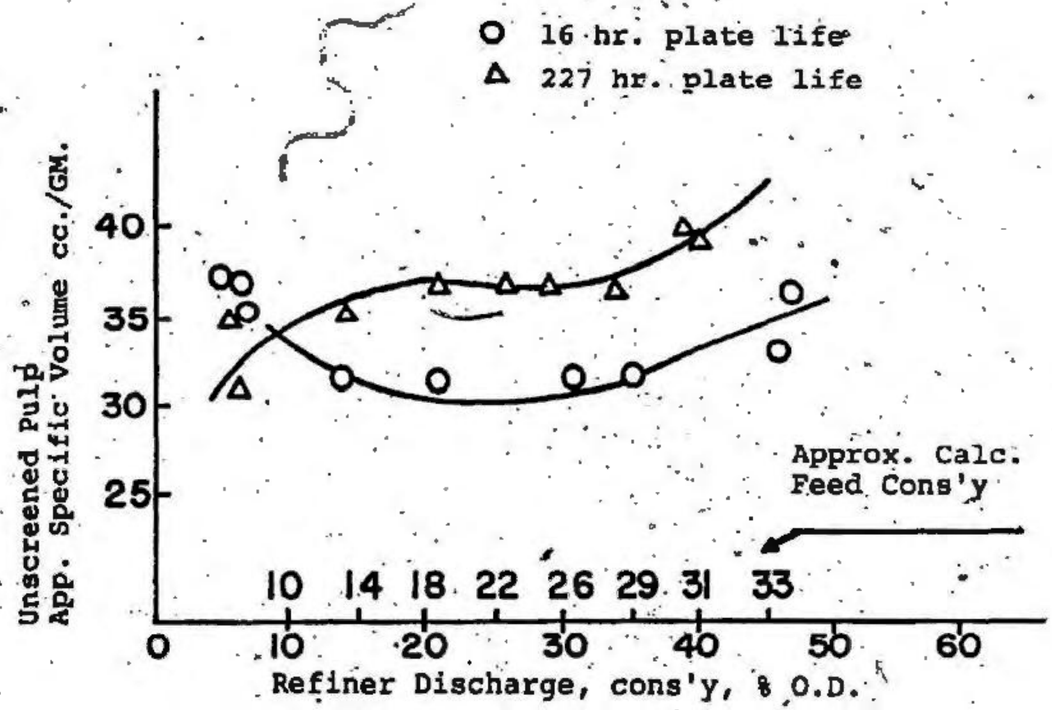


Fig. 17. Effect of refining consistency on specific volume.

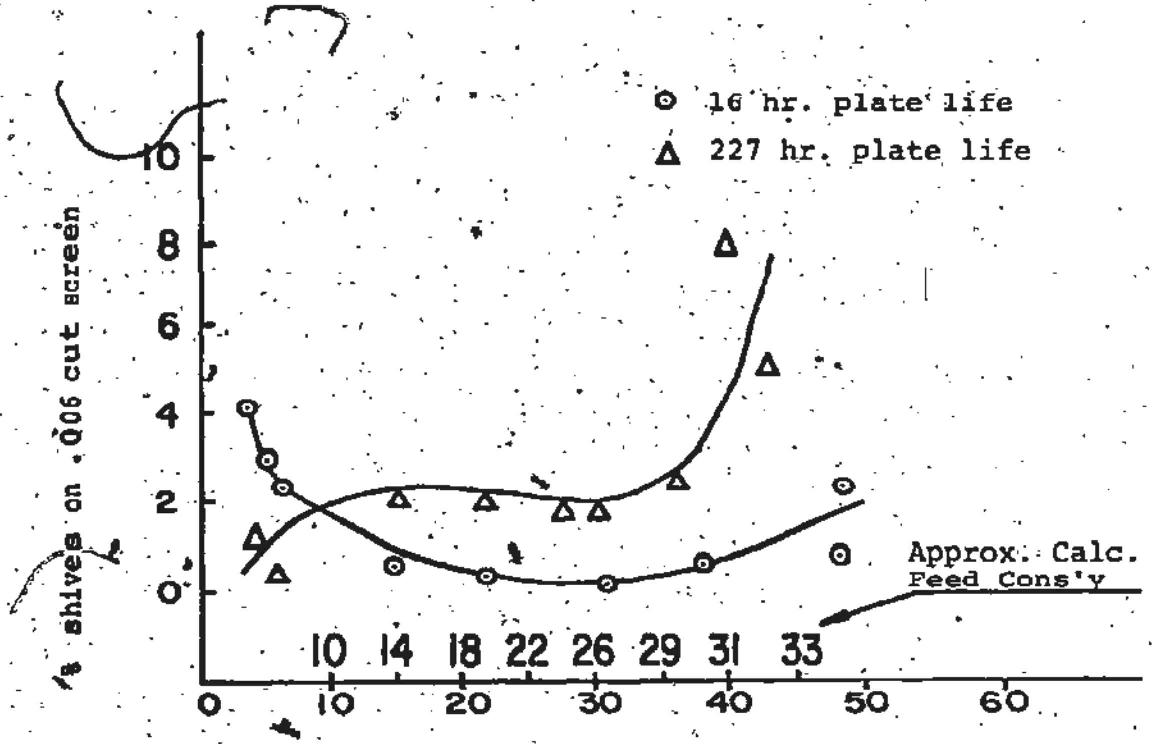


Fig. 18. Effect of refining consistency of shive content.

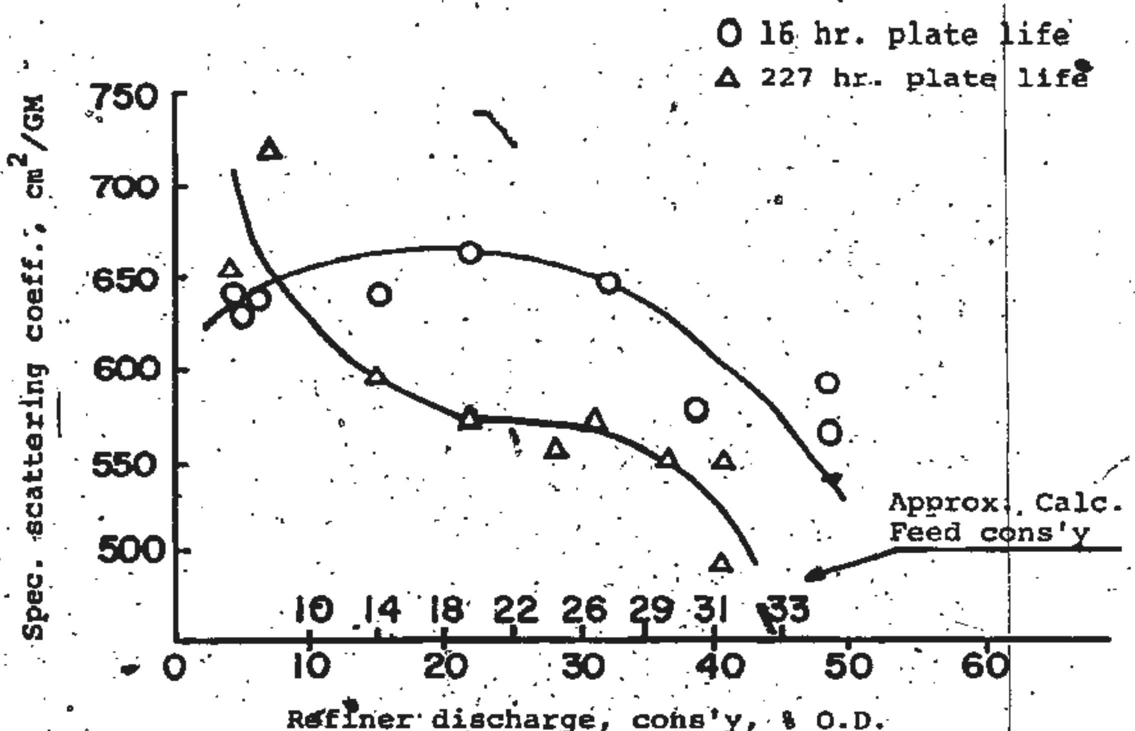


Fig. 19. Effect of refining consistency on specific scattering coefficient.

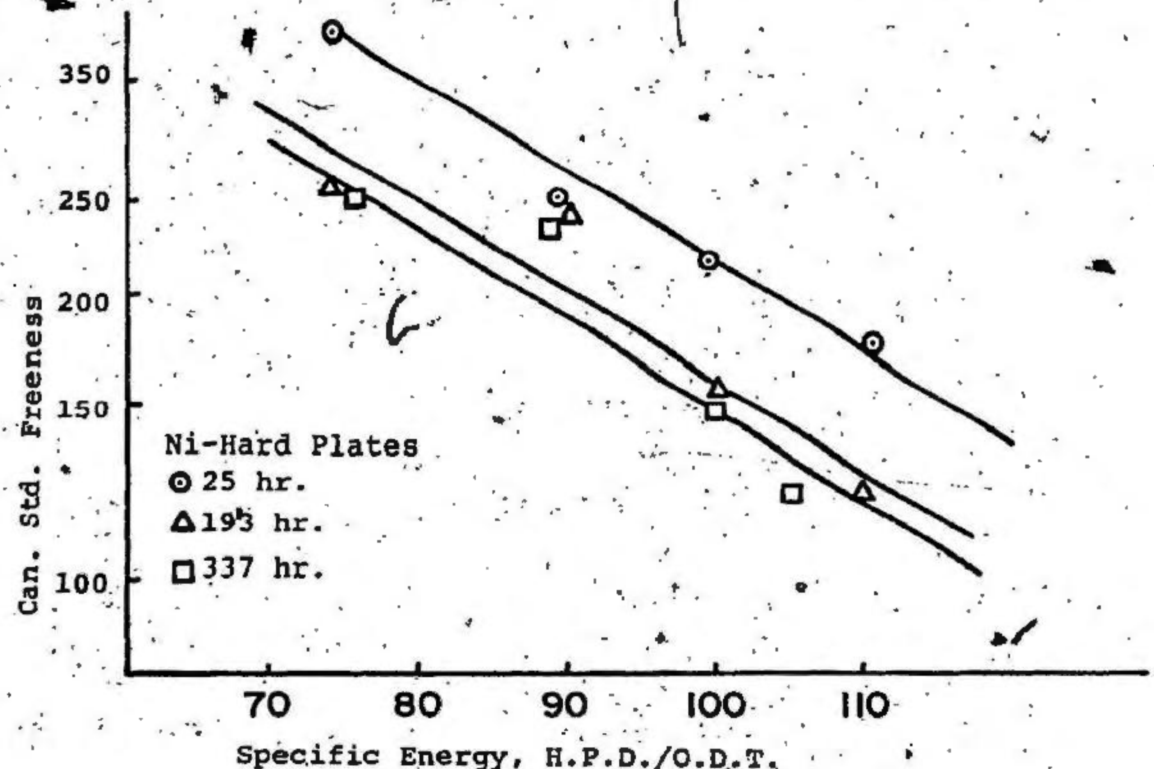


Fig. 20. Effect of plate wear on freeness.

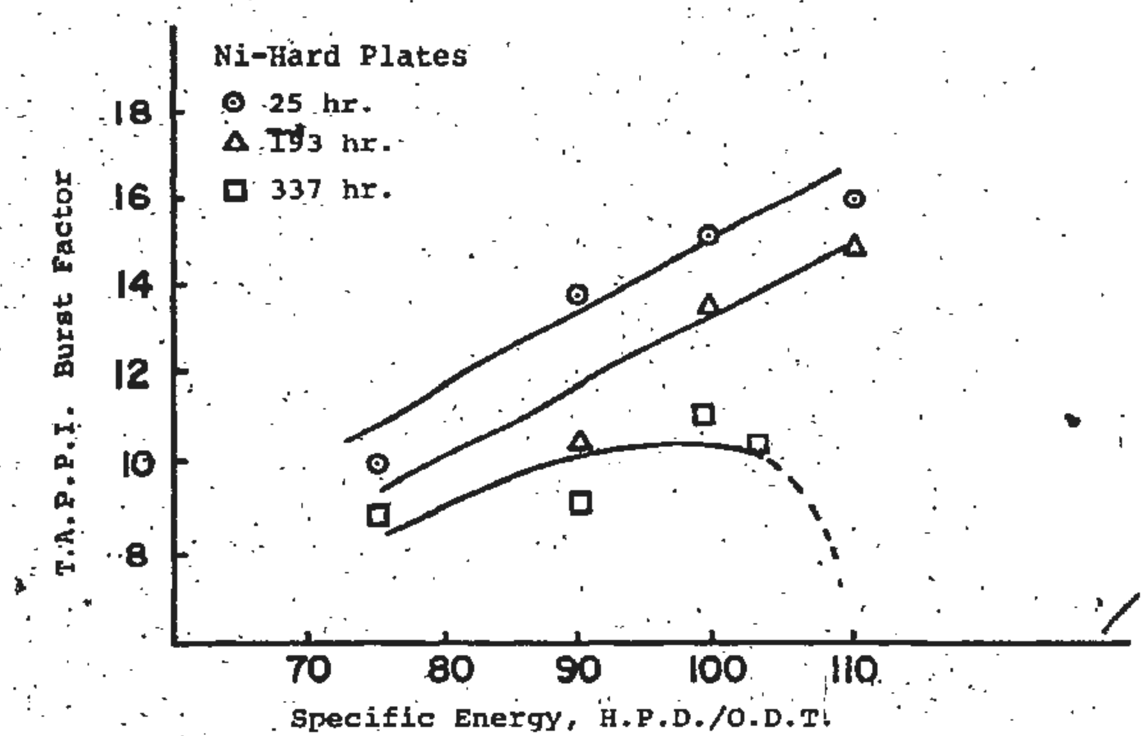


Fig. 21. Effect of plate wear on burst factor.

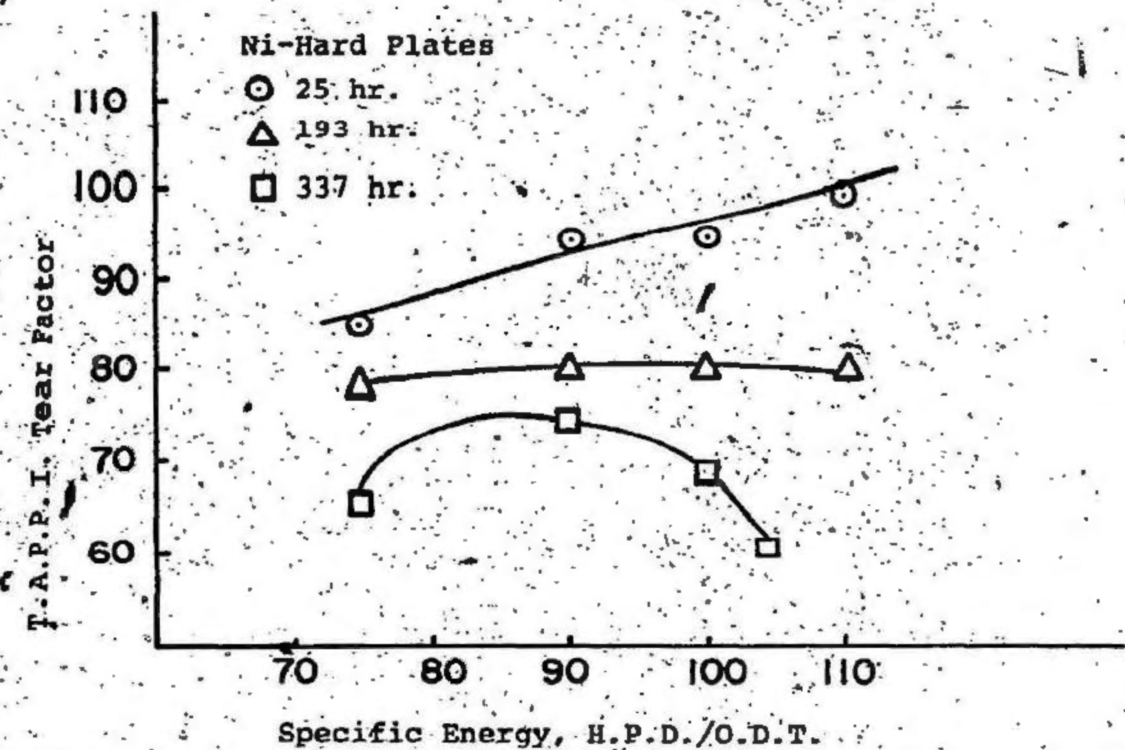


Fig. 22. Effect of plate wear on tear factor

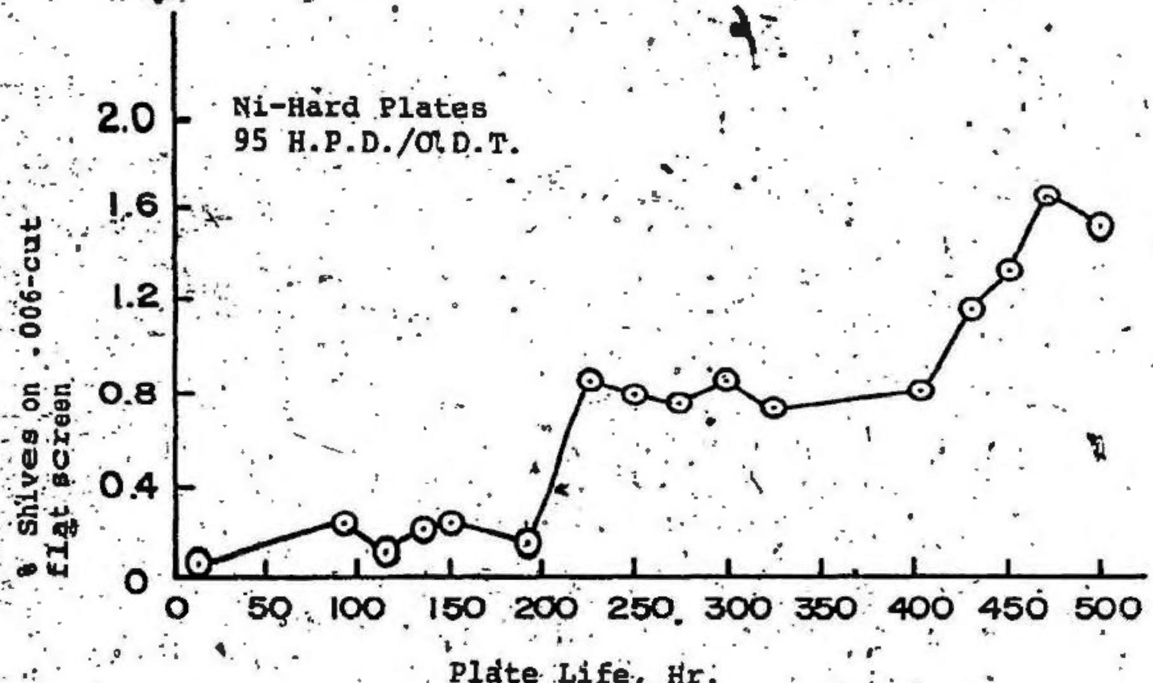


Fig. 23. Effect of plate wear on shive content.

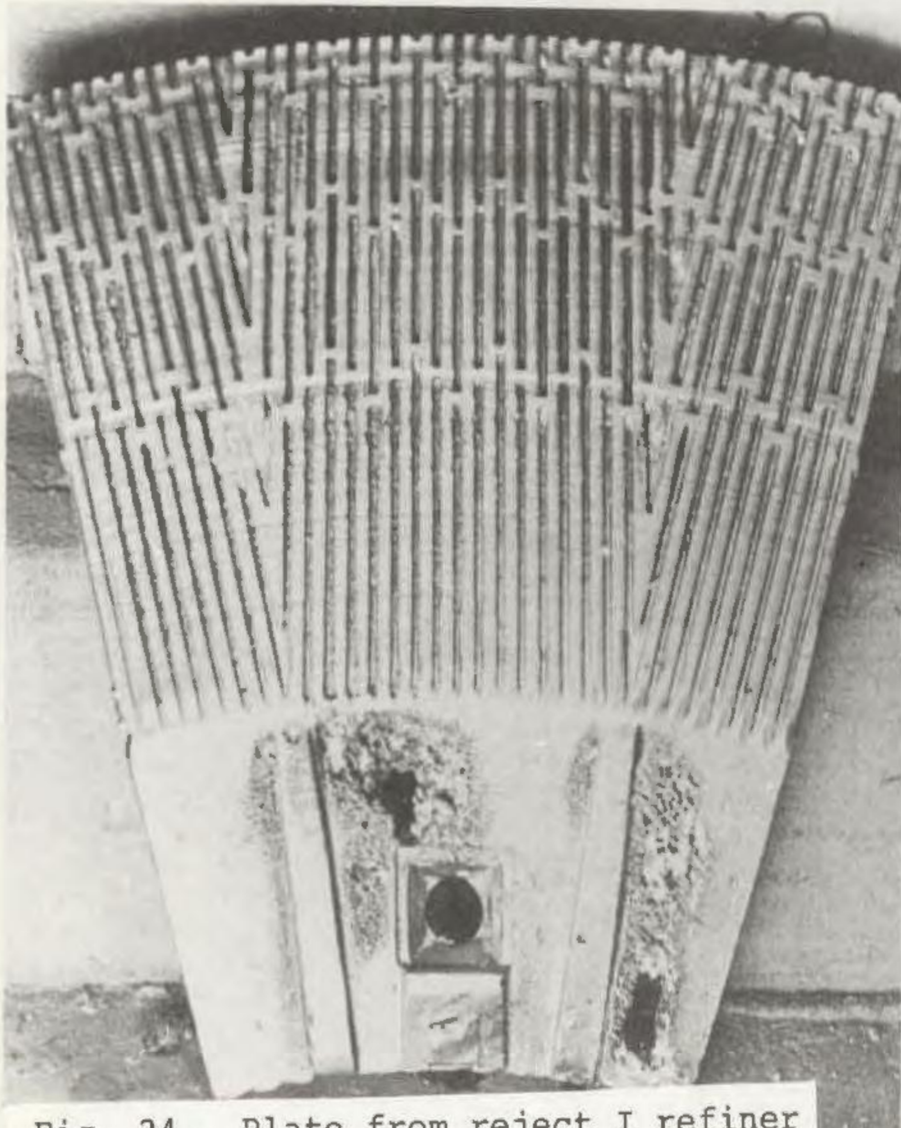


Fig. 24. Plate from reject I refiner after 383 hours; Uddeholm; 48Co 23; Taper 2%

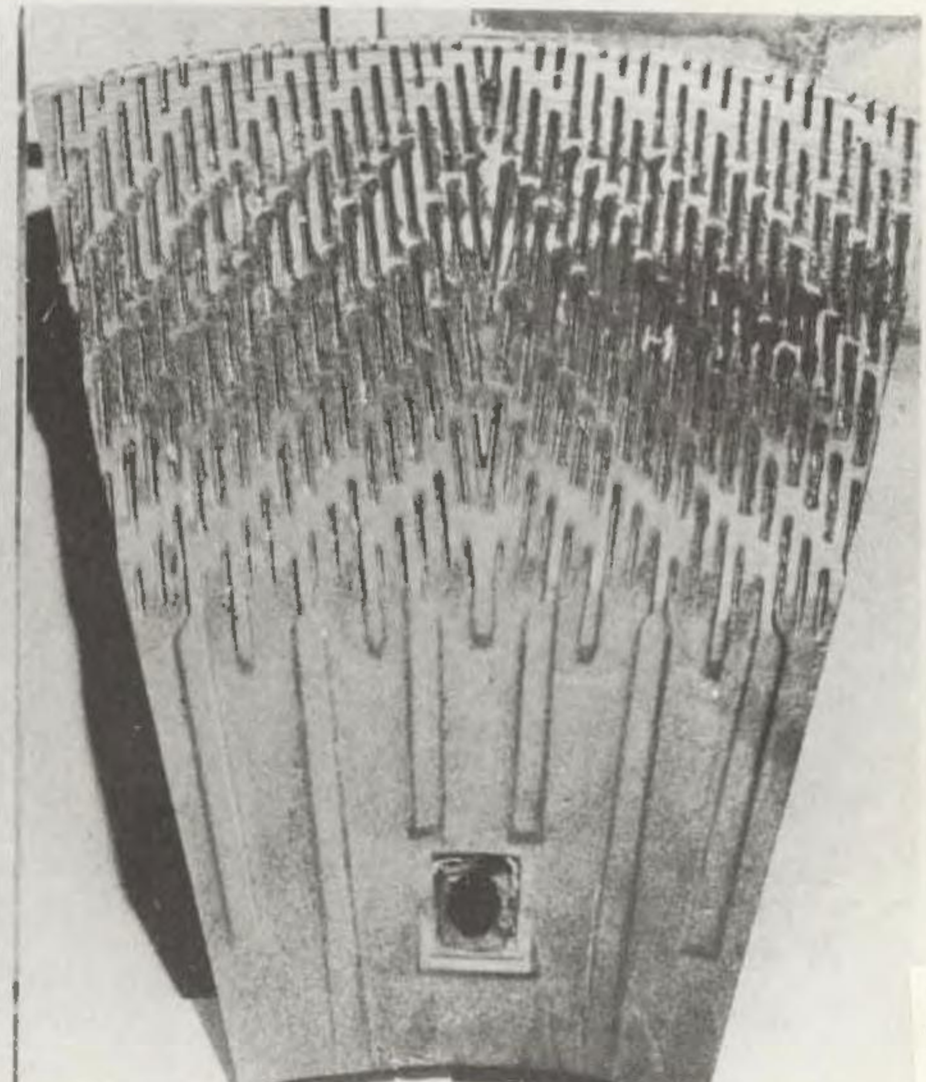


Fig. 25. Plate from sawdust I refiner after 320 hours; HI-MOLY; 48154; Taper 3%

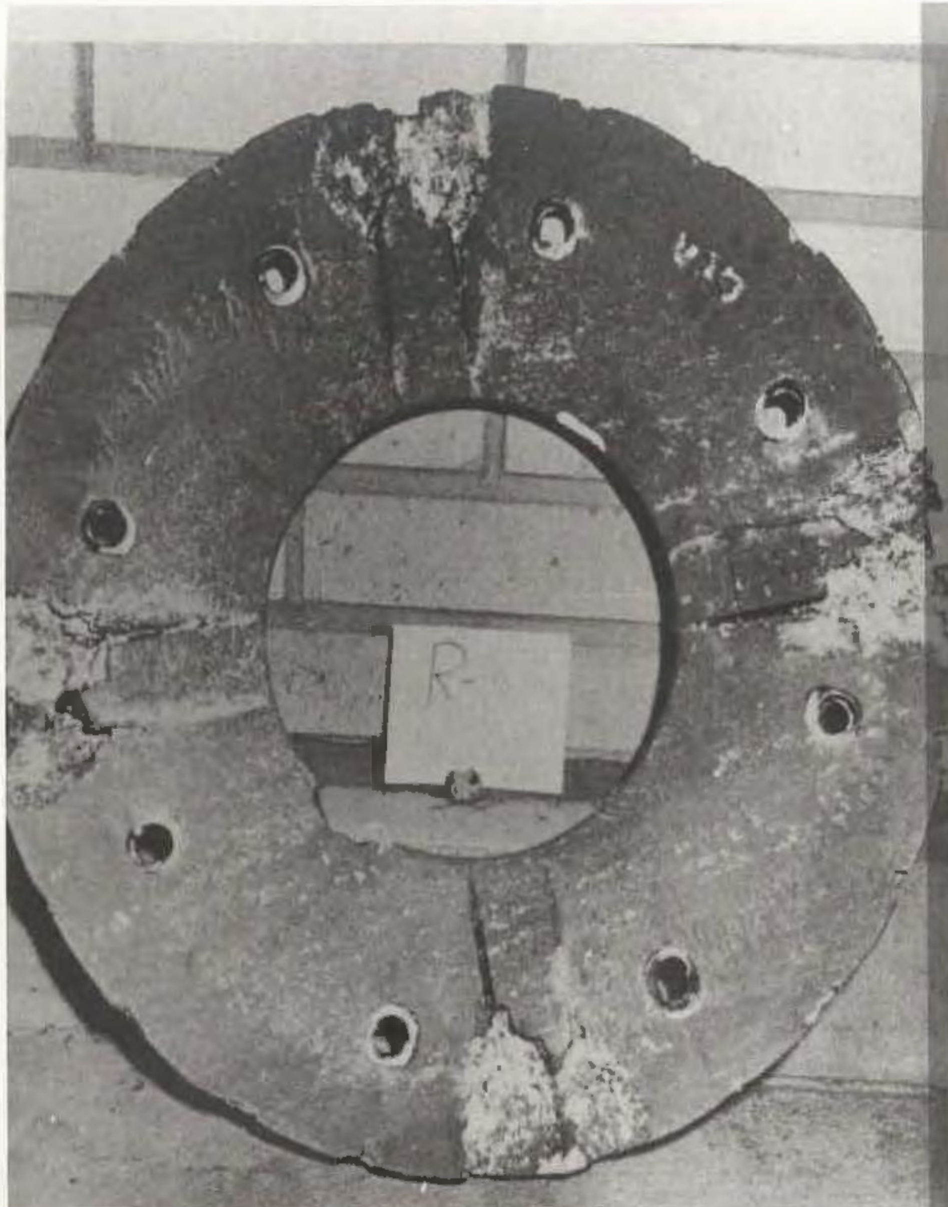


Fig. 26. Wearing plate from reject I refiner; Bauer 488

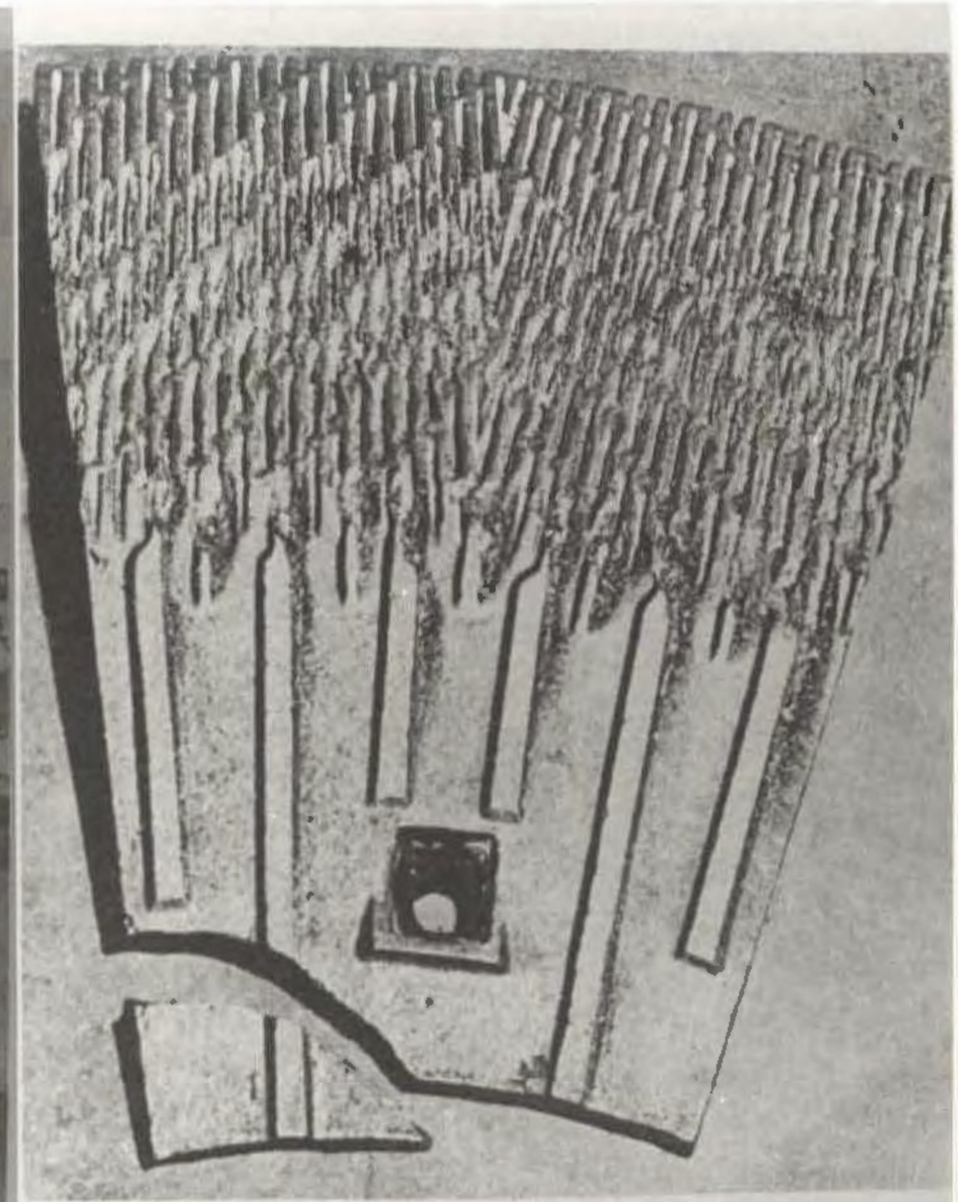


Fig. 28. Plate from sawdust I refiner after 307 hours; X-Metal; 48154; Taper 2%

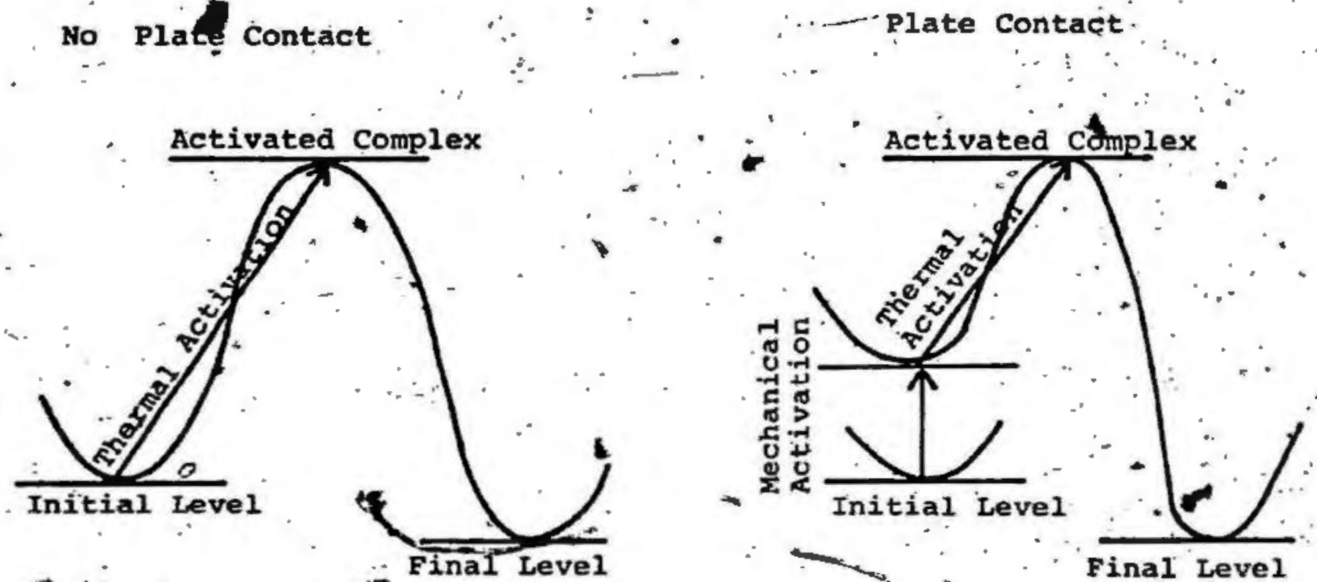


Fig. 27. Illustration of Heidemeyer's Theory: Mechanical action reduces amount of thermal energy necessary to cause corrosion.

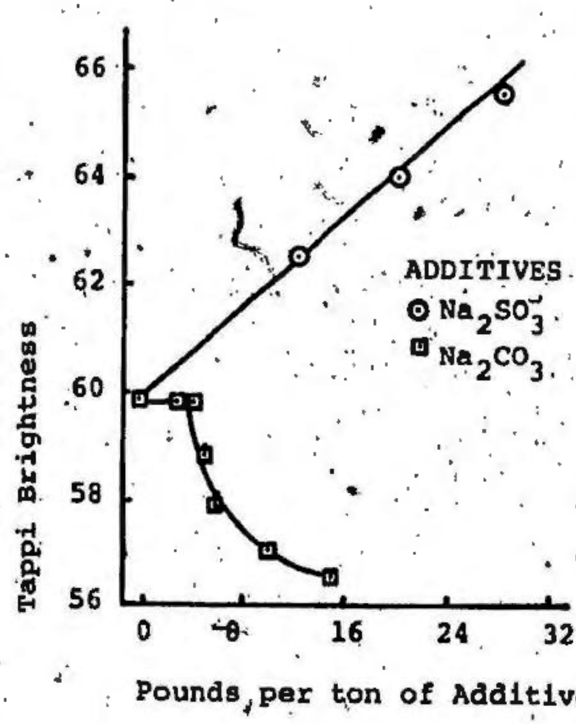
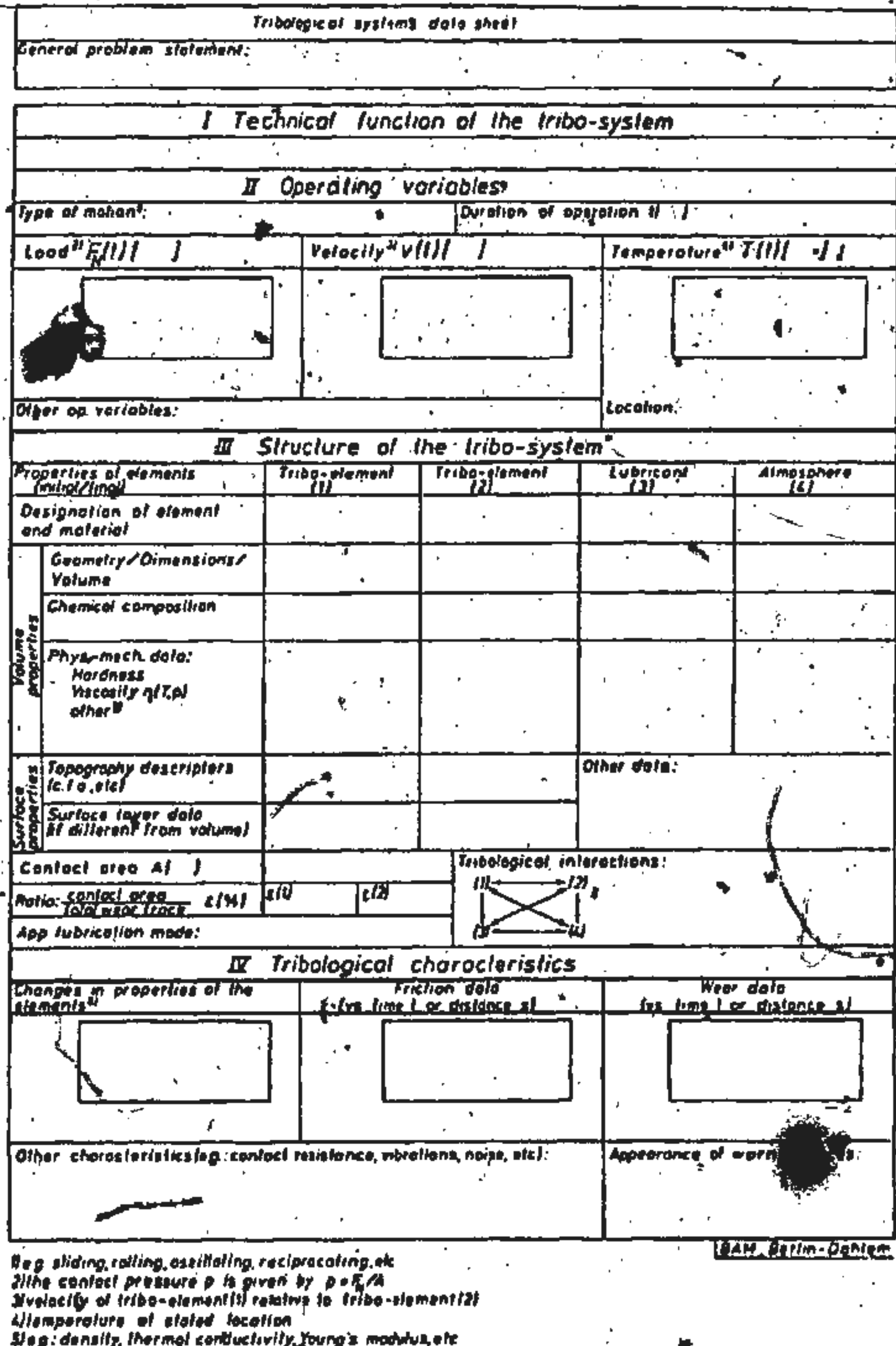


Fig. 29. Effects of sodium sulfite and soda ash on brightness



Tribological systems data sheet

General problem statement:

I Technical function of the tribo-system

II Operating variables

Type of motion[1]:		Duration of operation t/ [ ]
Load[2] $F_N(t)$/ [ ]	Velocity[3] $v(t)$/ [ ]	Temperature[4] $T(t)$/ [ ]
Other op. variables:		Location:

III Structure of the tribo-system

Properties of elements (initial/final)		Tribo-element (1)	Tribo-element (2)	Lubricant (3)	Atmosphere (4)
Designation of element and material					
Volume properties	Geometry/Dimensions/Volume				
	Chemical composition				
	Phys.-mech. data: Hardness, Viscosity $\eta(T,p)$, other[5]				
Surface properties	Topography descriptors (c.l.a., etc)			Other data:	
	Surface layer data (if different from volume)				
Contact area A/ [ ]					
Ratio: $\frac{\text{contact area}}{\text{total wear track}}$ ε(%)		ε(1)	ε(2)		
App. lubrication mode:					

Tribological interactions: (1) (2) (3) (4)

IV Tribological characteristics

Changes in properties of the elements[4]	Friction data f (vs. time t or distance s)	Wear data (vs. time t or distance s)
Other characteristics (e.g. contact resistance, vibrations, noise, etc):		Appearance of worn surfaces:

BAM, Berlin-Dahlem

1) e.g. sliding, rolling, oscillating, reciprocating, etc

2) the contact pressure p is given by $p = F_N/A$

3) velocity of tribo-element (1) relative to tribo-element (2)

4) temperature of stated location

5) e.g.: density, thermal conductivity, Young's modulus, etc

Fig.30. Tribological Systems Data Sheet

Tribological systems data sheet

General problem statement: to characterize a 42 in. single rotating disk Sprout Waldron refiner in operation

I Technical function of the tribo-system 3.2

to convert wood chips into refiner mechanical pulp

II Operating variables 3.3

Type of motion[1]	Duration of operation t /
Sliding(Rotational)	Continuous

Load[1] $F_N(t)$ [ ]	Velocity[3] $v(t)$ [rpm]	Temperature[4] $T(t)$ [°C]
Section 3.3.3	Section 3.3.4	Section 3.3.5
Other op. variables: Pressure 3.3.6		Location: over length of refiner plate

III Structure of the tribo-system 3.4

Properties of elements (initial/final)	Tribo-element (1) Sliding	Tribo-element (2) Stationary	Lubricant (3)	Atmosphere (4)
Designation of element and material	Ni-hard Refining Plate	Ni-hard Refining Plate	Water, Steam, Na_2SO_3, Wood Chips	
Volume properties: Geometry/Dimensions/Volume	Section 3.4.1	Section 3.4.1	Section 3.4.2	
Volume properties: Chemical composition	Section 3.4.4	Section 3.4.4	Section 3.4.3	
Volume properties: Phys.-mech. data: Hardness, Viscosity $\eta(T,p)$, other[5]	Section 3.4.4	Section 3.4.4	Section 3.4.5	
Surface properties: Topography descriptors (c.l.a., etc.)	Fine and Int. bars were wet surface ground - edges are dry ground		Other data: Section 3.4.6	
Surface properties: Surface layer data (if different from volume)	Plates need to be inspected with micro hardness tester			

Contact area $A(t)$	Section 3.4.7		Tribological interactions:
Ratio: contact area / total wear track ε (%)	ε(1) Fig. 52	ε(2) Fig. 52	(1) ↔ (2), (3) — Section 3.4.9
App. lubrication mode: Section 3.4.8			

IV Tribological characteristics

Changes in properties of the elements[1]	Friction data (vs time t or distance s)	Wear data (vs time t or distance s)
Section 3.5.1	Section 3.5.2	Section 3.5.3

Other characteristics (e.g.: contact resistance, vibrations, noise, etc.): Plates are removed when the cost/ad.t. versus plate life reaches a minimum value. Also can be removed if "blue glass" reveals a large proportion of shive.

Appearance of worn surfaces:
- tongue & groove scoring
- transfer of metal
- wedge formation
- corrosion on leading edge
- E.C.H.

BAM, Berlin-Dahlem

1) e.g. sliding, rolling, oscillating, reciprocating, etc.
2) the contact pressure p is given by $p = F_N/A$
3) velocity of tribo-element (1) relative to tribo-element (2)
4) temperature at stated location
5) e.g.: density, thermal conductivity, Young's modulus, etc.

Fig. 31 Tribological Systems Data Sheet Containing Data for a Single Rotating Disk Refiner

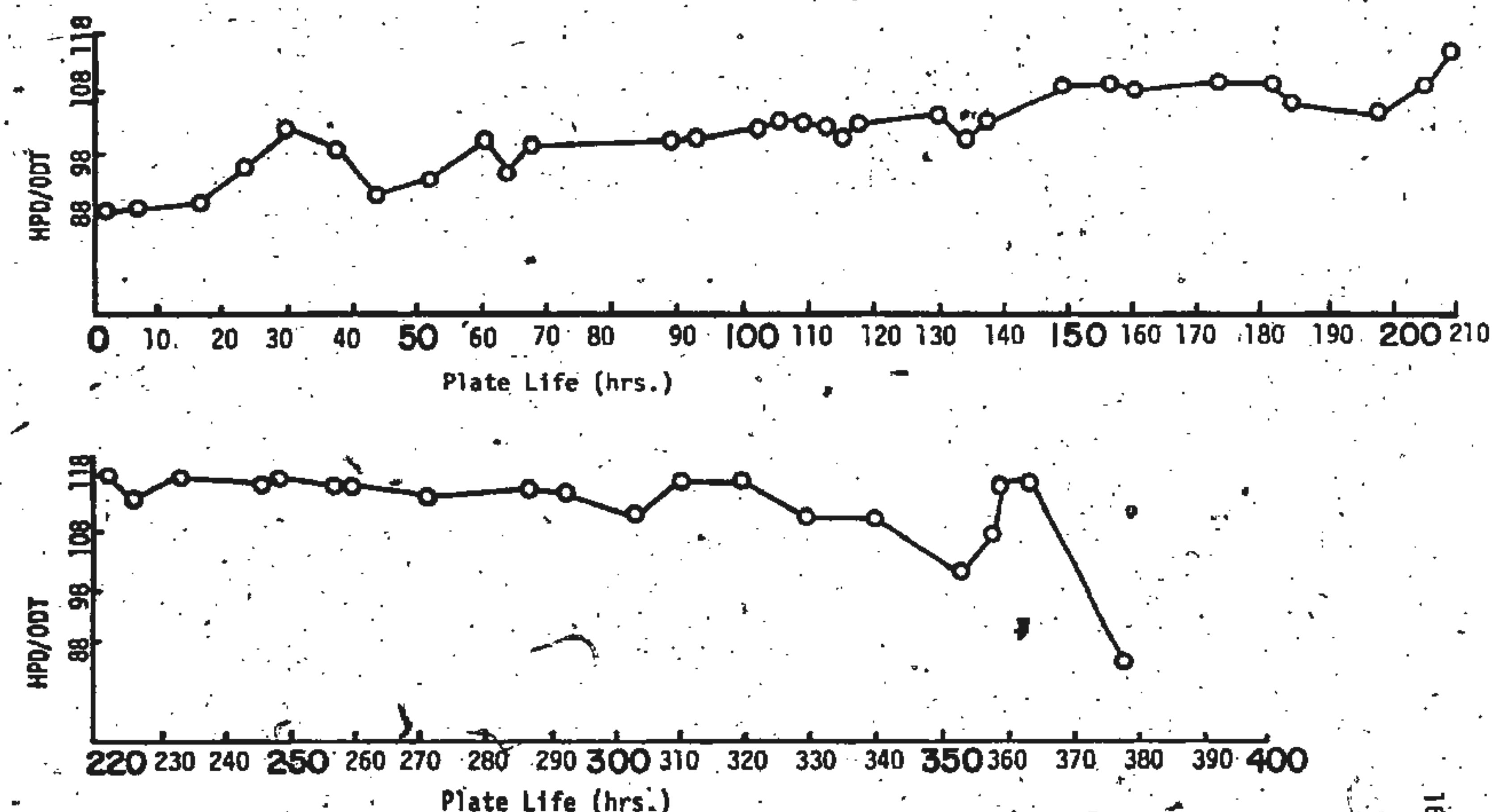


Fig. 32. Graph of horsepower days/o.d.t. over life of set of refiner plates.

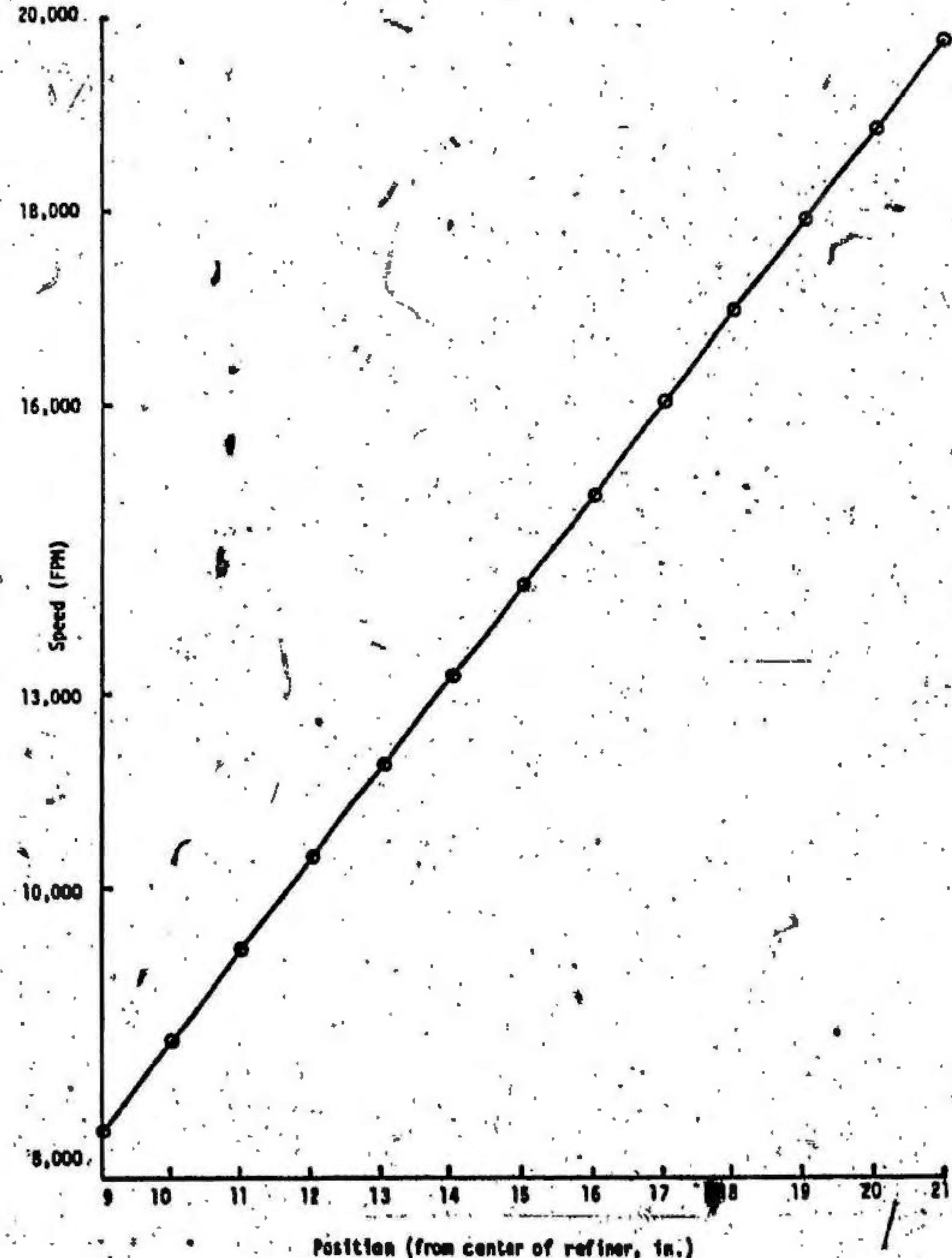


Fig.33. Graph of position (from center of refiner) versus speed.

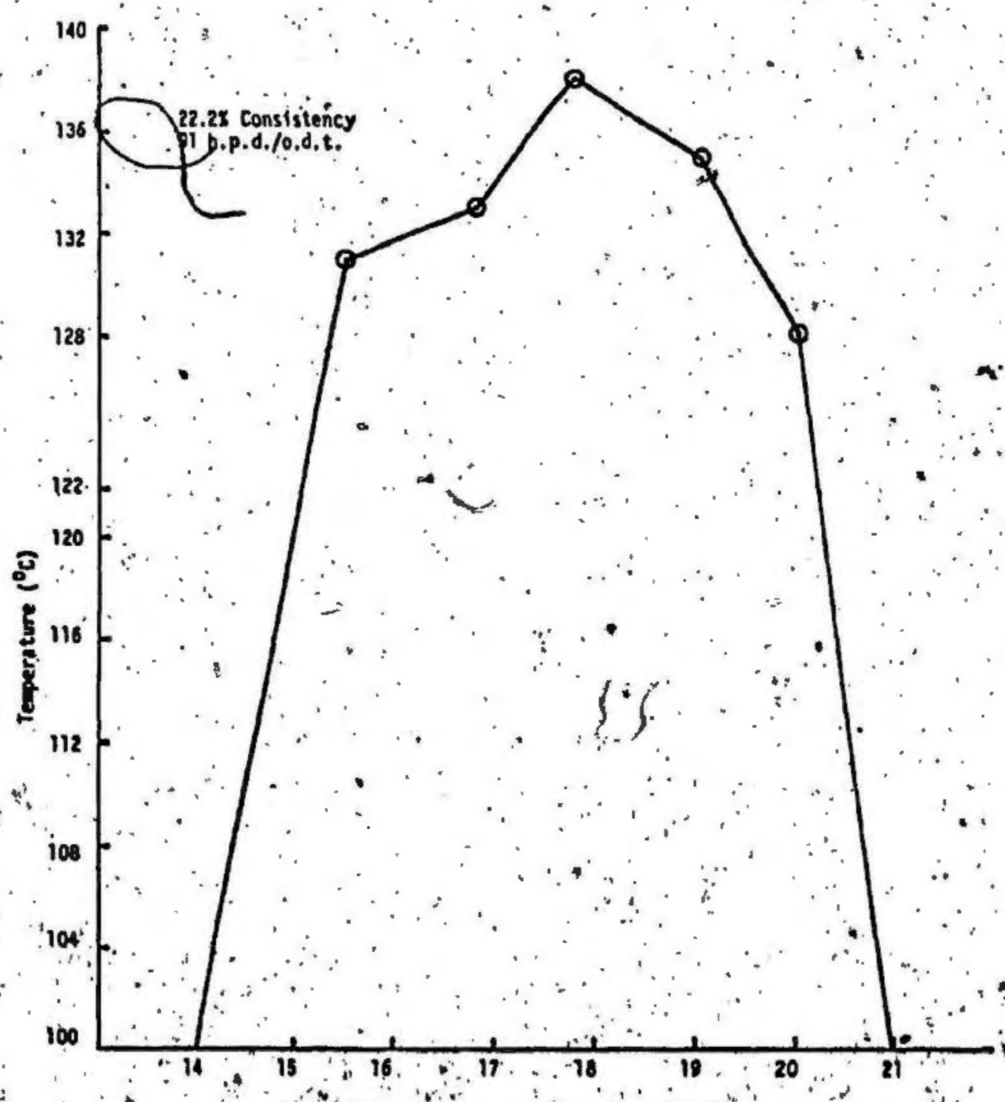


Fig.34. Dependence of temperature on distance from center of refiner.

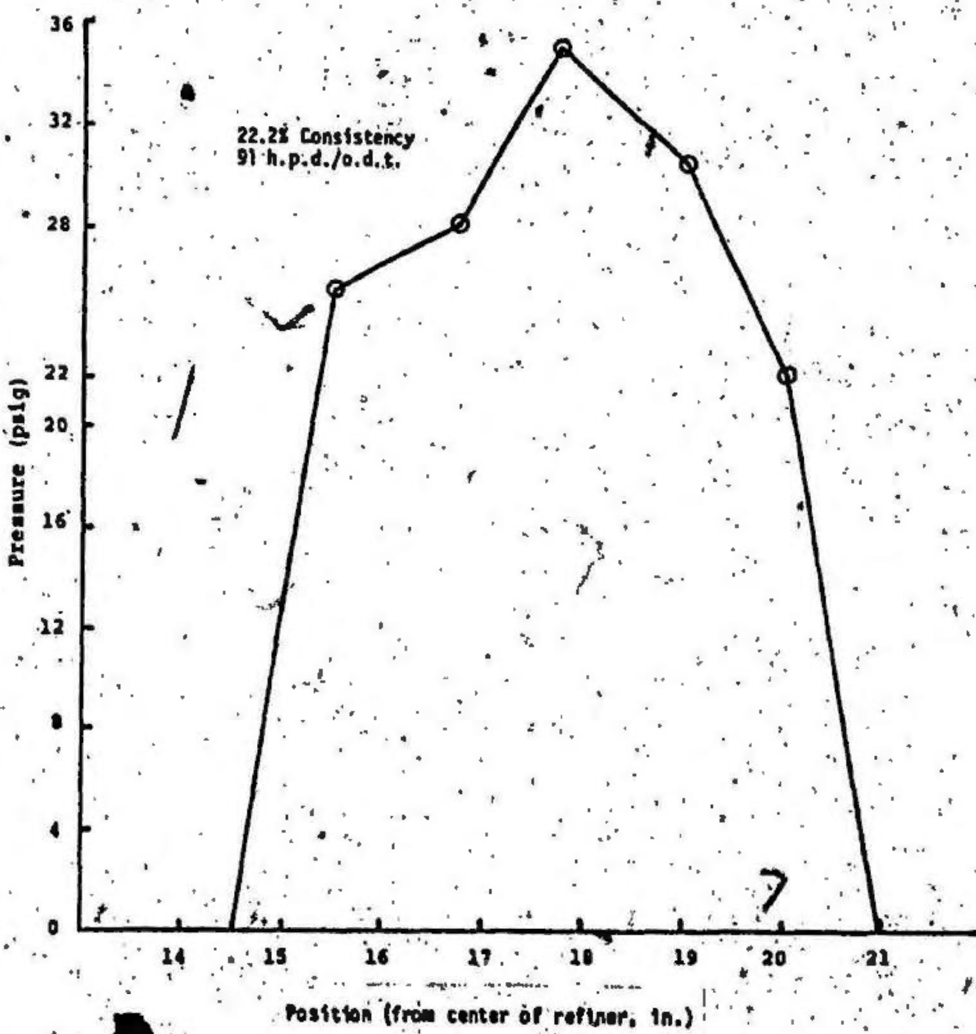


Fig.35. Pressure dependence with distance from center of refiner.

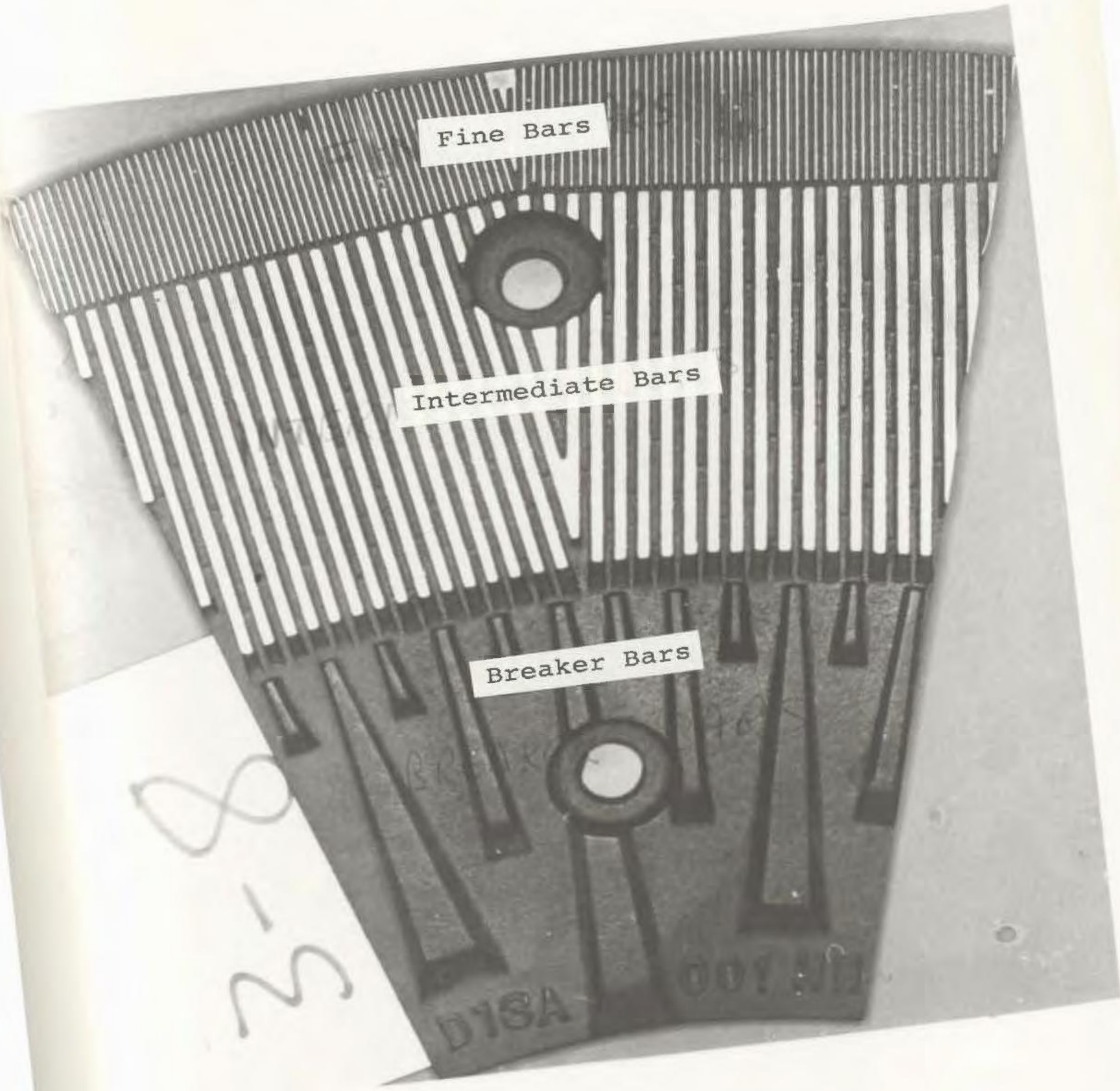


Fig. 36. Tribo-Element [1] and [2] before use

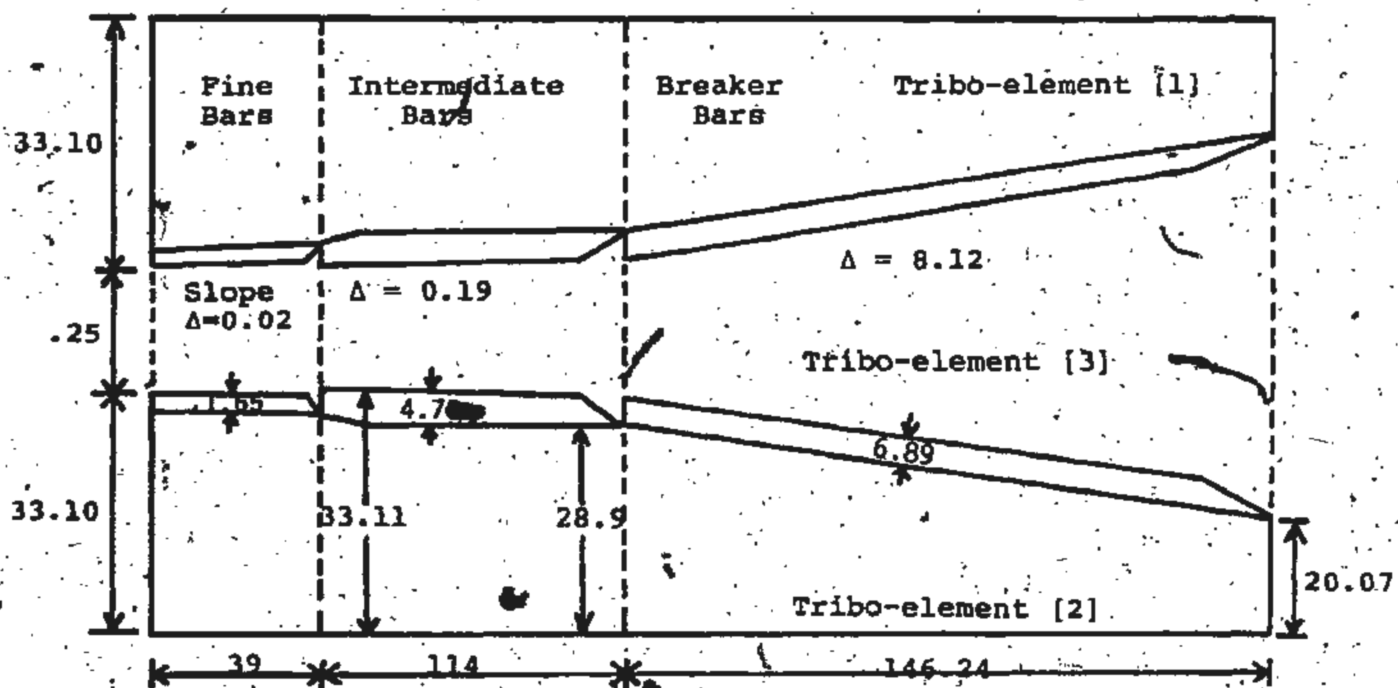


Fig. 37. Profile measurements of tribo-elements [1], [2] and lubricant [3]. All dimensions are in millimeters.

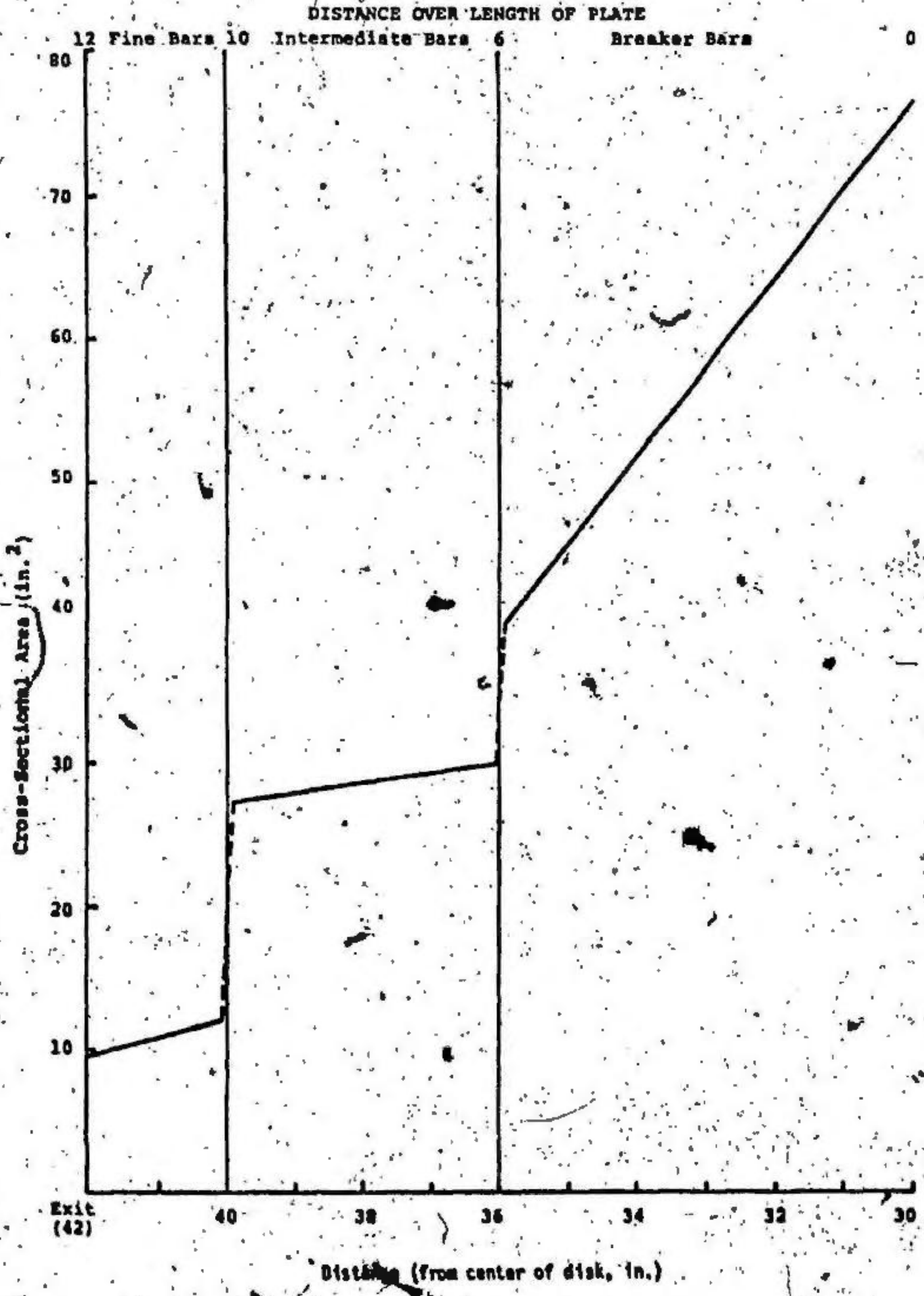


Fig. 38. Effective cross-sectional area through tribo-element [3], i.e., between elements [1] and [2].

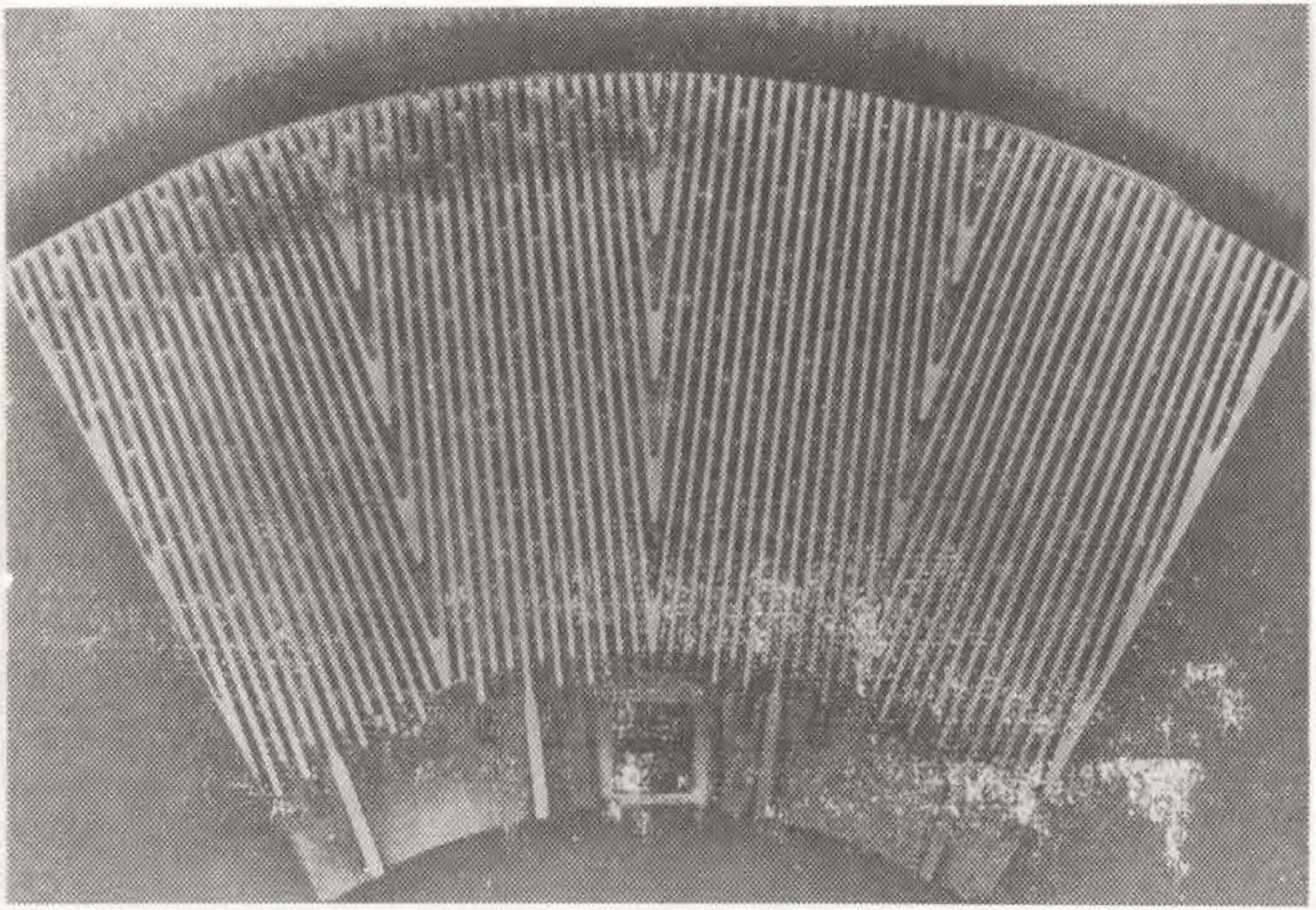


Fig. 39. Bauer C-906 refiner plate segment. Six such segments are attached to each refiner disk.

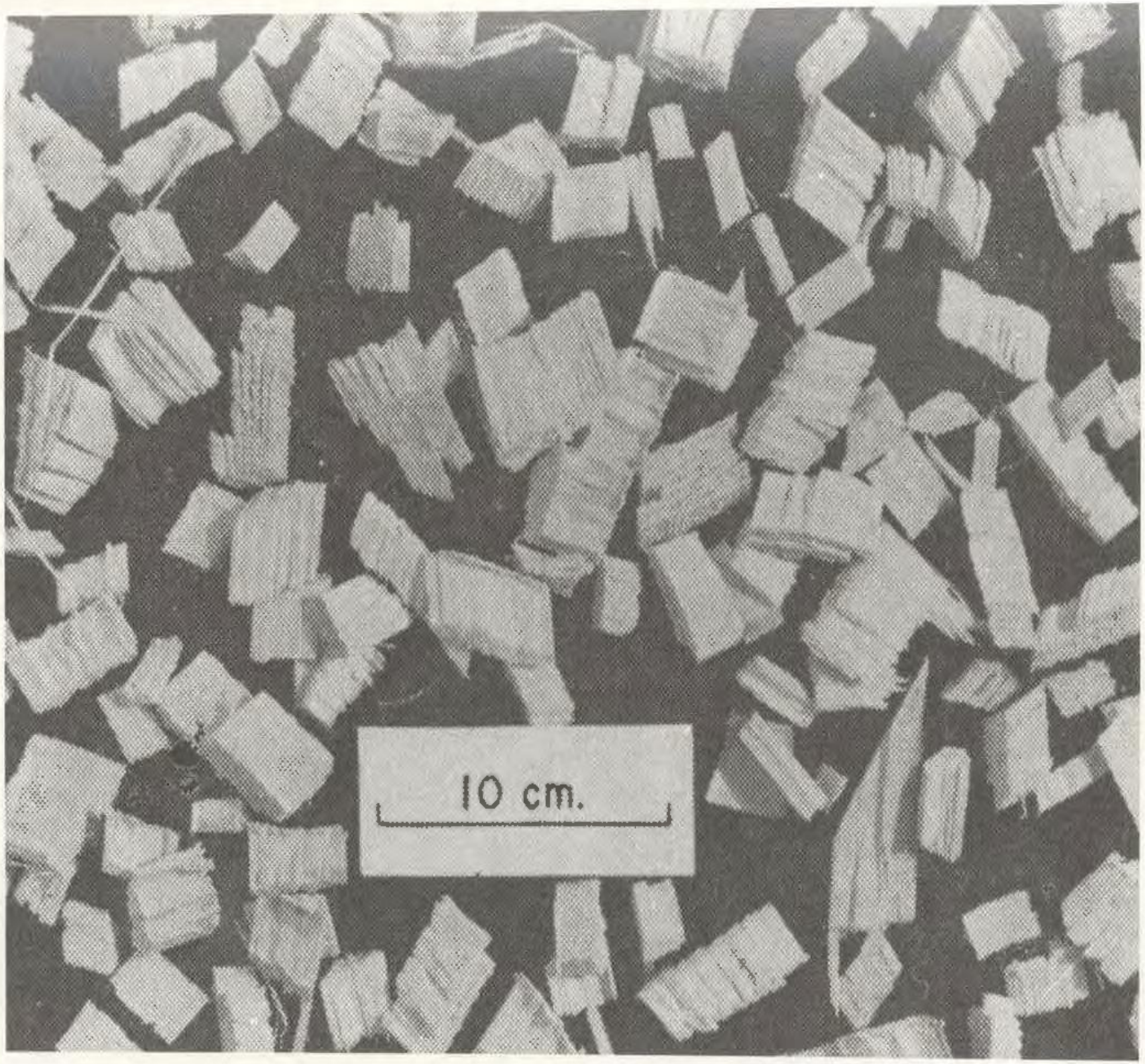


Fig. 40. Representative sample of black spruce chips employed in these refining experiments, showing the size and shape distribution of the feed material.

Fig. 41. Material sampled after passing through the breaker bar section alone. The fragments are seen to be quite uniform and the major axis of each is in the grain direction.

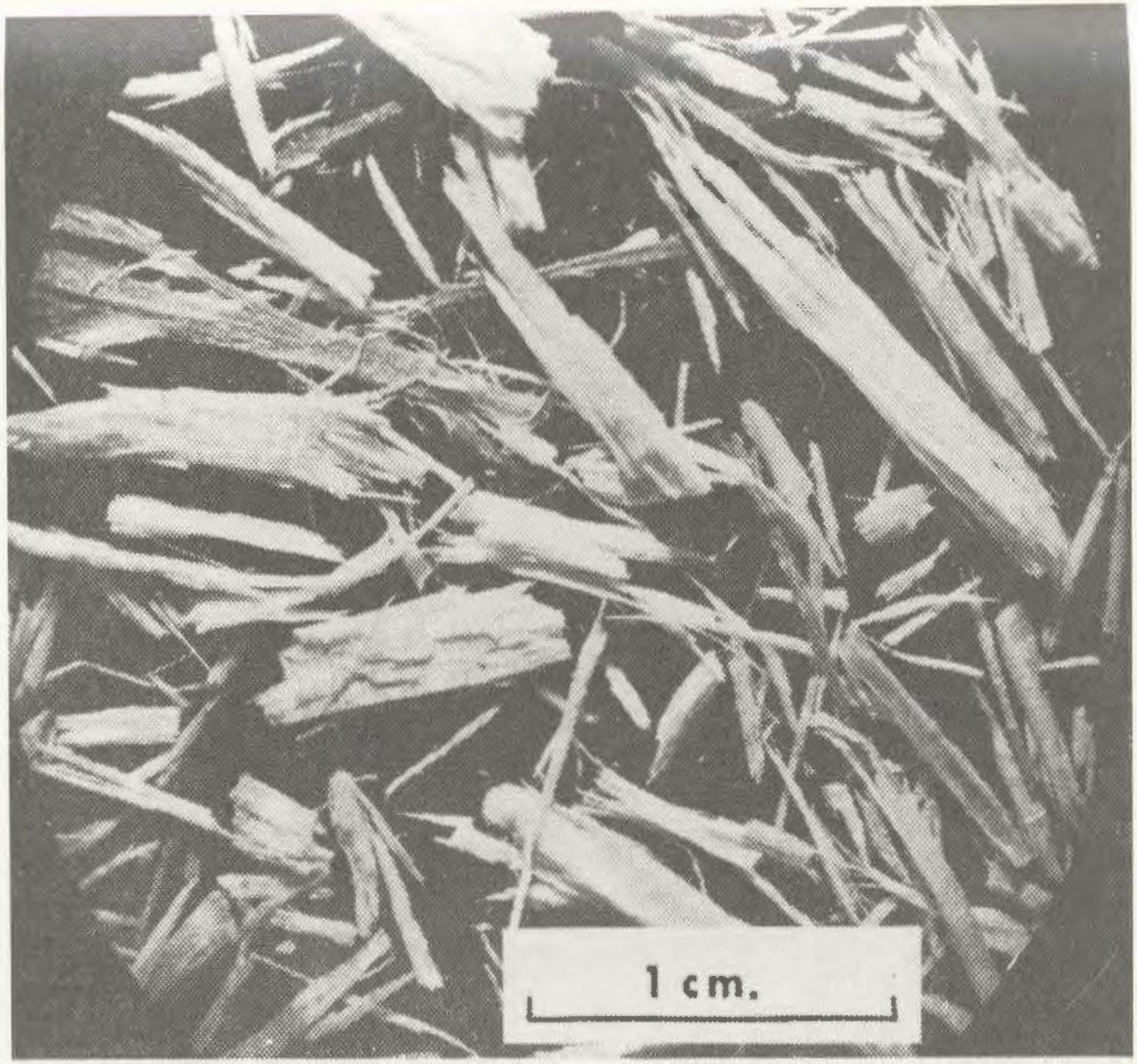


Fig. 42. Material sampled after moving a radial distance of one inch from the breaker bar section.

Fig. 43. Material sampled after moving a radial distance of 2.5 in. from the breaker bar section. Note the cylindrical aspect of some of the larger fragments.

Fig. 44. Material sampled after moving a radial distance of 4.0 in. from the breaker bar section. Note the broomed ends of many cylindrical fragments.

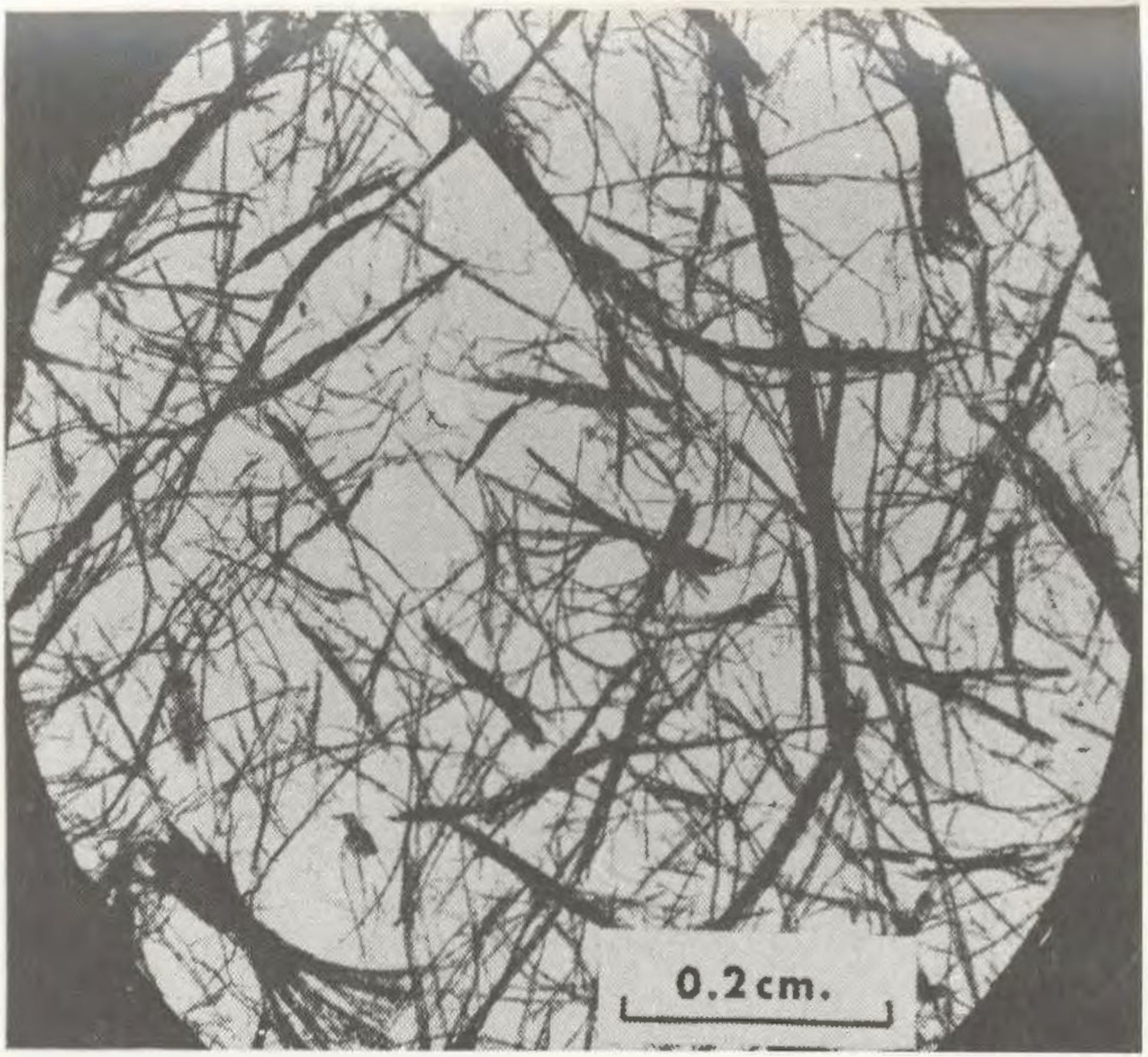


Fig. 45. Material sampled after moving a radial distance of 5.5 in. from the breaker bar section.

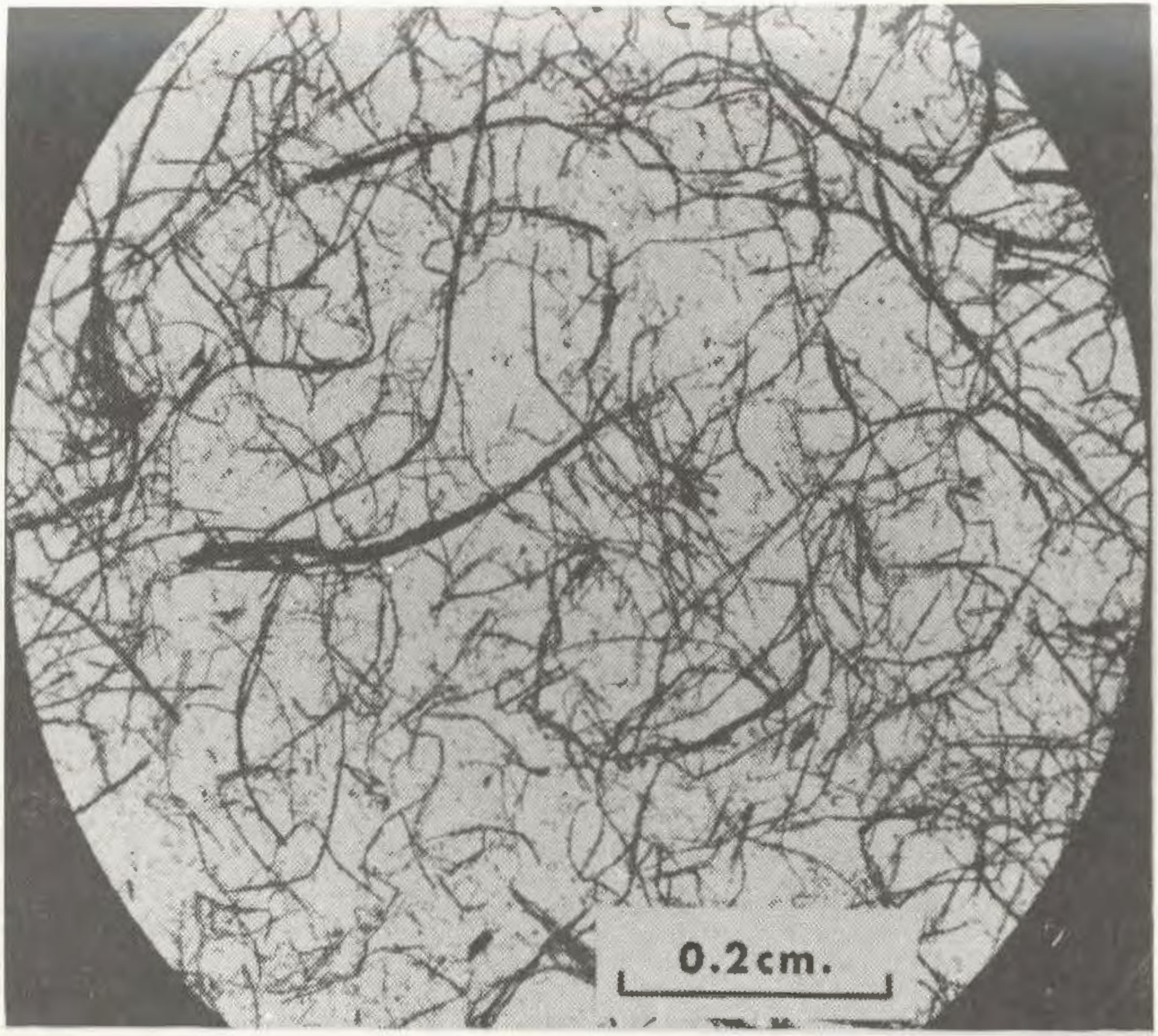


Fig. 46. Material produced by full refiner plate. This material has taken on the aspect of a papermaking pulp.

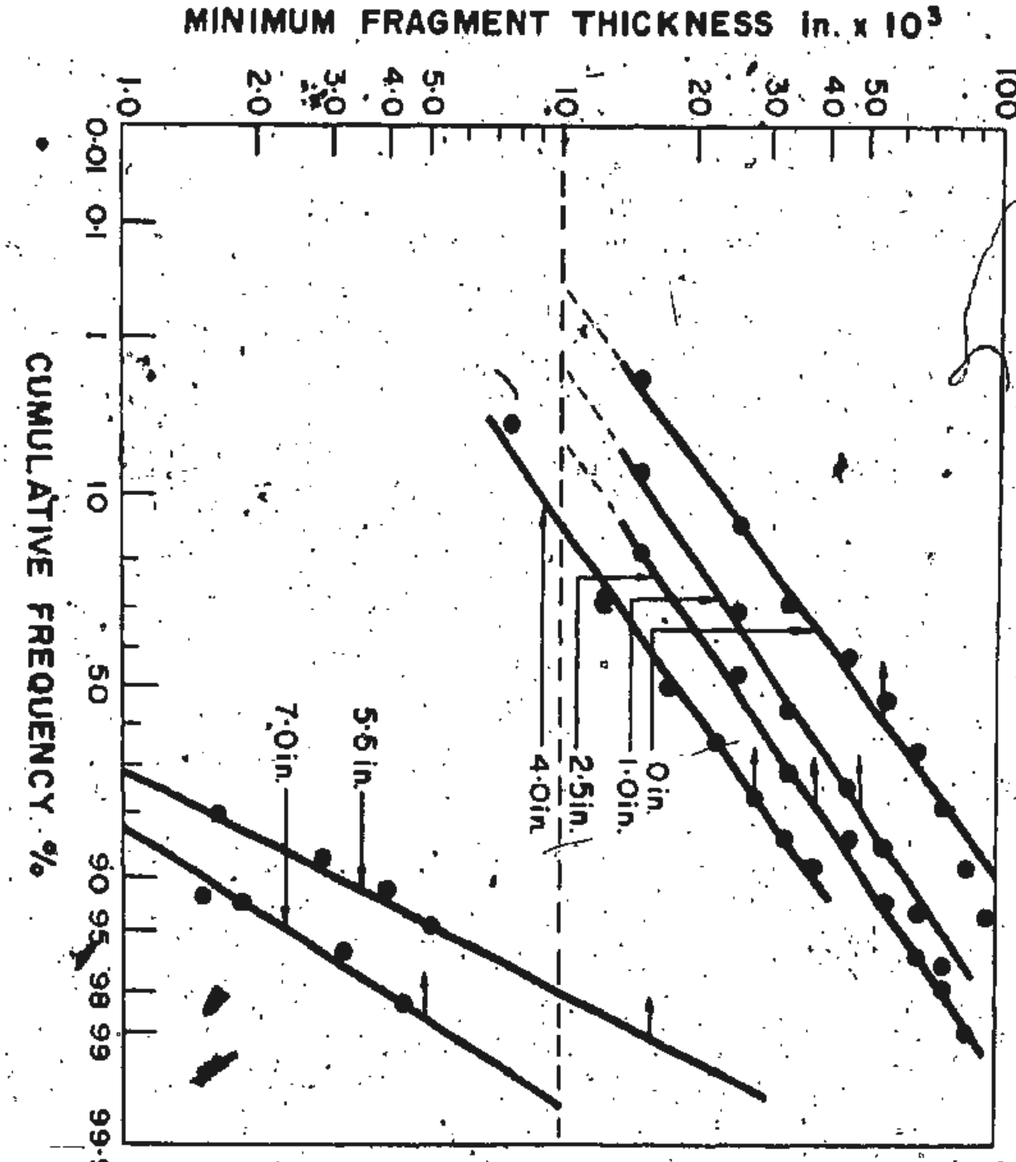


Fig. 47. Cumulative frequency curves of minimum fragment thickness of material produced at various points through the refining zone. The horizontal arrow on each curve denotes the minimum plate separation at the point of sampling.

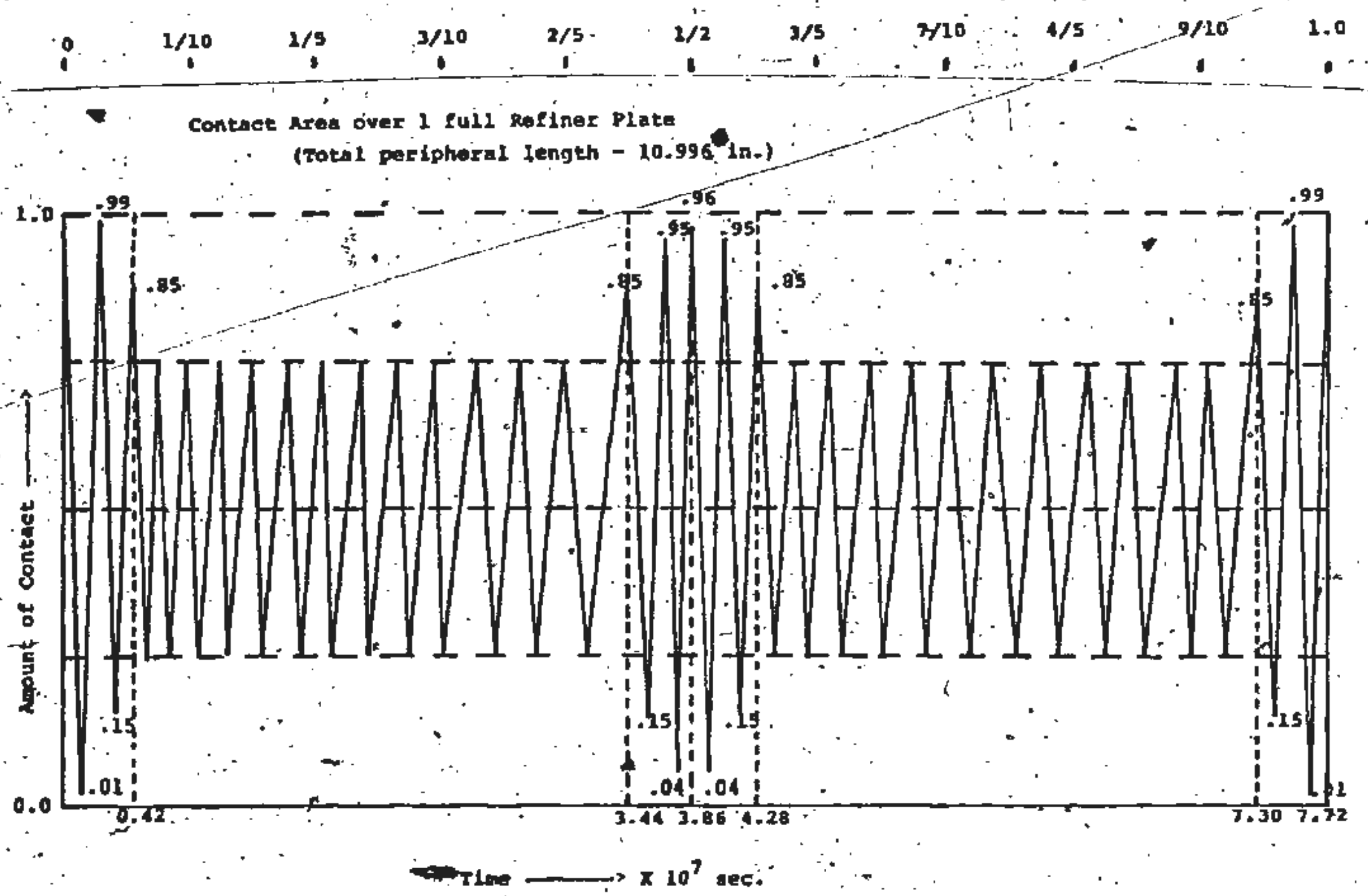


Fig. 48 Graph of contact area versus time (distance plate has travelled)

Note: Only the intermediate bar section has been considered here.

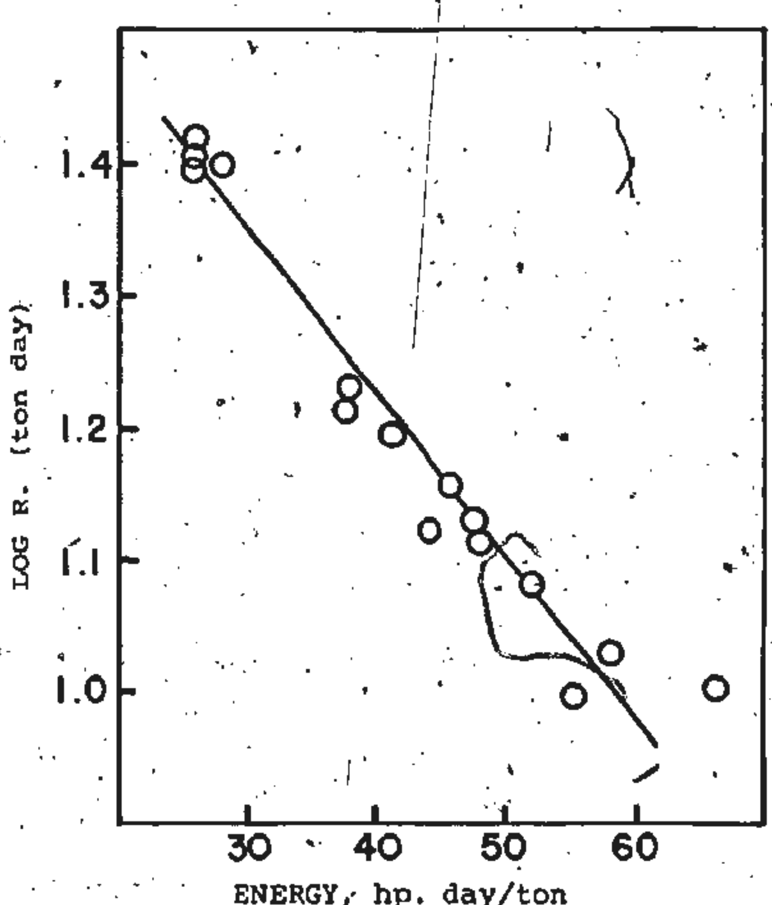


Fig. 49. Plot of specific energy vs. feed rate in a series of refining experiments.

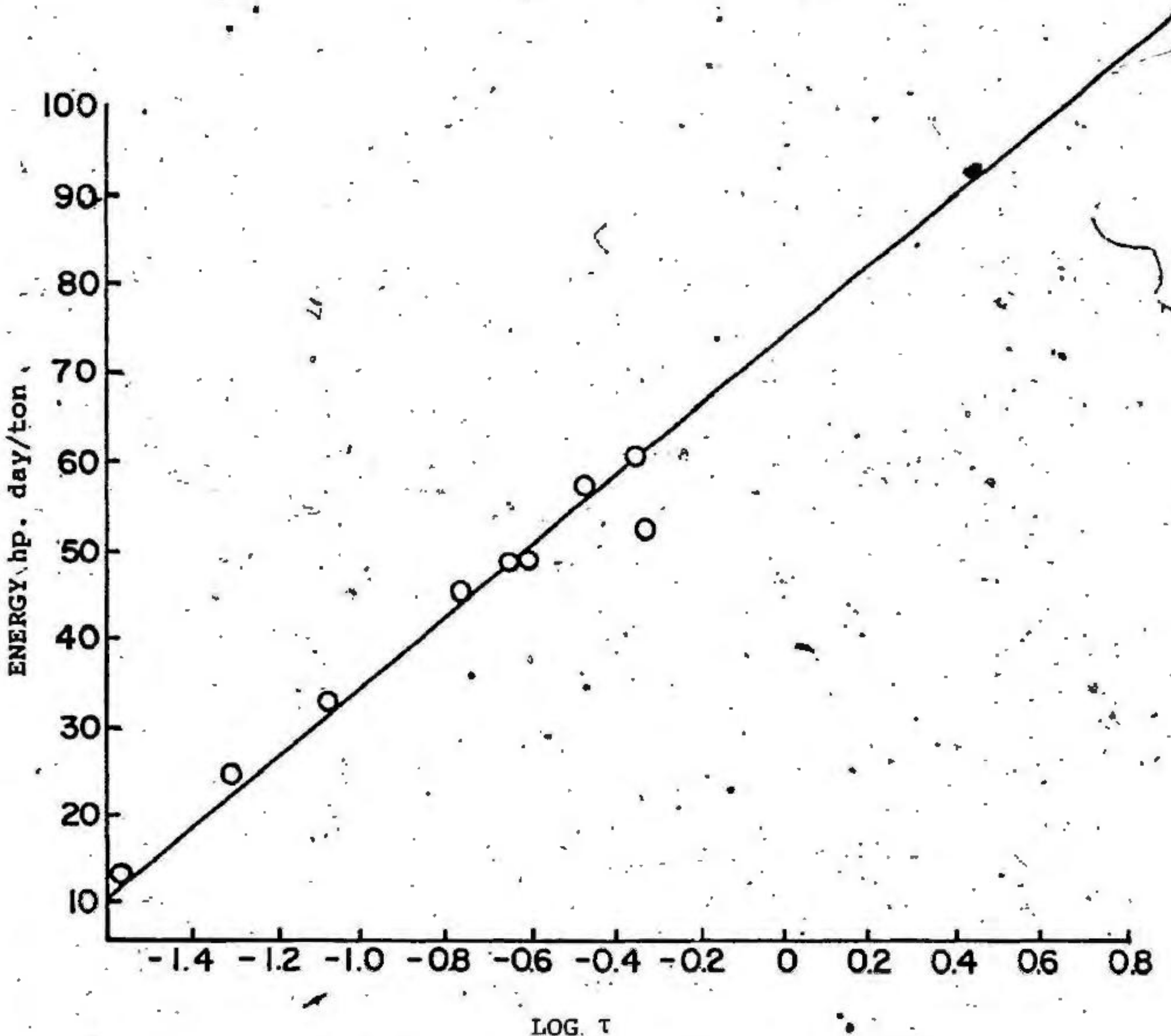


Fig. 50. Plot of specific energy vs. retention time (Extended to 100 hp. day/ton)

TO \ FROM	1	2	3
1	1	6	4
2	6	2	5
3	4	5	3

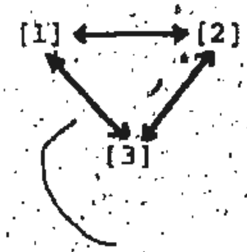


Figure 51. All possible tribological interactions between three tribo elements.

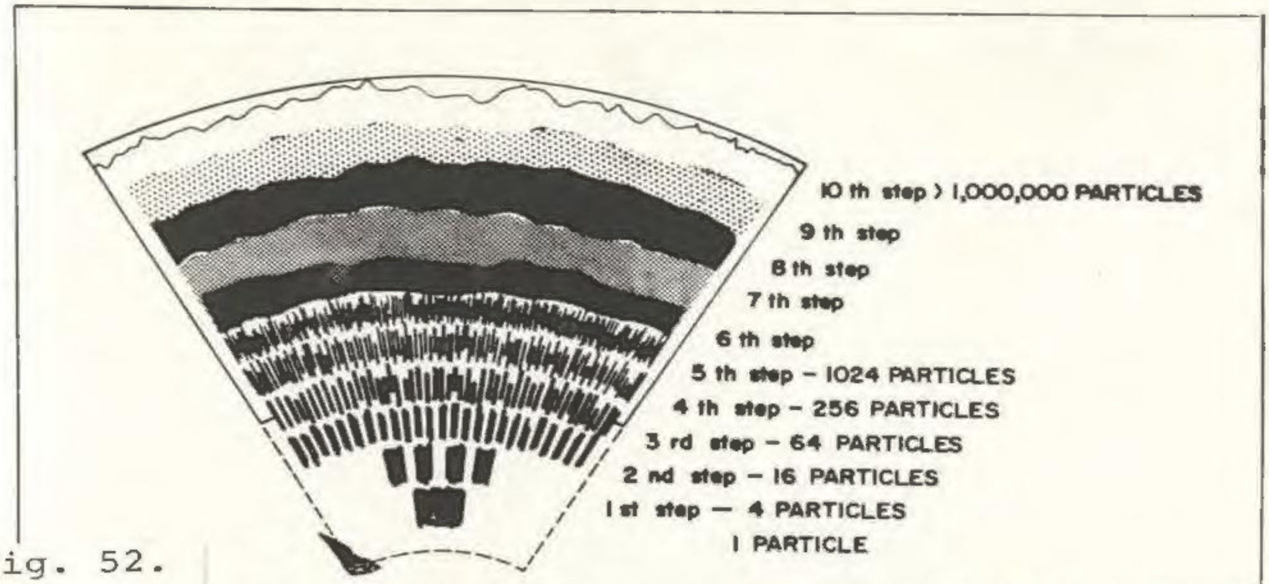


Fig. 52.

The model assumes that chips are sequentially disintegrated in discrete steps through the refining zone. The radial orientation depicted is for clarity of illustration - in reality this is probably random.

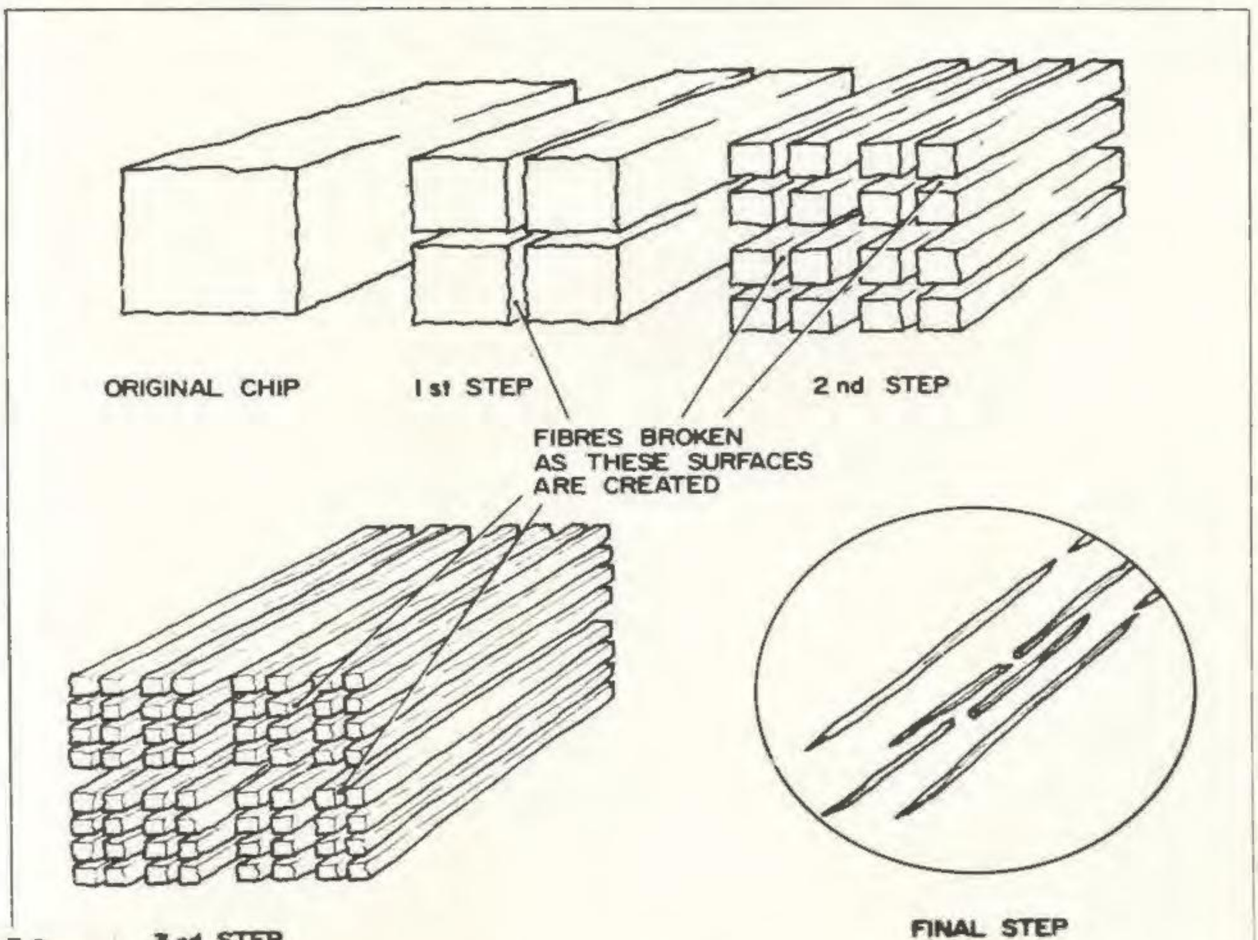


Fig. 53.

The model assumes that a chip breaks into four equal pieces during the first disintegration, and that these and subsequent fragments break in similar fashion to give an isomorphic pattern of breakdown, which ends when single fibers are liberated from bundles of four.

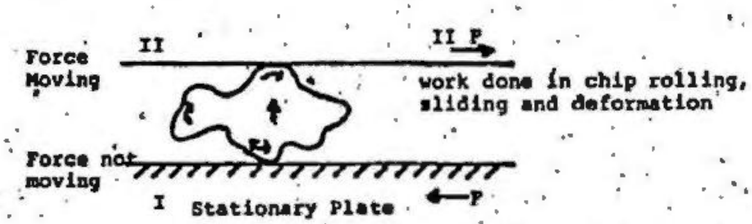


Fig. 54. Depiction of forces on chip from stationary plate as Reference.

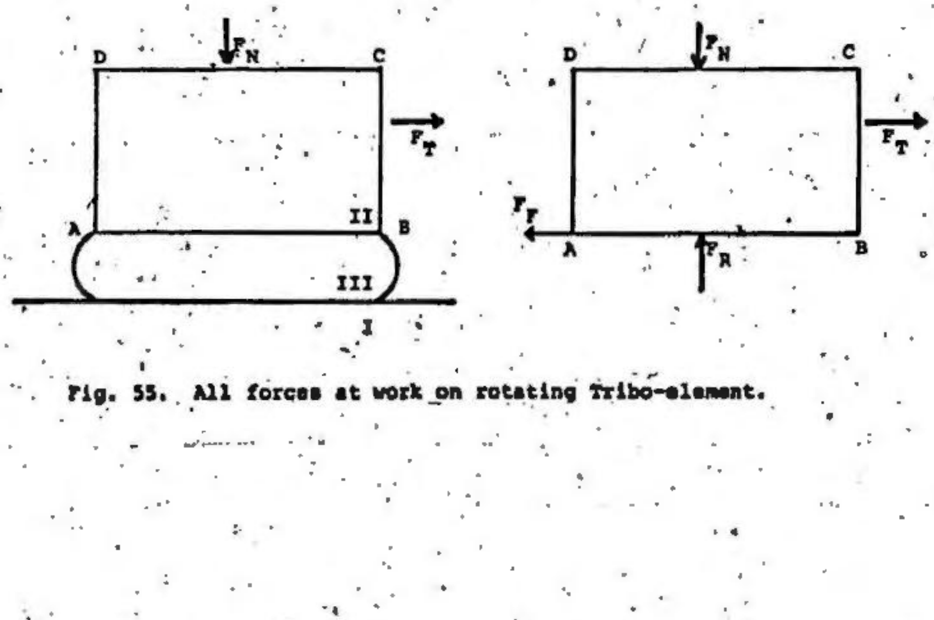


Fig. 55. All forces at work on rotating Tribo-element.

Fig. 56. Friction Mechanism--elastic deformations in wood chip transmit stress to be dissipated into plates or pulp.

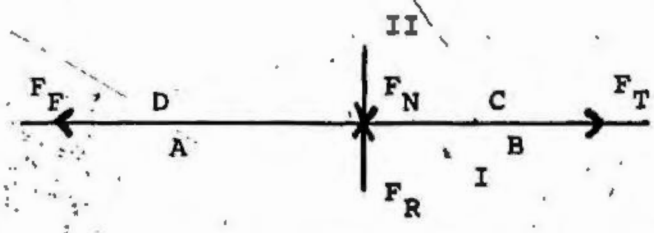


Fig. 57. Resultant forces and events if both plates were flat.

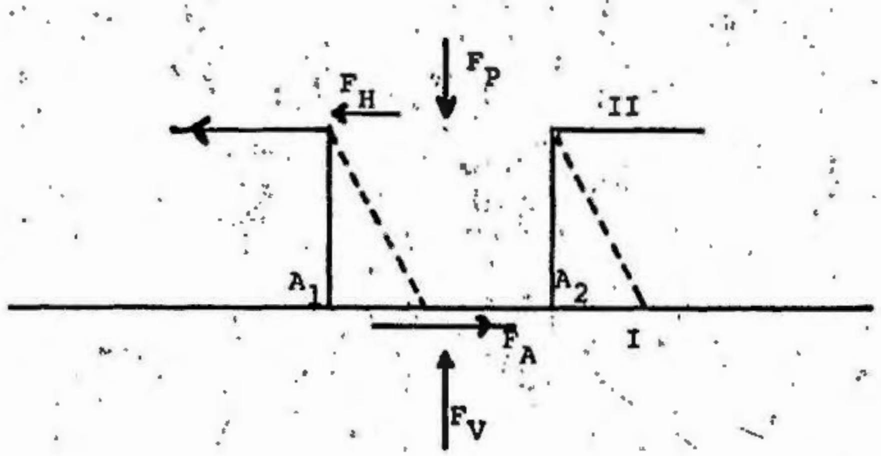


Fig. 58. Resultant forces and events (on a microscale) if one plate were flat.

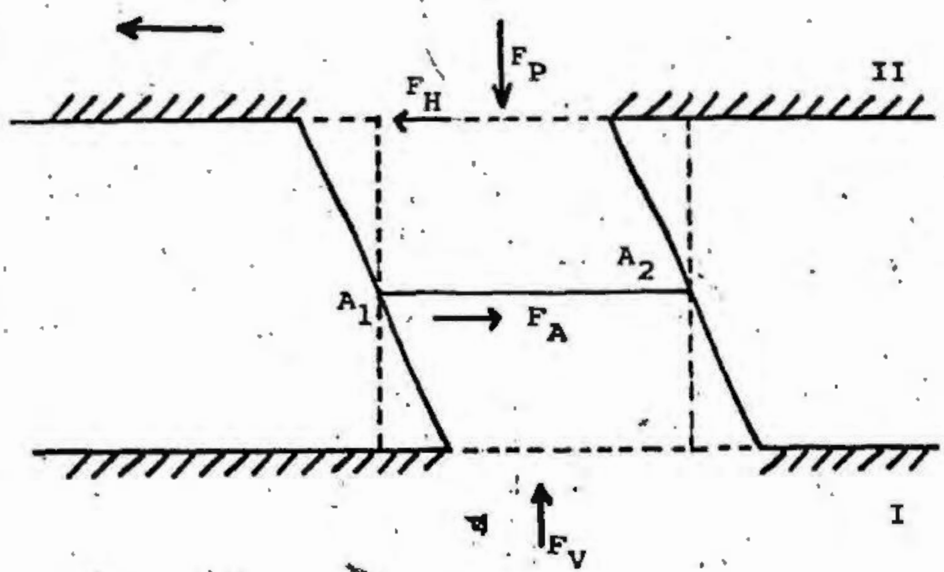


Fig. 59. Deformation and forces between two macro-asperities.

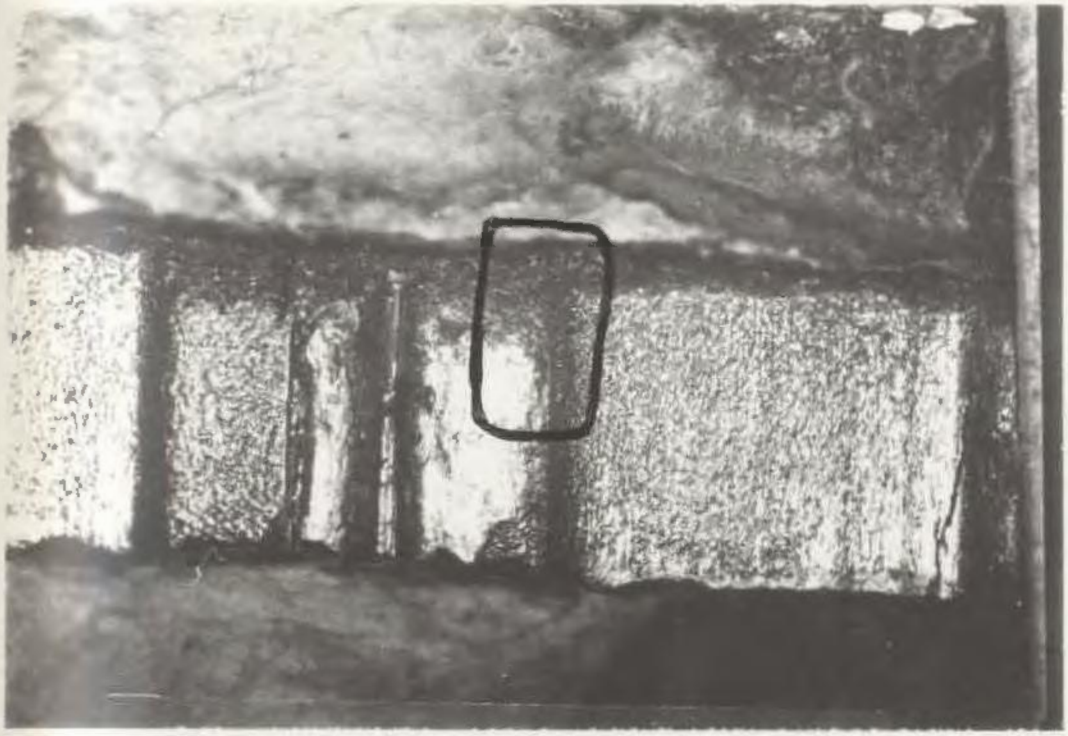


Fig. 60. Sample site R-1 I-8 on top of intermediate bar - chosen randomly.

Fig. 61. Sample Site R-1 I-8 - 80X magnification, no etch.

Fig. 62. Sample Site R-1 I-8 - 300X magnification, no etch.

Fig. 63. Sample Site R-1 I-8 - 1000X, Normanski interference, layer 1 in focus, etched.

Fig. 64. Sample Site R-1 I-8 - 1000X, Normanski interference, layer 2 in focus, etched.

Fig. 65. Sample Site R-1 I-8 - 1000X, Normanski interference, end of layer 3, layer 4 in focus, etched.

Fig. 66. Sample Site R-1 I-8 showing microhardness marks - 300X, etched.

Fig. 67.
Sample Site R-1 I-8 showing microhardness marks - 300X, Normanski interference, etched.

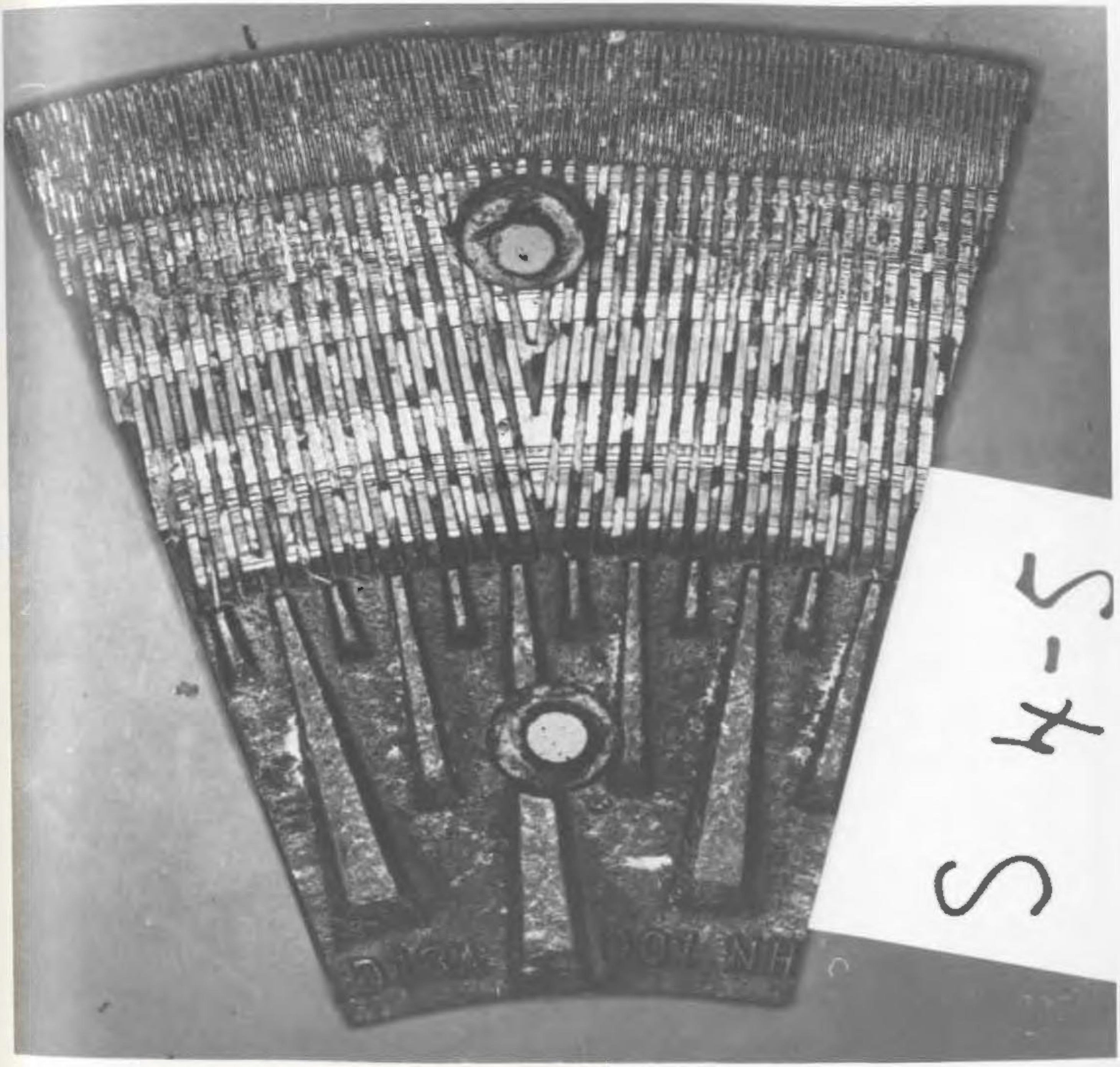


Fig. 68. Tribo-Element [1] (stator) after use.

Fig. 69. Tribo-Element [1] (rotor) after use.

Fig. 70. Site S-1 I-1 on stator bar.

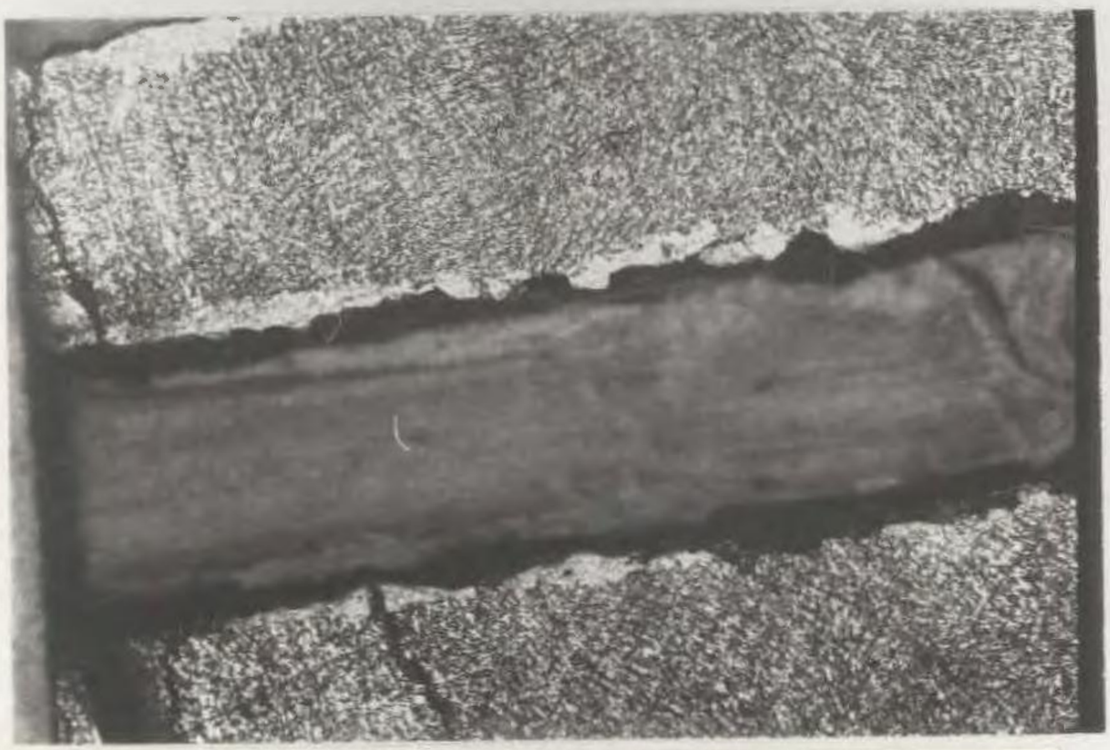


Fig. 71. Site R-1 I-1 on rotor bar.

Fig. 72. Site S-1 I-4 on stator bar.

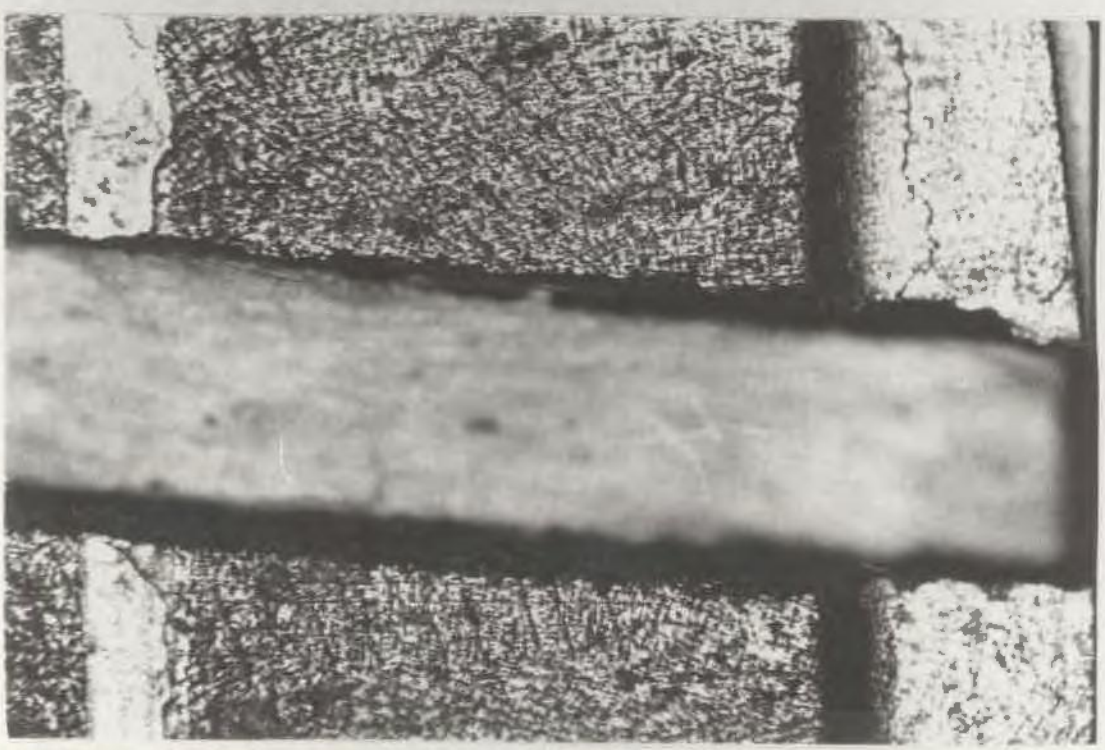


Fig. 73. Site R-1 I-4 on rotor bar.

Fig. 74. Site S-1 I-3 on stator bar.

Fig. 75. Site R-1 I-3 on rotor bar.

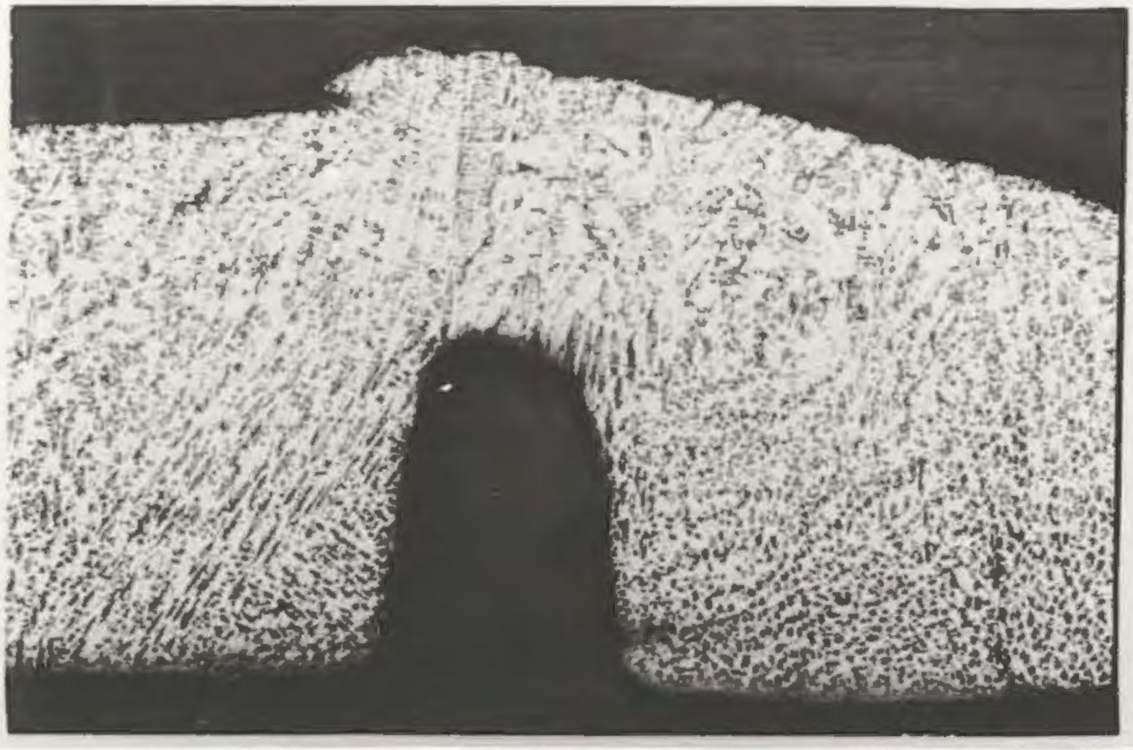


Fig. 76. Typical cut down area - 30X magnification.

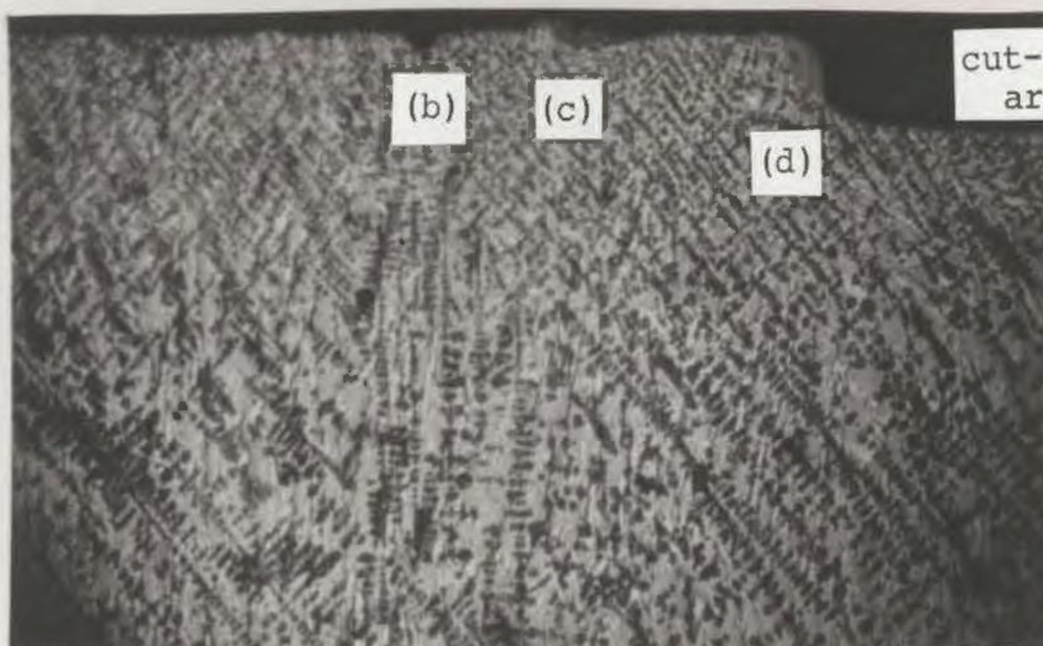
Fig. 77. Typical cut down area - 120X magnification.

Fig. 78. Typical worn area showing partial layer of grey material on an unworn area (c) and also a corner of grey material (d) on a cut down area.

(b) Two sides of cut down area made of harder material (120X)

(c) Partial layer of grey material (120X)

(d) Hardened corner (120X)



(a) Sample removed from a stator bar (30X)

Rc
1. 56.0
2. 62.0
3. 63.0
4. 65.3
5. 67.5
6. 65.0
7. 65.7

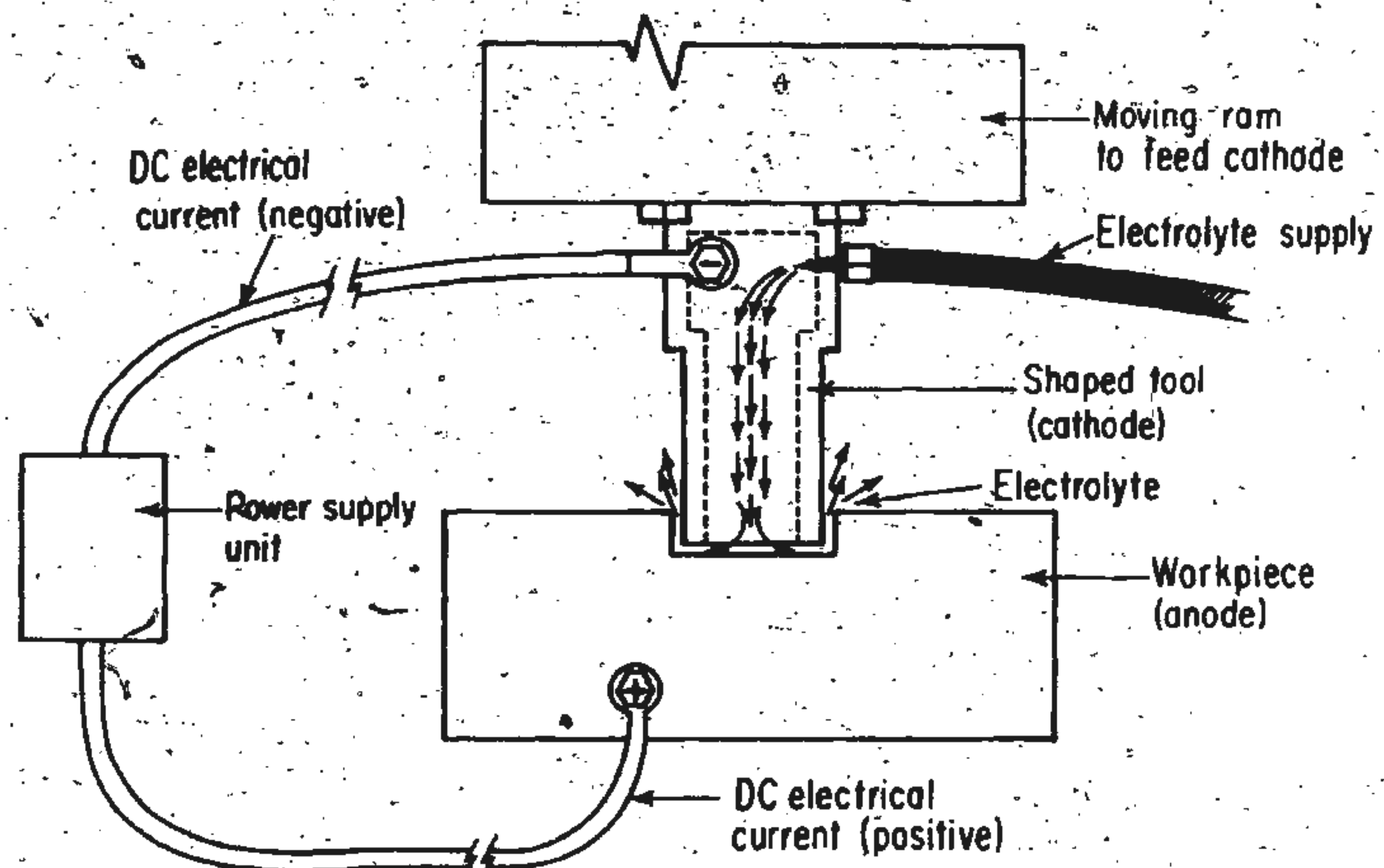


Fig. 79. Schematic arrangement for electrochemical machining.

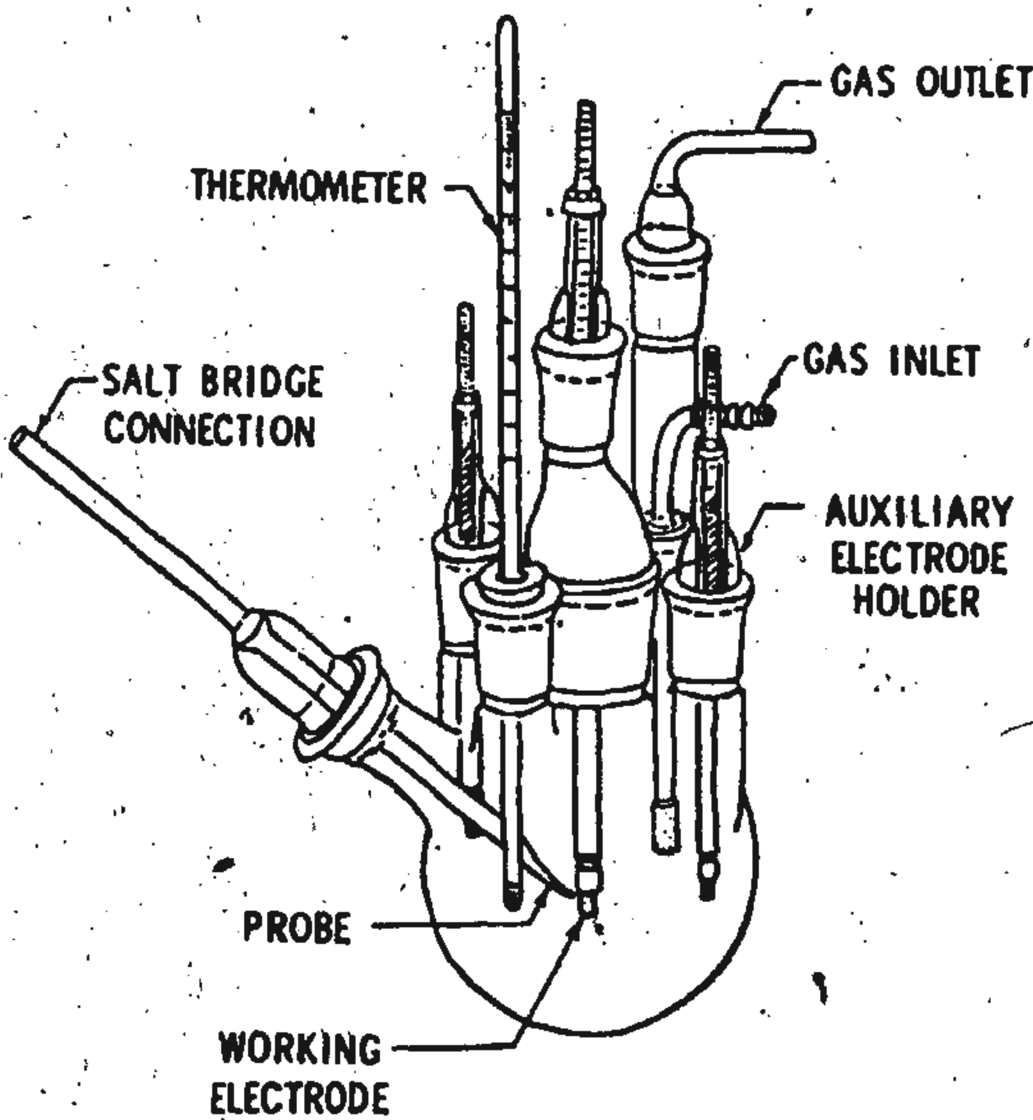


Fig. 80. Multi-Neck polarization cell - standard equipment

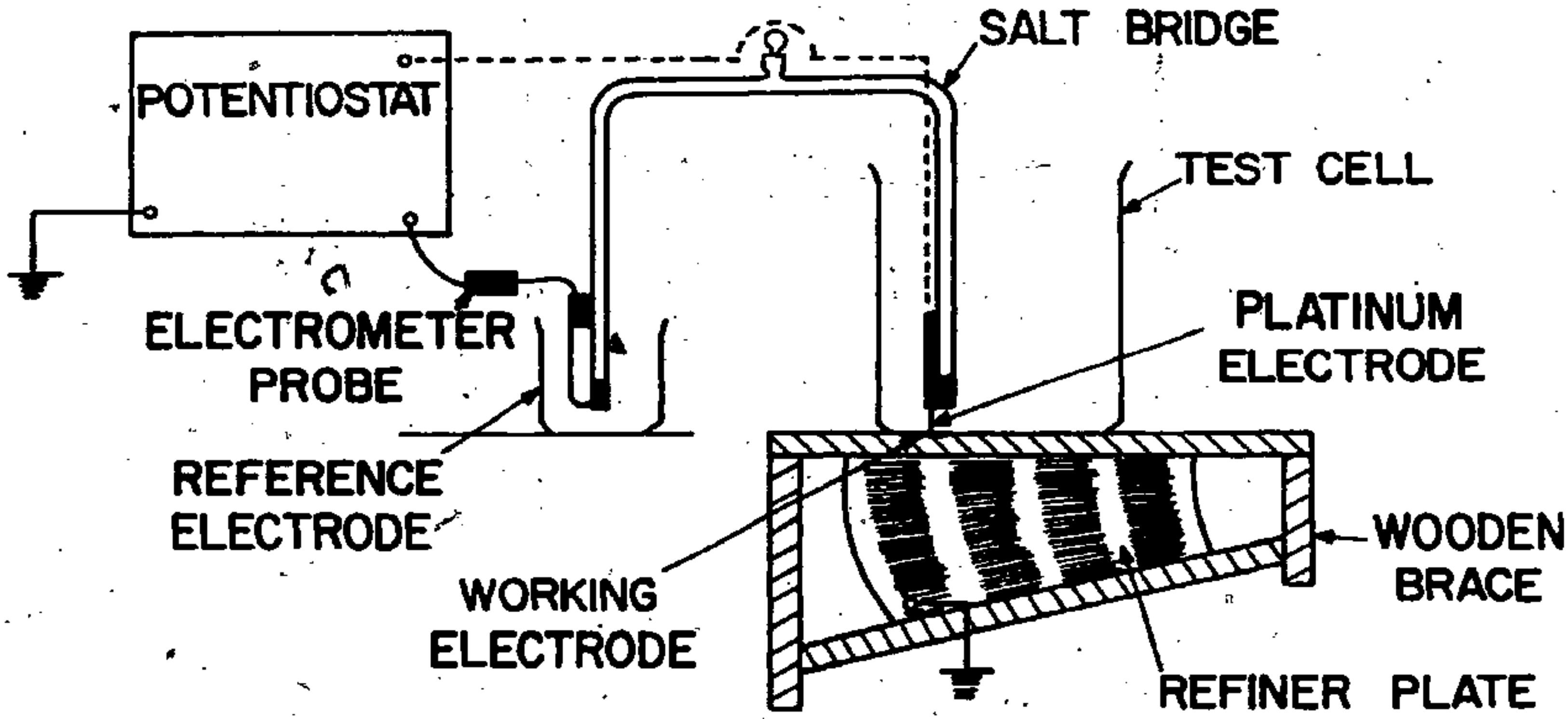


Fig. 81. Schematic diagram of experimental set-up

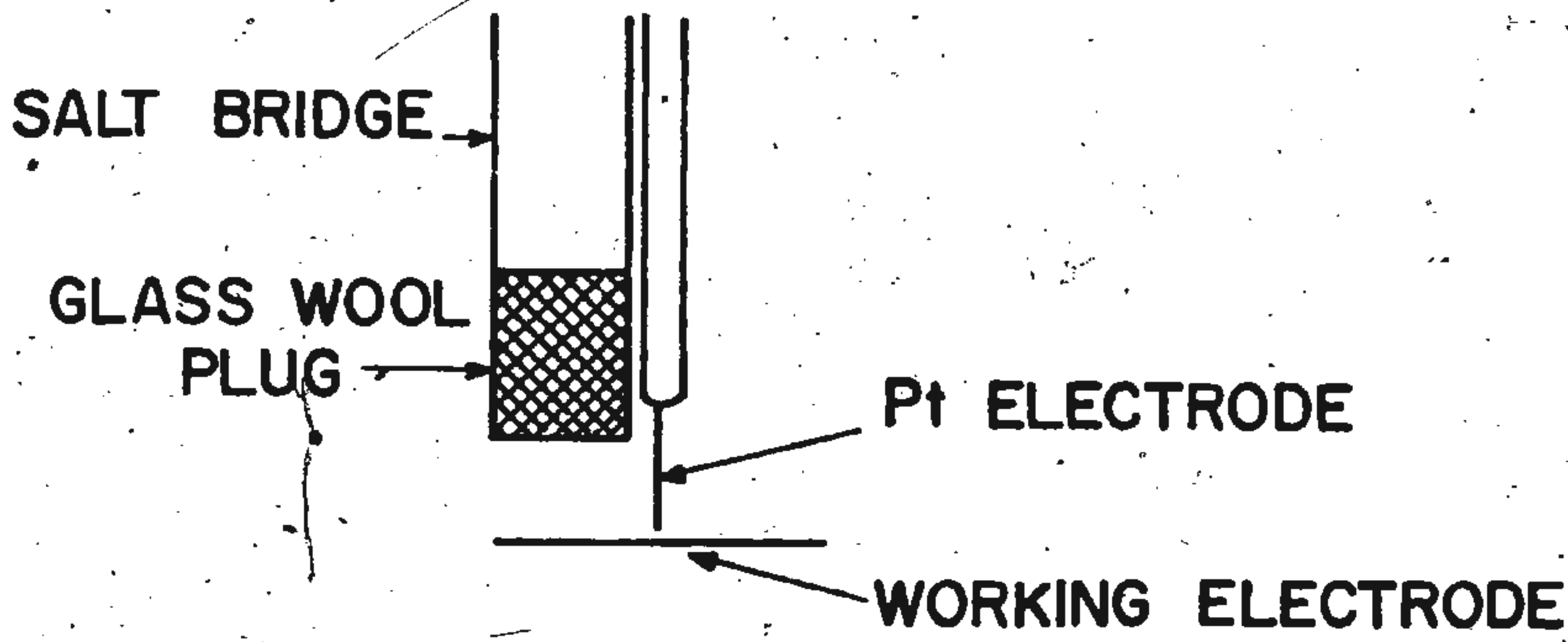


Fig. 82. Close-up of counter and working electrodes.

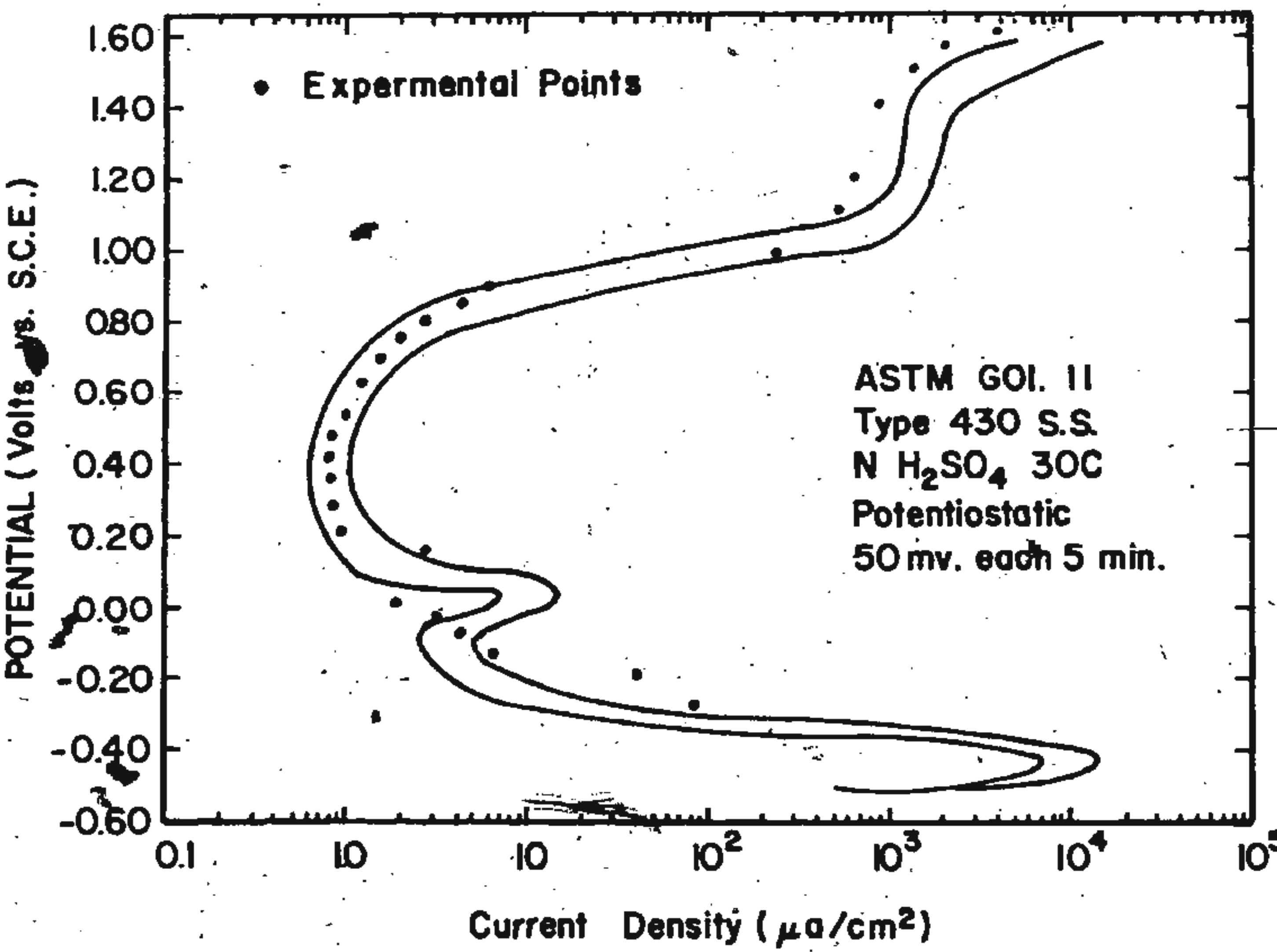


Fig. 83. Standard potentiostatic anodic polarization plot

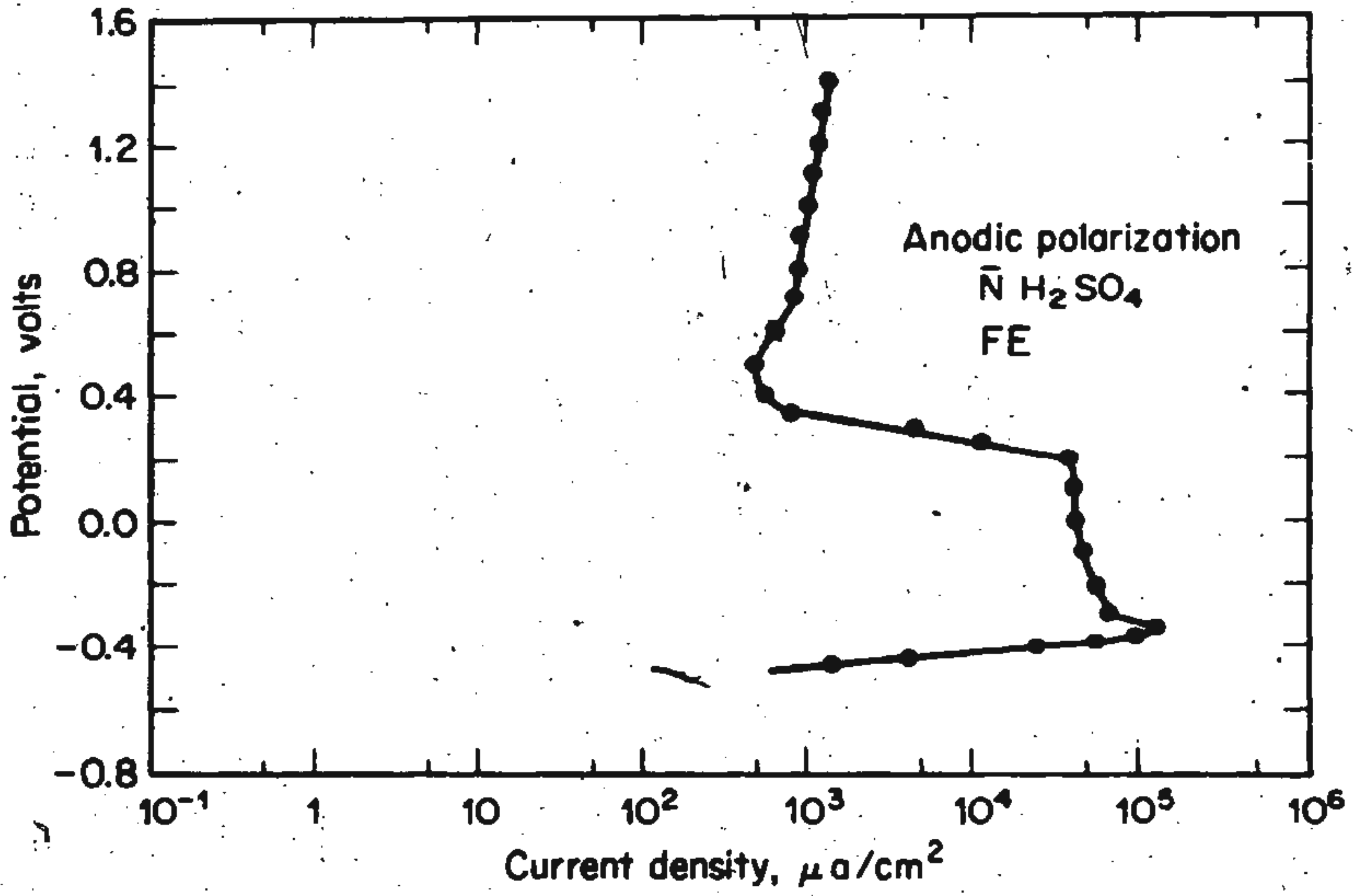


Fig. 84. Potentiostatic anodic polarization curve of iron in normal sulfuric acid.

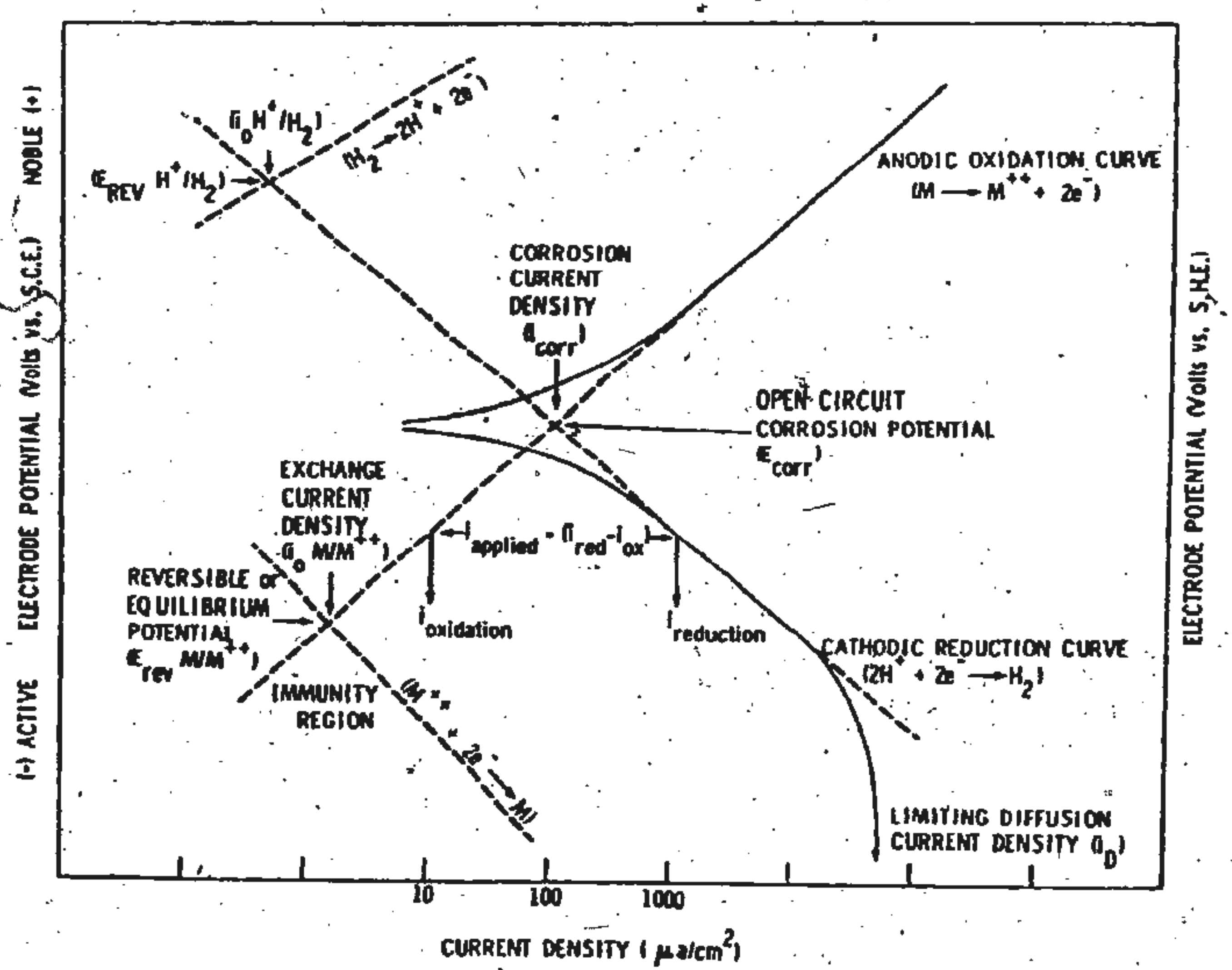


Fig. 85. Anodic and cathodic polarization curves illustrating some of the polarization terminology.

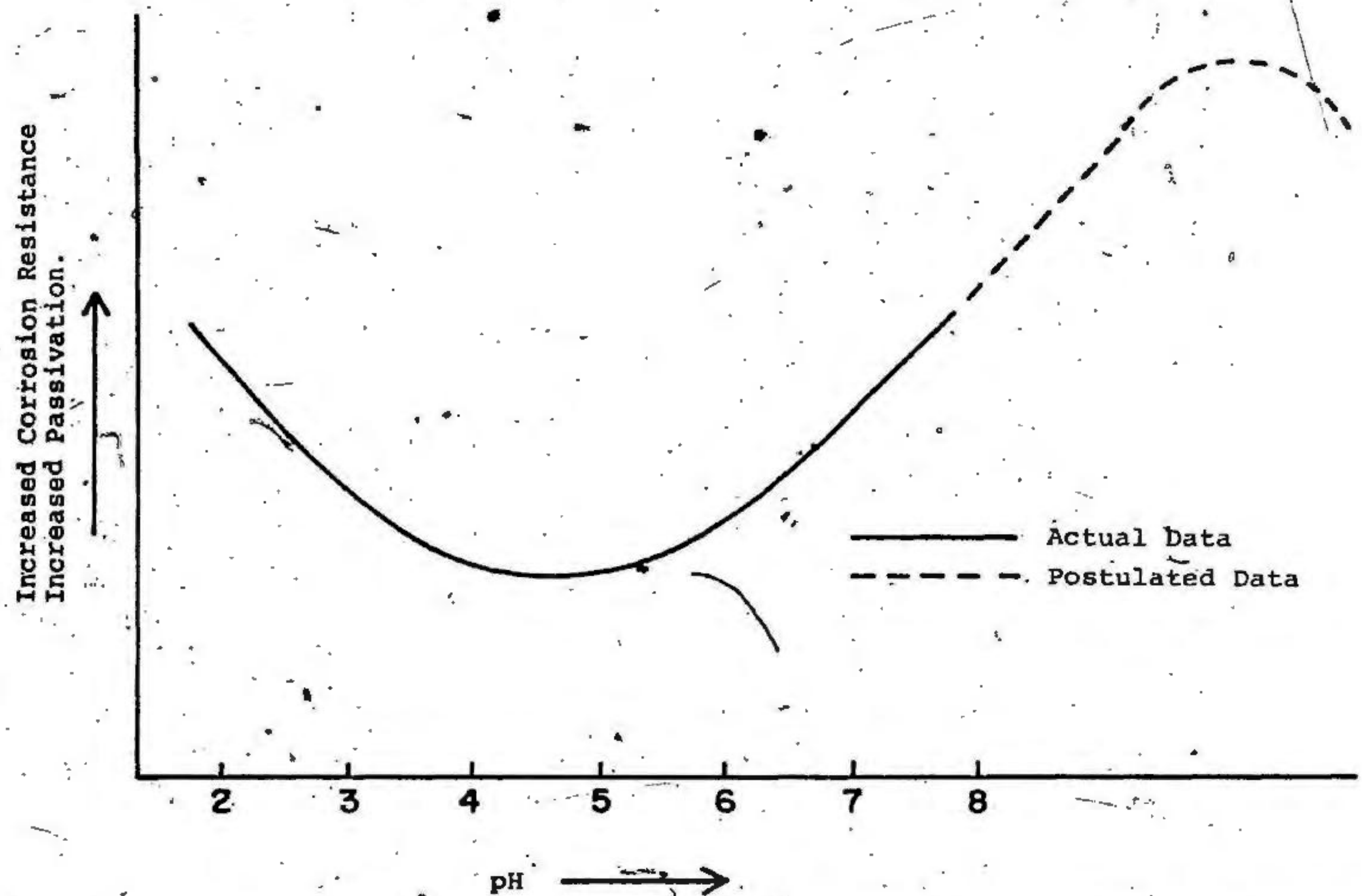


Fig. 86. Variation of pH with increased corrosion resistance or passivation

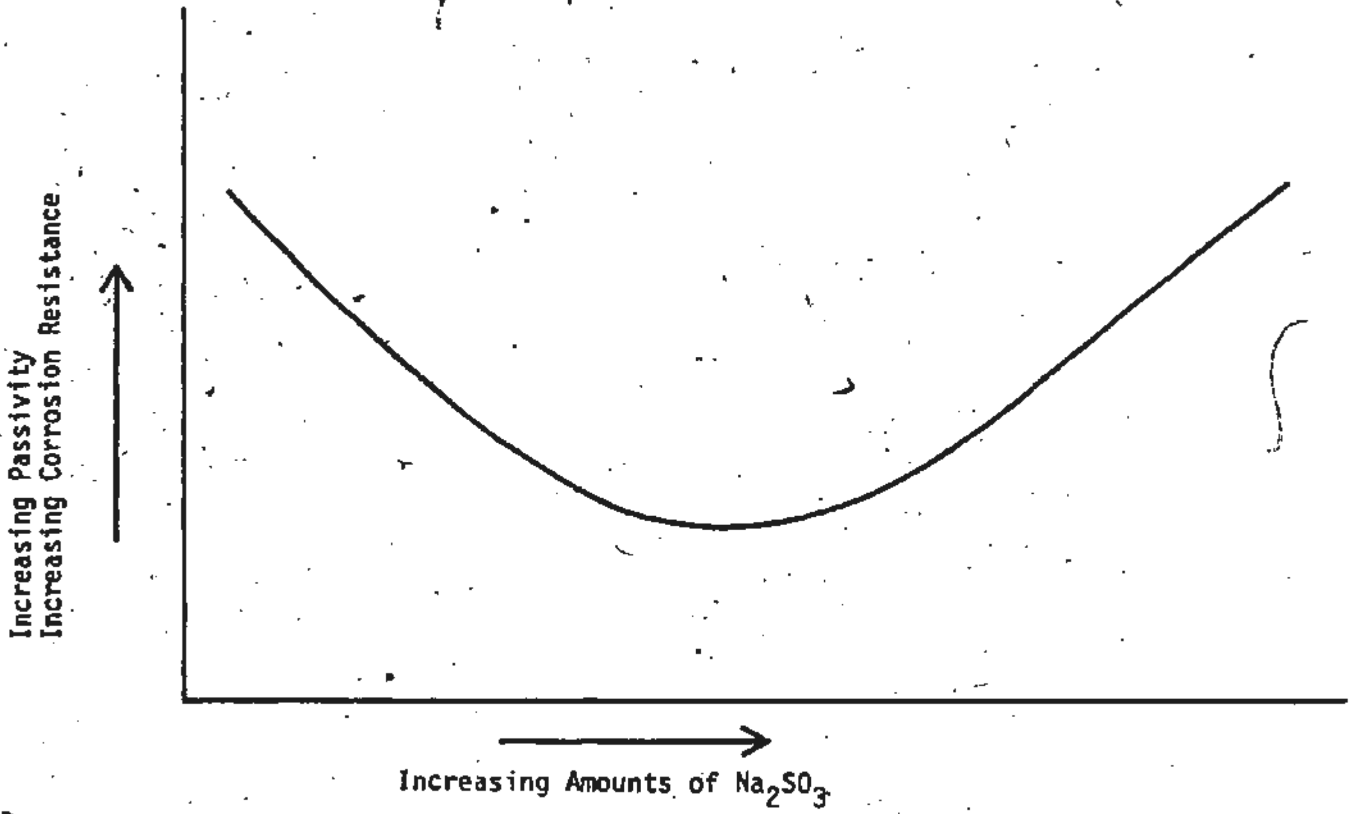


Fig. B7. Theoretical Curve of Na_2SO_3 added versus Increased Passivity

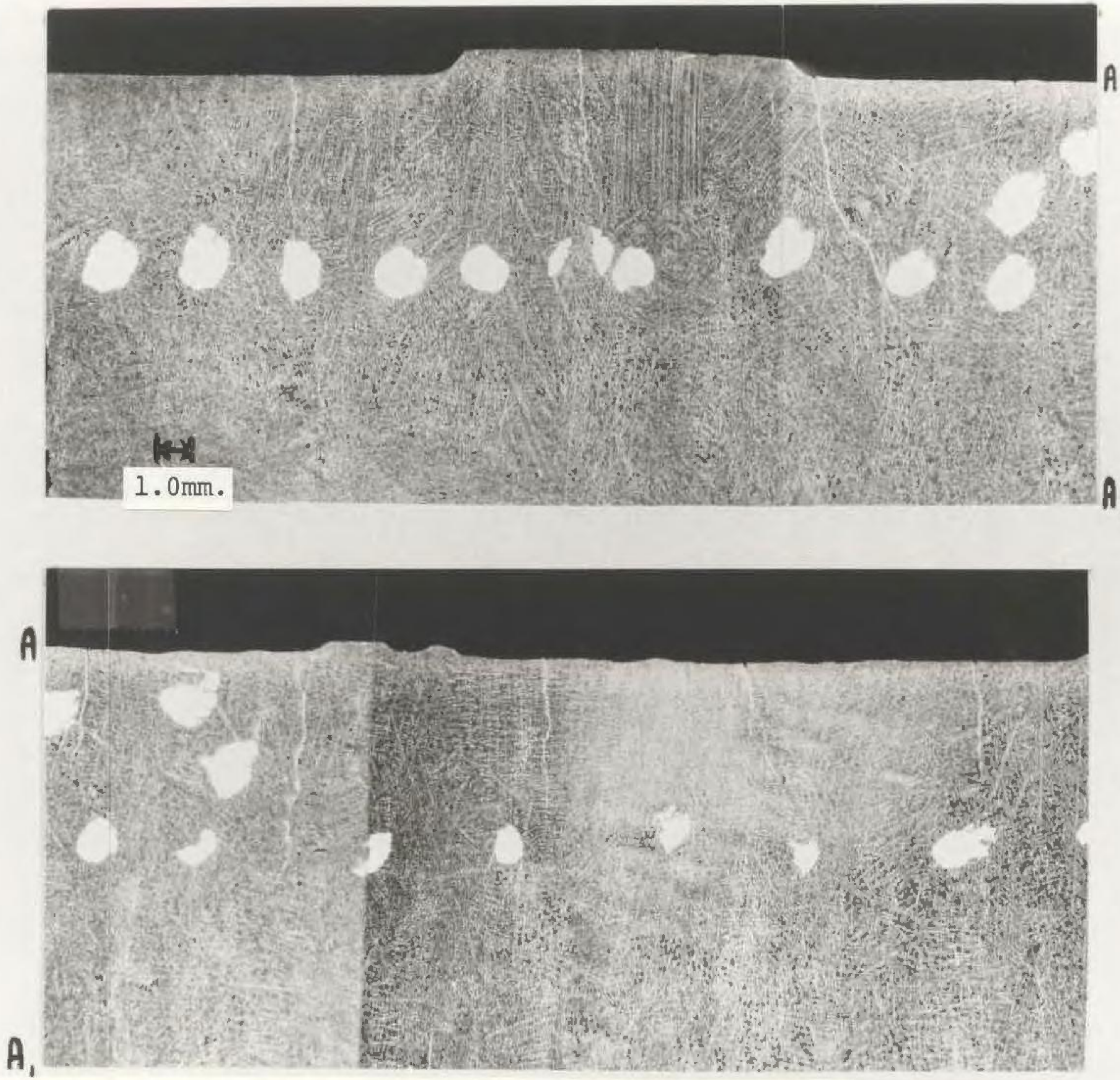


Fig. 88. Radial cracks along intermediate bar (6X)

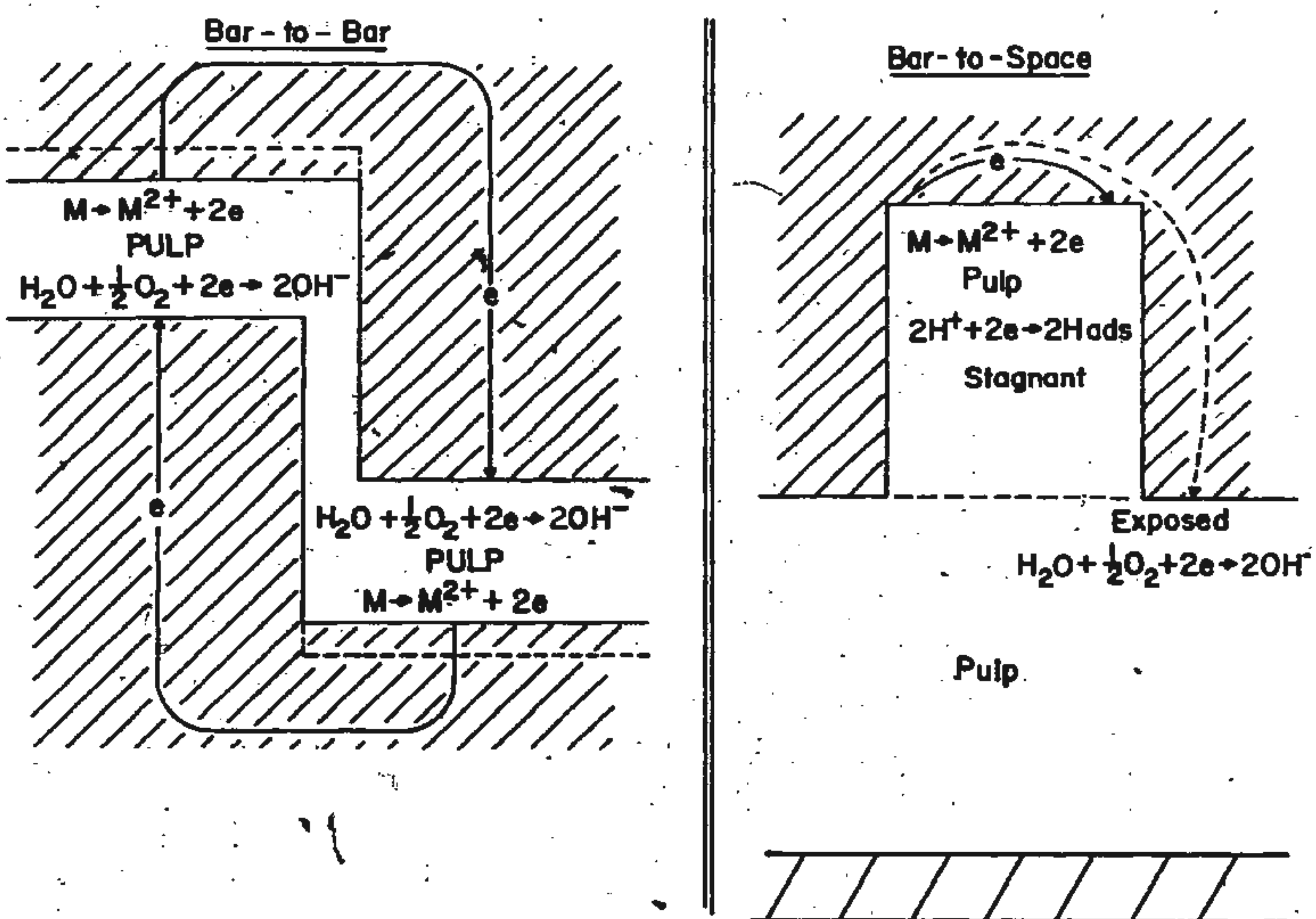


Fig. 89. Hypothesis for formation of ridge-groove pattern.

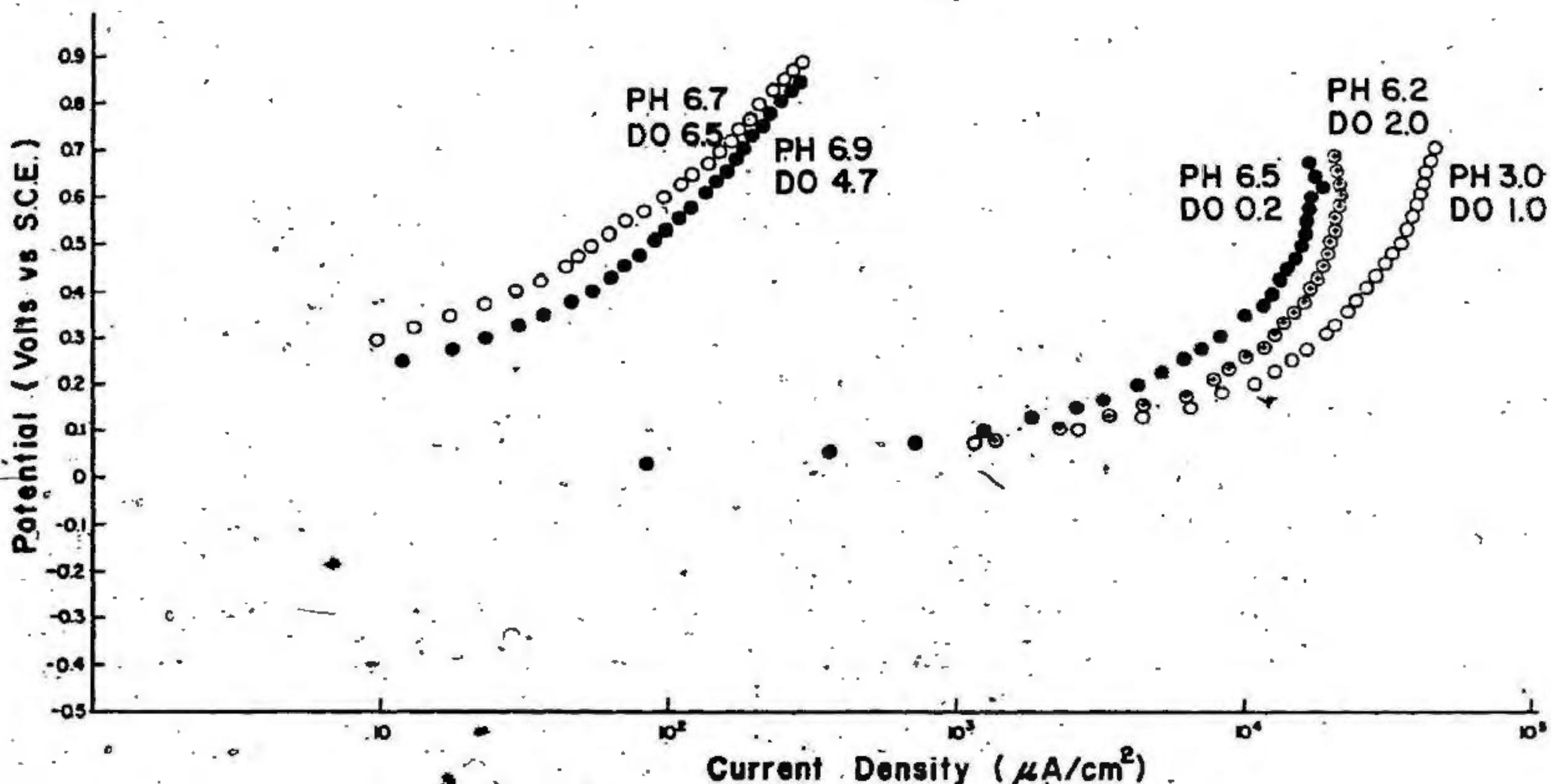


Fig. 90. Anodic polarization curves for Ni-hard refiner plate, buffered with Na_2SO_3 - solution agitated.

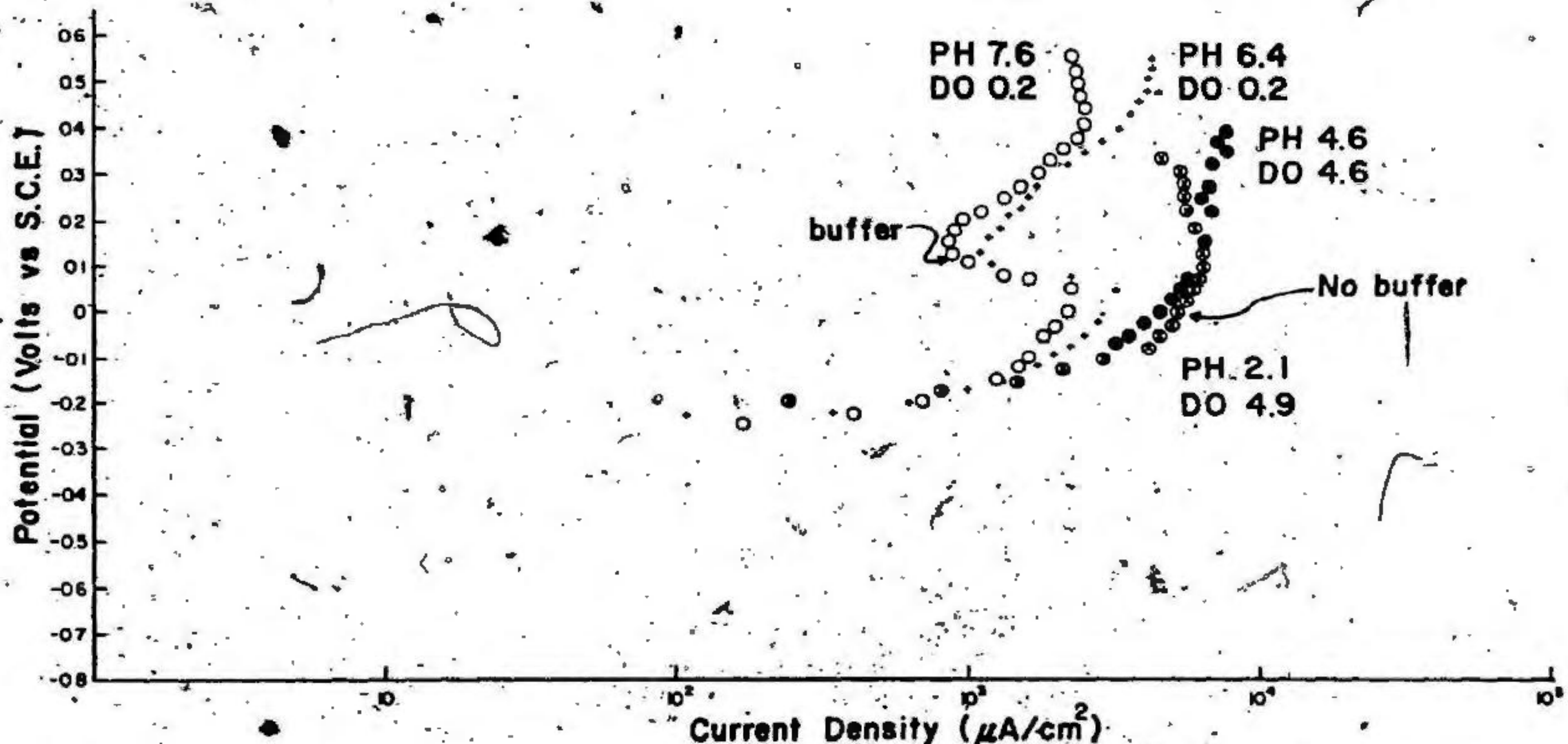


Fig. 91. Anodic polarization curves for Ni-hard refiner plate, buffered with Na_2SO_3 - solution stagnant.

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APPENDIX A

DETAILS OF ELECTROCHEMICAL MACHINING

APPENDIX A

DETAILS OF ELECTROCHEMICAL MACHINING (ECM)

- controlled removal of metal without the use of mechanical or thermal energy
- electric current is combined with a chemical to form a reaction of reverse plating
- direct current of relatively high amperage and low voltage is continuously passed between the anodic workpiece and cathodic tool (electrode) through a conductive electrolyte
- at the anode surface, electrons are removed by the current flow, and the metallic bonds of the molecular structure of this surface are broken
- these surface atoms proceed to go into solution as metal ions
- simultaneously, positive hydrogen ions are attracted to the negatively charged surface, and emitted at the cathode surface to form hydrogen atoms, which combine to form hydrogen molecules
- dissolved material is removed from the gap between workpiece and tool by the flow of electrolyte, which also aids in carrying away the heat and hydrogen formed
- machines surfaces without burrs and without the striation marks left by milling cutters
- freedom from metallurgical damage
- during ECM, hydroxides are generated rapidly, and large volumes of electrolyte are therefore required
- the products of machining are generally metal oxides or hydroxides. They have an extremely small particle size (in the order of 1.0μ) and cannot be easily filtered
- ECM machining is stress-free and thus only relieves stresses in the part
- major advantages of the ECM process include stress – and burr-free machining, no burning or thermal damage to workpiece surfaces, and elimination of tool wear (since there is no tool-to-workpiece contact)

- as a result, undesirable surface defects that can occur with mechanical machining or grinding operations are avoided. Also, the surfaces produced frequently have better wear, friction, and corrosion resistant characteristics than those obtained with mechanical finishing

- surface finishes produced depend on the metal or alloy being processed, the electrolyte, and the operating conditions used

- average surface finishes obtained range from 10 to 30 μ in. ECM of nickel-base, cobalt base, and S.S. alloys generally produces smoother surfaces (5 to 15 μ in.) than those obtained from iron-base alloys and steels (25 to 60 μ in.)

- electrolytes are usually aqueous solutions of inorganic salts such as sodium chloride, potassium chloride, sodium nitrate or sodium chlorate

- current density, in amperes per square inch of cutting area, is the chief factor in determining the permissible rate of tool feed, as the metal removal process is governed by Faraday's law

- a change in pH of a salt electrolyte has little effect on its conductivity

- the conductivity of an electrolyte changes greatly with temperature

- rate of flow of the electrolyte is important because the electrolyte must remove the heat and the products of the chemical reaction

- rate of flow also has an effect on surface finish and on accuracy of machining. High electrolyte flow rate often improves the uniformity of metal removal with a given electrolyte without reducing the removal rate

- a peculiarity of ECM is the production of striations, ridges or proturbances on the workpiece opposite or near the electrolyte flow channels in the tool or at other points where sudden changes in flow direction cause a stagnant condition

- microscopic surface defects may be caused by selective attack on certain constituents in an alloy

- the resistance of most nickel alloys to chemical attack does not seem to retard electrochemical solution

APPENDIX B

ASTM DESIGNATION G5-72 - STANDARD RECOMMENDED PRACTICE FOR STANDARD REFERENCE METHOD FOR MAKING POTENTIOSTATIC AND POTENTIODYNAMIC ANODIC POLARIZATION MEASUREMENTS

Standard Recommended Practice for

STANDARD REFERENCE METHOD FOR MAKING POTENTIOSTATIC AND POTENTIODYNAMIC ANODIC POLARIZATION MEASUREMENTS[1]

This Standard is issued under the fixed designation G 5; the number immediately following the designation indicates the year of original adoption or, in the case of revision, the year of last revision. A number in parentheses indicates the year of last reapproval.

1. Scope

1.1 This recommended practice describes an experimental procedure which can be used to check one's experimental technique and instrumentation. If followed, this practice will provide repeatable potentiostatic and potentiodynamic anodic polarization measurements that will reproduce data determined by others at other times and in other laboratories.

1.2 Standard potentiostatic and potentiodynamic polarization plots are included. These reference data are based on the results from different laboratories (15 for the potentiostatic and 12 for the potentiodynamic) that followed the standard procedure, using a specific ferritic Type 430 stainless steel in 1.0 N H_2SO_4. Maximum and minimum current values are shown at each potential to indicate the acceptable range of values.

1.3 Deviations from the standard reference plots and the causes for such deviations are discussed in the Appendix.

1.4 Samples of the standard ferritic Type 430 stainless steel used in obtaining the standard reference plots are available for those who wish to check their own test procedure and equipment.[2]

2. Equipment

2.1 *Standard Polarization Cell*,[3] described herein, can be used for most polarization measurements. This cell and its component parts have been described in more detail by Greene (1).[4]

2.1.1 A schematic diagram of the cell is shown in Fig. 1. A 1-liter, round-bottom flask has been modified by the addition of various necks to permit the introduction of electrodes, gas inlet and outlet tubes, and a thermometer. The Luggin probe-salt bridge separates the bulk solution from the saturated calomel reference electrode, and the probe tip can be easily adjusted to bring it in close proximity with the working electrode.

2.2 *Electrode Holder* (1):

2.2.1 The auxiliary and working electrodes are mounted in the type of holder shown in Fig. 2. A longer holder is required for the working electrode than for the auxiliary electrode. A leak-proof assembly is obtained by the proper compression fit between the electrode and a TFE-fluorocarbon gasket. (Too much pressure may cause shielding of the electrode or breakage of the glass holder, and too little pressure may cause leakage.)

2.3 *Potentiostat* (Note 1):

2.3.1 A potentiostat that will maintain an electrode potential within 1 mV of a preset value over a wide range of applied currents should be used. For the type and size of standard specimen supplied, the potentiostat should have a potential range of −0.6 to 1.6 V and an anodic current output range of 1.0 to 10^6

[1] This recommended practice is under the jurisdiction of ASTM Committee G-1 on Corrosion of Metals.

Current edition approved Sept. 29, 1972. Published November 1972. Originally published as G 5 - 69. Last previous edition G 5 - 71.

[2] These standard samples are available from ASTM Headquarters at a nominal cost. Generally, one sample can be repolished and reused for many runs. This procedure is suggested to conserve the available material. Request Adjunct No. 12-700050-00.

[3] This cell is available from Special Apparatus Section, Laboratory Glassware Dept., Corning Glass Works, Corning, N. Y.

[4] The boldface numbers in parentheses refer to the list of references at the end of this recommended practice.

(1975 Annual Book of ASTM Standards, Part 10, American Society for Testing and Materials, Philadelphia)

μA. Many commercial potentiostats meet the specific requirements for these types of measurements.

2.4 *Potential-Measuring Instruments* (Note 1):

2.4.1 The potential-measuring circuit should have a high input impedance on the order of 10^{11} to 10^{14} Ω to minimize current drawn from the system during measurements. Instruments should have sufficient sensitivity and accuracy to detect a change of 1.0 mV over a potential range between −0.6 and 1.6 V.

2.5 *Current-Measuring Instruments* (Note 1):

2.5.1 An instrument that is capable of measuring a current accurately to within 1 percent of the absolute value over a current range between 1.0 and 10^5 μA for the approximately 5-cm^2 specimen of Type 430 stainless steel that is supplied should be used. Many commercial instruments are satisfactory for this purpose.

2.6 *Anodic Polarization Circuit:*

2.6.1 A schematic potentiostatic anodic polarization wiring diagram (2) is illustrated in Fig. 3. Note that the milliammeter is placed between the potentiostat and the auxiliary electrode. The potentiometer-electrometer combination provides the high impedance necessary for potential measurement.

2.6.2 A scanning potentiostat is used for potentiodynamic measurements. A record of the potential and current is plotted continuously using such instruments as an X-Y recorder and a logarithmic converter incorporated into the circuit described in 2.6.1.

NOTE 1—The instrumental requirements are based upon values typical of the instruments in the 15 laboratories that provided the data used in determining the standard polarization plot.

2.7 *Electrodes:*

2.7.1 *Working Electrode*, prepared from a $^1/_2$-in. (1.27-cm) length of $^3/_8$-in. (0.95-cm) diameter rod stock. Each electrode is drilled, tapped, and mounted in the manner discussed in 2.2.1.

2.7.1.1 The standard AISI Type 430 stainless steel should be used if one wishes to reproduce the standard reference plot. This material was prepared from a single heat of metal that was mill-annealed for $^1/_2$ h at 1500 F (816 C) and air cooled. The chemical composition of the standard stainless steel is shown in Table 1.

2.7.2 *Platinum Electrodes*—Two platinum auxiliary electrodes are prepared from high-purity rod stock. Each electrode is drilled, tapped, and mounted with a TFE-fluorocarbon gasket in the same manner as the working electrode.

2.7.2.1 A platinized surface is recommended because of the increased surface area. This may be accomplished by cleaning the surface in hot aqua regia (3 parts concentrated HCl and 1 part concentrated HNO_3), washing, and then drying. Both electrodes are platinized by immersing them in a solution of 3 percent platinic chloride and 0.02 percent lead acetate and electrolyzing at a current density of 40 to 50 mA/cm^2 for 4 or 5 min (1,3). The polarity is reversed every minute. Occluded chloride is removed by electrolyzing in a dilute (10 percent) sulfuric acid solution for several minutes with a reversal in polarity every minute. Electrodes are rinsed thoroughly and stored in distilled water until ready for use. Since certain ions can poison these electrodes, periodic checks of platinized platinum potentials against a known reference electrode should be made.

2.8 *Calomel Electrode* (4)—A saturated calomel electrode with a controlled rate of leakage (about 3 μl/h) is recommended. This type of electrode is durable, reliable, and commercially available. The normal precautions should be taken to ensure that it is maintained in the proper condition. The potential of the calomel electrode should be checked at periodic intervals to ensure the accuracy of the electrode.

3. Standard Experimental Procedure

3.1 *Test Specimen Preparation:*

3.1.1 Prepare the surface within 1 h of the experiment. Wet grind with 240-grit SiC paper, wet polish with 600-grit SiC paper until previous coarse scratches are removed, rinse, and dry. (Drilled and tapped specimens can be threaded onto an electrode holder rod and secured in a lathe or electric drill for this operation.)

3.1.2 Determine the surface area by measuring all dimensions to the nearest 0.01 mm, subtracting the area under the gasket (usually 0.20 to 0.25 cm^2).

3.1.3 Mount the specimen on the electrode holder as described in 2.2.1. Tighten the assembly by holding the upper end of the mounting rod in a vise or clamp while tightening the mounting nut until the gasket is properly compressed.

3.1.4 Clean the specimen just prior to immersion by degreasing for 5 min in boiling benzene (Caution: Use under hood), followed by rinsing in distilled water.

3.2 Prepare 1 liter of 1.0 N H_2SO_4 from reagent grade acid and distilled water, using 27.2 ml of 98 percent H_2SO_4/liter of solution. Transfer 900 ml of solution to clean polarization cell.

3.3 Bring the temperature of the solution to 30 $\pm$ 1 C by immersing the test cell in a controlled-temperature water bath or by other convenient means.

3.4 Place the platinized auxiliary electrodes, salt-bridge probe, and other components in the test cell and temporarily close the center opening with a glass stopper. Fill the salt bridge with test solution.

NOTE 2—The levels of the solution in the reference and polarization cells should be the same to avoid siphoning. If this is impossible, a closed solution-wet (not greased) stopcock can be used in the salt bridge to eliminate siphoning.

3.5 Purge the solution prior to immersion of the test specimen, for a minimum of ½ h with oxygen-free hydrogen gas at the rate of 150 cm^3/min to remove oxygen from solution.

3.6 Transfer the specimen to the test cell and adjust the salt-bridge probe tip so it is about 2 mm from the specimen electrode.

3.7 Record the open-circuit specimen potential, that is, the corrosion potential, after 55 min immersion. Record the platinized platinum potential 50 min after immersion of the specimen.

3.8 *Potential Scan:*

3.8.1 Start the potential scan 1 h after specimen immersion, beginning at the corrosion potential (E_{corr}) for potentiodynamic measurements and the nearest 50-mV increment above E_{corr} for the potentiostatic measurements. Proceed through +1.60 V versus saturated calomel electrode (SCE) (active to noble).

3.8.2 Use a potentiostatic potential step rate of 50 mV every 5 min, recording the current at the end of each 5-min period at potential.

3.8.3 Use a potentiodynamic potential sweep rate of 0.6 V/h ($\pm$5 percent) recording the current continuously with change in potential.

3.9 Plot anodic polarization data on semilogarithmic paper in accordance with ASTM Recommended Practice G 3, for Conventions Applicable to Electrochemical Measurements in Corrosion Testing[3] (potential-ordinate, current density-abscissa).

4. Standard Reference Plots

4.1 Standard polarization plots based on potentiostatic data from 15 different laboratories and potentiodynamic data from 12 different laboratories are shown in Figs. 4A and 4B (5). The plots show a range of acceptable current density values at each potential. The average corrosion potential is −0.52 V, and the average platinized platinum potential is −0.26 V.

4.2 These plots were prepared from data obtained by following the standard procedure discussed in this recommended practice.

4.3 Typical deviations from the standard potentiostatic plot are shown and discussed in Appendix A1. Reference to this discussion may be helpful in determining the reasons for differences between an experimental curve and the standard plots.

4.4 The potentiodynamic standard curve shows good agreement with the potentiostatic standard curve determined at an equivalent overall polarization rate.

5. Reproducibility

5.1 It is possible to show excellent repeatability in the same laboratory when following a set procedure. However, these data may not agree with that in another laboratory. An example of repeatable data is shown in Fig. 5, but the curve does not agree completely with the standard plot in that the secondary current density maximum occurs at a potential of about 100 mV more active than the standard.

5.2 The small spread in data obtained from a number of laboratories and used in the preparation of the standard plot demonstrated that good reproducibility is possible when a stand-

[3] *Annual Book of ASTM Standards*, Part 10.

ard procedure is followed.

5.3 The availability of a standard procedure, standard material, and a standard plot should make it easy for an investigator to check his techniques. This should lead to polarization curves in the literature which can be compared with greater confidence than is possible now.

TABLE 1 Chemical Composition of Standard Type 430 Stainless Steel, Weight Percent

Chromium	16.52
Carbon	0.052
Manganese	0.40
Silicon	0.49
Phosphorus	0.013
Sulfur	0.009
Nickel	0.27
Molybdenum	0.03
Copper	0.07
Iron	balance

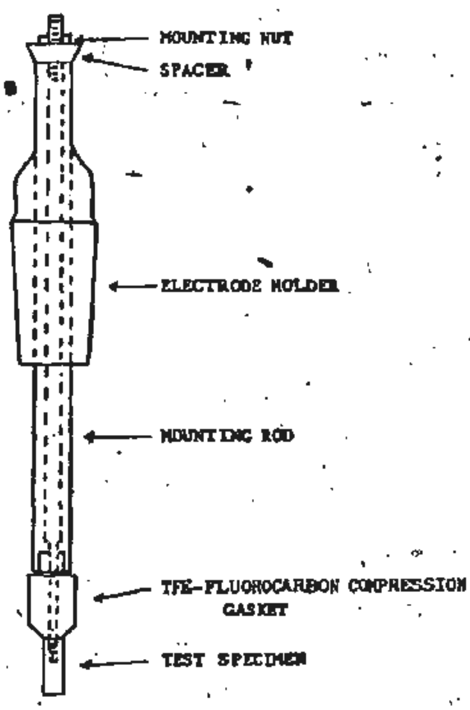

FIG. 2 Specimen Mounted on Electrode Holder.

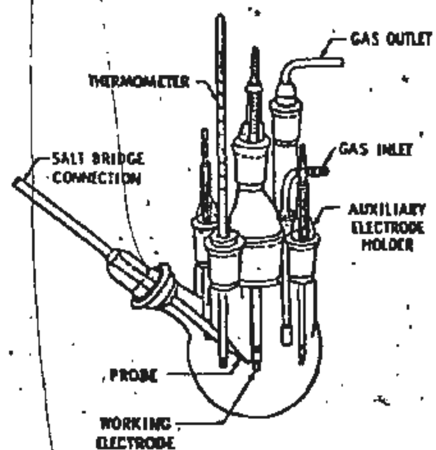

FIG. 1 Schematic Diagram of Polarization Cell (1).

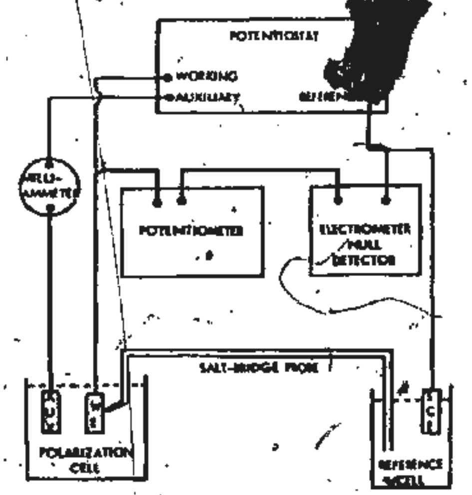

FIG. 3 Schematic Potentiostatic Anodic Polarization Wiring Diagram (2).

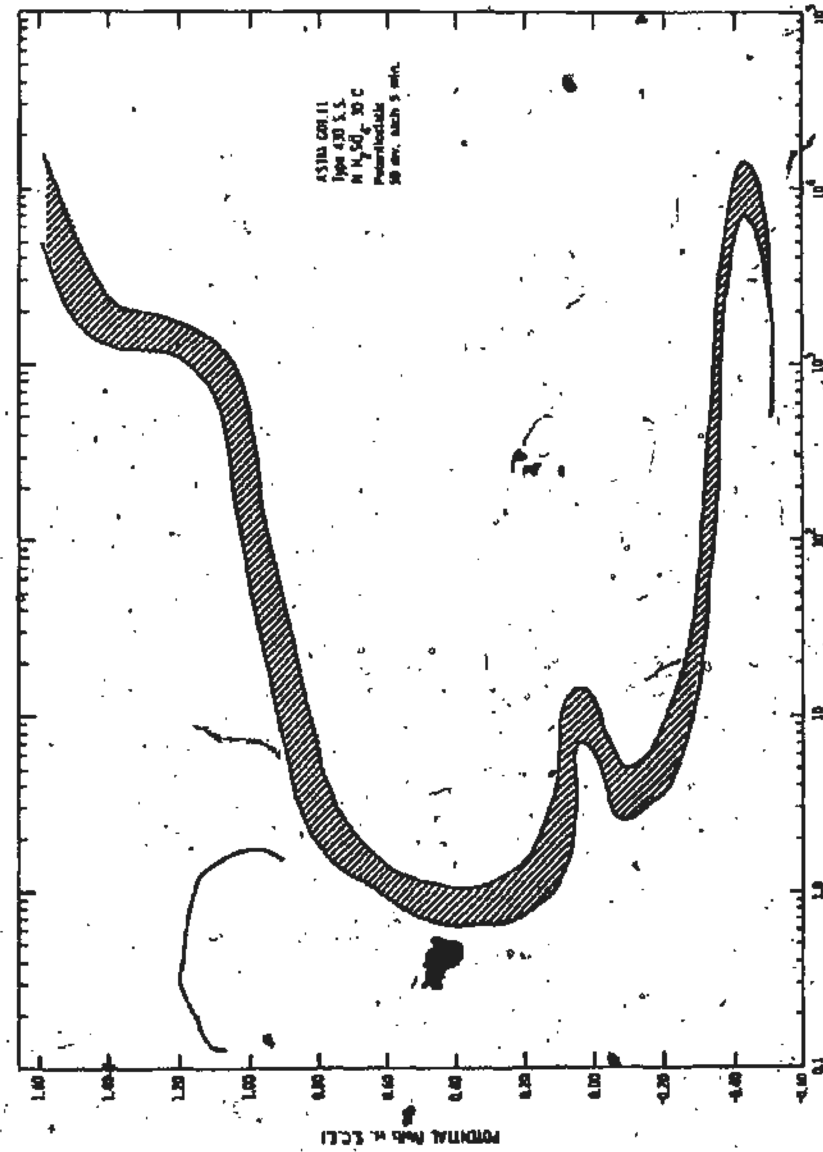

FIG. 4A Standard Potentiostatic Anodic Polarization Plot.

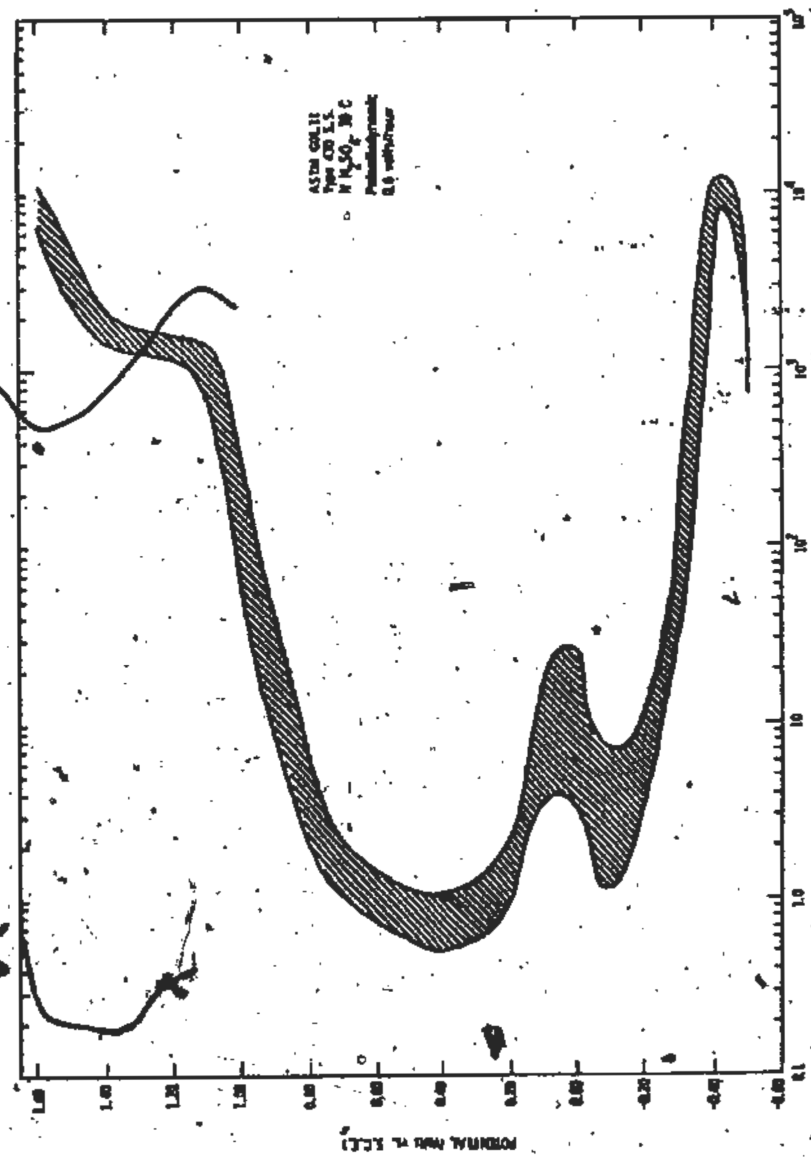

FIG. 4B Standard Potentiostatic Anodic Polarization Plot.

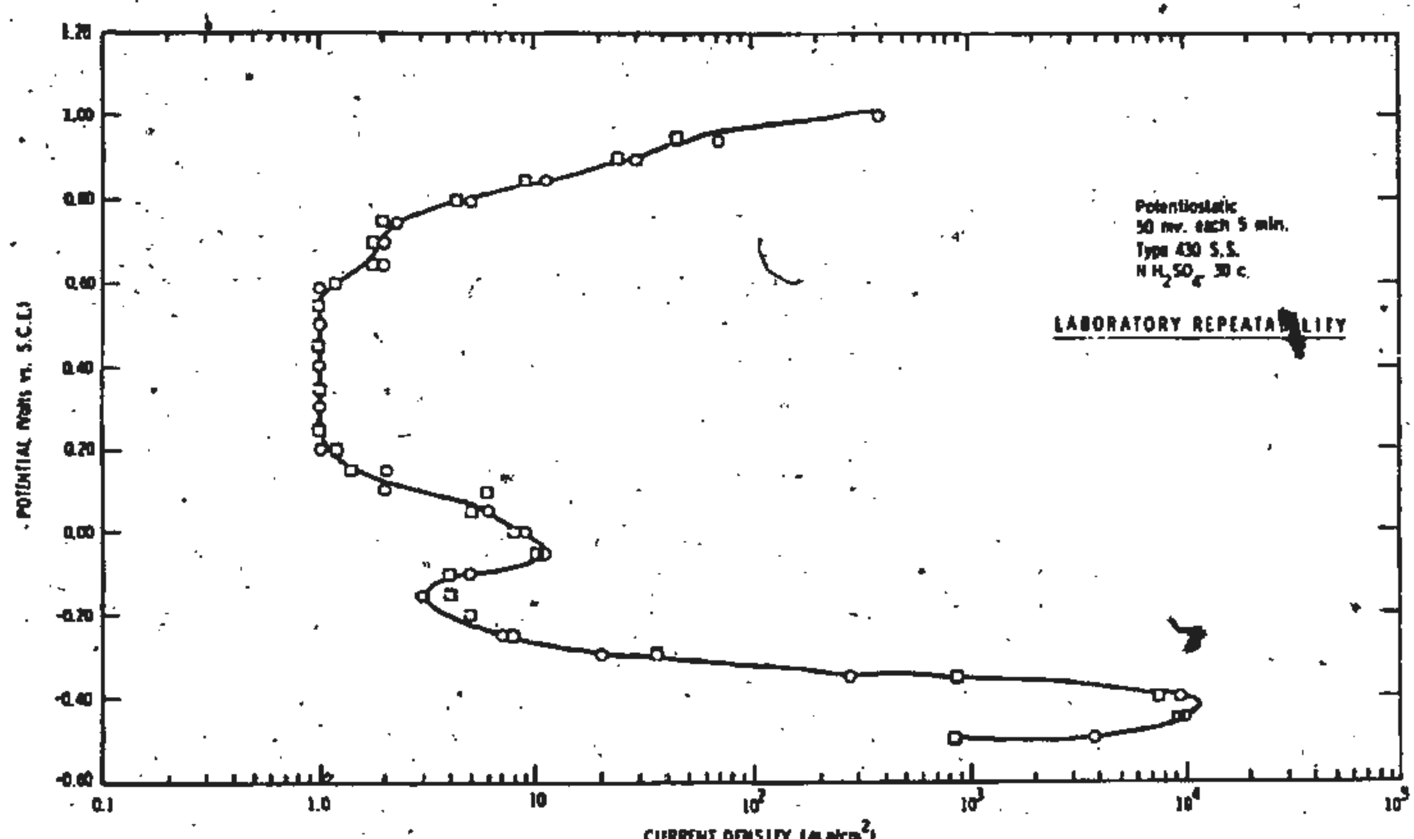

FIG. 9 Laboratory Repeatability of Potentiostatic Anodic Polarization Curve.

APPENDIX

A1. DEVIATIONS FROM STANDARD POLARIZATION PLOTS

A1.1 High Passive Current Densities (Crevice Effect)

A1.1.1 Examples of passive current densities which are greater than those for the standard potentiostatic plot are shown in Fig. A1. This effect is attributable to a crevice between the specimen and mounting material (6). The crevice may be the result of the mounting technique or the material used for mounting.

A1.1.2 The potential drop along the narrow path of the electrolyte within the crevice between the specimen and the mounting material prevents this area from passivating. Although the face of the specimen passivates, the high current density associated with the active crevice contributes to an increase in the measured current density. Specimen electrodes for polarization measurements must be mounted without crevice sites to avoid such erroneous passive current densities.

A1.2 Low Passive Current Densities (Instrumental Effect)

A1.2.1 The low passive current densities shown in Fig. A2 are undoubtedly the result of instrumental problems. This effect can be eliminated by calibrating the current over the entire range of interest before conducting an experiment.

A1.3 Cathodic Currents During Anodic Polarization (Oxygen Effect)

A1.3.1 The "negative loop" at potentials between −0.350 V and −0.050 V, shown by dashed lines in Fig. A3, occurs when the total cathodic current exceeds the total anodic current. Such results are characteristics of oxygen being present in the solution (7). This effect can be anticipated if the recorded platinum potential is considerably more noble than −0.26 V. The hydrogen purge should remove oxygen from the system, but there may be an air leak or the hydrogen may be contaminated with oxygen. It is necessary to take extreme care in the design of glassware equipment and to ensure a high order of purity in the gas that is used to avoid oxygen contamination.

REFERENCES

(1) Greene, N. D., *Experimental Electrode Kinetics*, Rensselaer Polytechnic Institute, Troy, N. Y., 1965.

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(3) Mellon, M. G., *Quantitative Analysis*, Thomas Y. Crowell Co., New York, 1955.

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(6) Greene, N. D., France, Jr., W. D., and Wilde, B. E., "Electrode Mounting for Potentiostatic Anodic Polarization Studies," *Corrosion*, CORRA, Vol 21, 1965, p. 275.

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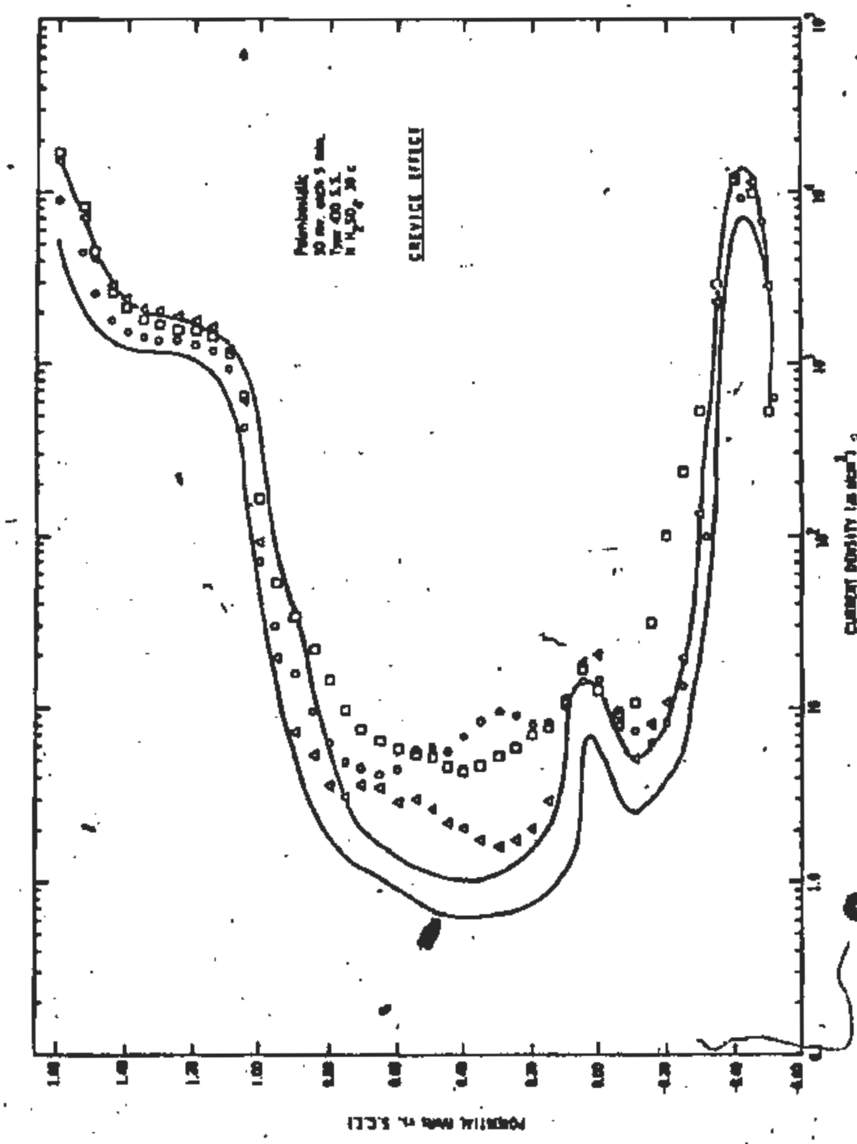

FIG. A1 Crevice Effect During Potentiostatic Anodic Polarization.

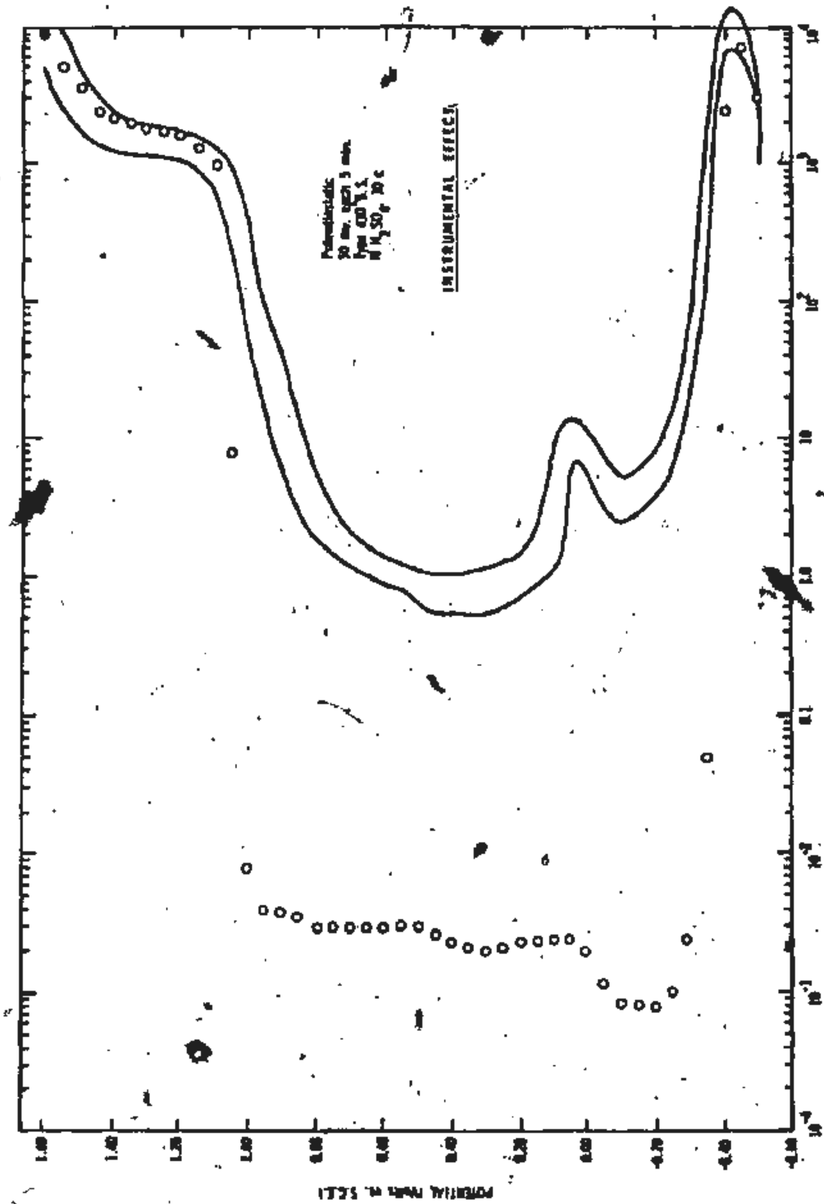

FIG. A2 Instrumental Effect During Potentiostatic Anodic Polarization

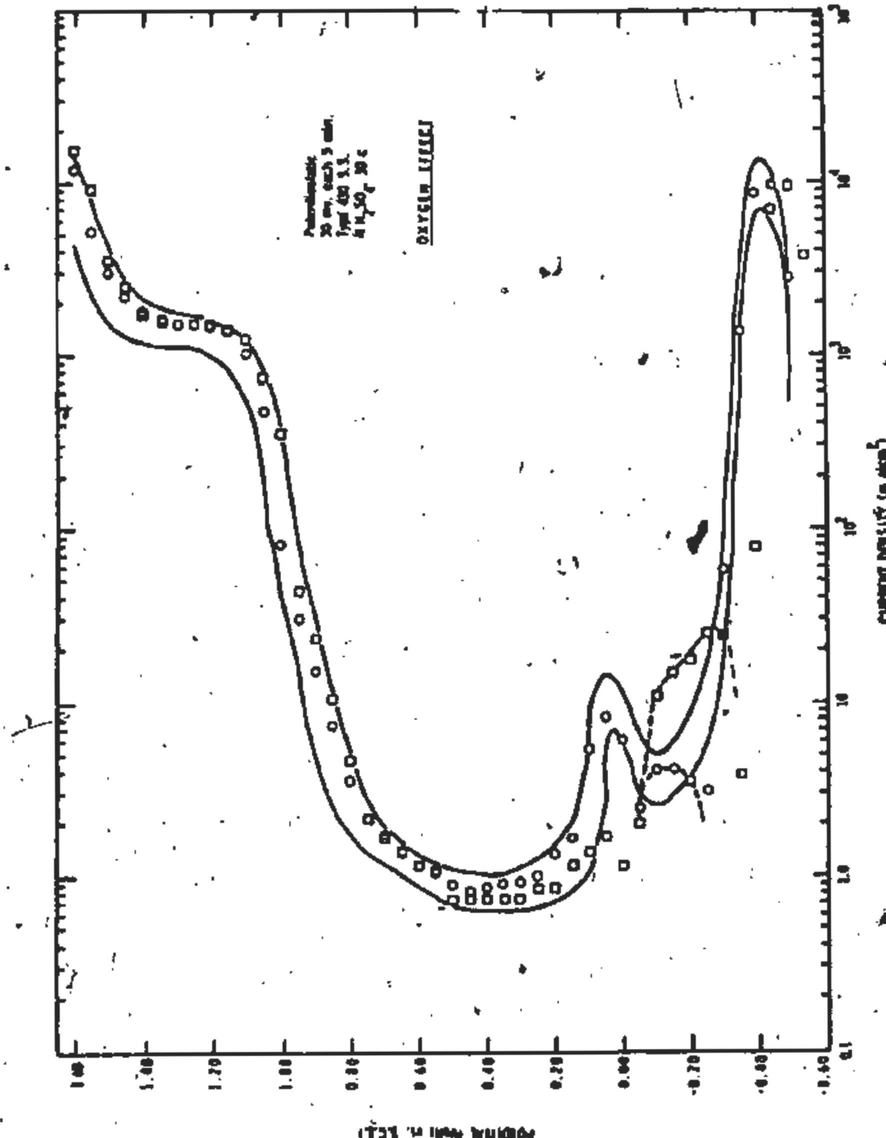

FIG. A3 Oxygen Effect During Potentiostatic Anodic Polarization.