EVALUATION OF FIVE LABORATORY GRINDERS ON THE BASIS OF THE PARTICLE SIZE OF THE GROUND MATERIAL AND THE ENERGY CONSUMPTION

by

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INTRODUCTION

The need to break down a solid material in the laboratory is a daily requirement. Laboratory grinders have been extensively used by research and control laboratories, nutritional laboratories, malting companies, flour mills, and feed mills, for routine analysis of grains. The operation performed by laboratory grinders has been described by various terms such as: grinding, size reduction, comminution.

There are many types of grinders available on the market and, in selecting one of them for a specified duty, the questions that are raised are about the same as for large units of commercial mills, that is (5):

- What type of machine should be selected, i.e. what type of size reduction forces would best do the job for the intended purpose?

- What maintenance will be required, or how can wear be reduced to tolerable levels?

- What will be the performance of the mill under varying feed conditions and what are the optimum operating conditions?

The first two questions are closely related, and their answers depend primarily on the feed material itself. The answers to the third and fourth questions concerns what the theory of size reduction is all about.

Another factor which should be taken into consideration is the initial cost of the grinder. Certain grinders are priced far beyond their usefulness, and, also, the most expensive grinders are not necessarily the best from aspects of either durability or performance.

However, to truly determine a unit's benefit, it is necessary to compare it with other machines that are designed to do the same job. This comparison should deal with the different points mentioned, i.e. capacity, life and maintenance of the machine, quality of the finished product, and cost of the grinding operation.

The purpose of this study is to evaluate five laboratory grinders on the basis of the particle size of the ground material and the energy consumption.

REVIEW OF LITERATURE

Since the operation conducted on laboratory grinders is the subdivision of large particles or of solids into particles of smaller size, a review of the overall process of size reduction is a must. This will include the mechanism and theory of size reduction, together with the properties of material which play a major part in the process, and the different ways to achieve size reduction. Particle size and particle size measurement methods are essential to fundamental and practical development in the field of size reduction and, therefore, should not be overlooked. Additionally, the critical factors that affect the work of a laboratory grinder should also be considered.

Mechanism and Theory of Size Reduction

In the grinding process, materials are reduced in size by fracturing them. In the process, the material is stressed by the action of mechanical members of the grinding machine, and, initially, the stress is absorbed internally by the material as strain energy. When the local strain energy exceeds a critical level, which is a function of the material, fracture occurs along cleavage planes or lines of weakness in the material, and the stored energy is taken up in the creation of new surface; however, the greater part of it is dissipated as heat. Grinding is, therefore, achieved by mechanical stress followed by rupture (10).

Loncin and Merson (21), describing the behavior of a solid under an applied stress, refer to an elastic state before fracture. They define the elastic stress limit, the yield stress, the region of ductility, and the breaking stress. They also state that the most important characteristic is the modulus of elasticity, that is the stress causing a unit change in length in the same direction as the applied force. The "modulus of rigidity," on the other hand, expresses the relationship between a purely shear stress and shear strain.

As far as the theory of size reduction is concerned, Austin and Klimpel (5) stress the inadequacy of the existing grinding "laws." After a review of the laws of comminution proposed by Rittinger, Kick, Bond, the Rosin-Rammler distribution, they conclude that "reliance on these laws must be abandoned." This point of view is shared by Snow et al (26) who consider that the conventional laws of comminution have failed to yield a starting point for further development of understanding of milling.

Furthermore, Austin and Klimpel suggest a mechanistic approach to the operation of grinding. The basic concept involved is to split the operation into two parameters, the selection function, now termed the grinding rate function, and the distribution or breakage function. The grinding rate function represents the fractional amount of any given size present in the mill which is selected for breakage in a differential increment of grinding. The distribution function, on the other hand, represents the primary breakage distribution of a given size on breakage.

The mechanistic approach to grinding operations as proposed by Austin and Klimpel, however, is limited to the batch milling process. To extend the theory to continous milling processes, Reid (29) suggests consideration of a third function: the retention time distribution of particles flowing through a mill. This function represents the effect of mixing on the product size distribution in a mill. An application of this theory to the design of a closed-circuit grinding system is described by Furuya <u>et al</u> (12).

Characteristics of the Feed Material

The properties of material which are of importance from the standpoint of the mechanism of size reduction are hardness, toughness (or friability), abrasiveness, stickiness, moisture content, softening point of the material, and structure (8). These properties may not be uniform throughout a material due to changes of composition and may, also, change with temperature.

A knowledge of the hardness of the feed material can be important in selecting comminution equipment: hard materials are more difficult to grind, more energy is required, and residence times in the "action zone" must be longer. This may necessitate a slower throughput for a given mill or a larger capacity mill (7). Methods for testing kernel hardness are reviewed by Shellenberger (32); they are classified as compressing, cutting, pearling, grinding, and penetrating, according to the type of treatment applied to the kernel. The effects of hardness both in conditioning and milling are examined by MacRitchie (23) who also exposes a theory of grain hardness.

Another property of material closely related to hardness, which plays an important role, is abrasiveness. Hard materials are usually abrasive so wear of working parts can be pronounced, resulting in additional maintenance costs.

The presence of water can both aid and hinder a comminution process. With many materials moisture content in excess of 2% to 3% can lead to clogging of the mill (7). Throughput and grinding efficiency may suffer. Agglomeration can also occur in the presence of moisture whereas, on the opposite side, dust formation arising during the dry milling of many solids can cause problems.

Also, the softening point of the material has to be considered. Heat generated during the grinding operation can lead to a considerable rise in temperature of the material being processed which in return can result in the development of a sticky charge that will clog the mill. Williams (41) reports that there is no grinder of practical value to the routine processing of grain that does not heat up and cause moisture loss during prolonged grinding.

A knowledge of the mechanical structure of the feed material can indicate the type of force most likely to effect disintegration. Whereas compressive forces are preferred in a grinding operation dealing with friable materials, because fracture occurs easily along cleavage planes; impact reduction may be better if the material presents only few cleavage planes and new crack tips have to be formed. In the case of a fibrous structure, cutting will be advised.

Nature of Forces Involved in Size Reduction

There are four basic ways to reduce a material: compression, impact, attrition or rubbing, and cutting. Size reduction machines make use of one or more of these methods, and the selection of any of them for a specific purpose is governed to a great extent by the nature of the feed and the degree of fineness which is desired.

Compression:

Compression is accomplished by applying the compressive force to the particle to be ground with a more or less slow crushing action. Various machines may be used to apply the compressive force, but preference is given to the roller mill. The effect of roll pressure on the grinding process when grinding with commercial size roller mills was investigated by Ward and Shellenberger (38). Among the factors investigated was the energy consumption. The study showed that horsepower required to drive the rolls increased proportionally with roll pressure.

A description of a roller mill will show that it consists of a pair of rolls and drive arrangement. An integral feeder mechanism is part of the equipment. The mill is enclosed in a casing for confining the dust. The rolls rotate toward each other at the same or different speeds, so one is described as the holding roll and the other a steering roll. Thus, along with direct pressure, the roller mill effects size reduction partly by shear between the rotating cylindrical surfaces. The surfaces are either smooth or corrugated. Corrugations and differential speeds are usually arranged for a specific purpose of size reduction. It is also worth noting that the distance between the rolls can be adjusted, owing to the fact that one of the rolls is set in fixed bearings, while the other is set in adjustable bearings.

In considering the capacity and grinding action of the rolls, Ward (37) refers to the surface of the rolls, speed, differential, spiral, corrugations for break rolls, and surface, speed, differential on smooth rolls as being the principal factors to deal with.

Impact Grinding:

In impact grinding, a particle in free flight strikes, or is struck by, a heavy machine element such as a screen or a hammer, or even may collide with another particle. Thus two variations of impact may occur: gravity impact and dynamic impact. A solid material dropped onto a hard surface such as steel plate is an example of gravity impact. Material dropping in front of a moving hammer, both objects in motion, illustrates dynamic impact.

The energy for the rupture of the particle is produced essentially from kinetic energy. The reduction taking place would then depend on the relative velocity of the particle and the impact surface (27). A classification of impact grinders into three groups, with reference to the number of impacts received by the material, is given by Hibbs (14). The three groups are 1) single-stage grinders (one type of impact only), 2) two-stage grinders (two kinds of impact occur), and 3) multi-stage grinders (several impacts occur).

Regarding the field of application of impact forces in the size reduction of food materials, Brennan et al (7) consider these as general purpose forces used for coarse, medium,and fine grinding. Impact grinding is well exemplified by hammermills of various designs. In general, these machines consist of fixed or swinging hammers mounted on a rotating shaft. The rotor shaft may be vertical or horizontal, generally the latter. The rotor runs in a housing containing grinding plates or liners. A cylindrical screen usually encloses all or part of the rotor. Even though attrition forces play a part in the grinding process, it is when the hammers strike the material as it falls into the mill that most of the grinding occurs (27).

The factors affecting grinding efficiency have been reviewed by many workers (26, 27, 34). Sterrett and Sheldon (34) report that screen opening and number of hammers, together with the clearance of the hammers to the screen, are among the principal parameters affecting hammermill grinding. They furthermore point out a relationship existing between the size of the screen opening and hammer-to-screen-clearance. Included in their study is the effect of air on hammermill performance. On the other hand, Leniger and Beverloo (20) and Slade (33) also include peripheral speed as one of the most important factors in efficient hammermill operation.

Another type of impact mill frequently used is the pin mill. In its simpliest form, the mill consists of a stationary disc with a rotating disc a short distance away; both discs are set with pegs, pins, or teeth. There are always a number of concentric rows of pegs. The pegs in the inner circles are often different in shape and are placed at different distances from each other, compared with the pegs in the outer circles (20). Size reduction is accomplished by impact at the studs of the inter-meshing stud rows arranged on the two grinding discs. The material being ground is sucked in by the air current produced by the stud discs and then arrives at the center of the grinding discs. Every particle passes the different stud rows, from inside to outside, where it is reduced to the desired fineness (2).

Attrition Mills:

Attrition is the term applied to the reduction of material by scrubbing it. It is believed to be perhaps the best known form of grinding (18). Mills utilizing attrition forces are called under various names: burr mills, attrition mills, plate mills, and disc mills.

Grinding takes place between the plates which may operate in a vertical or a horizontal plane. These plates can be provided with all kinds of grooves to improve grinding efficiency. In some cases, one disc is stationary and the other rotates, while in others both discs revolved in opposite directions, thus the distinction between single disc attrition mill and double disc attrition mill. These mills are reviewed by Snow et al (26).

Among the factors affecting grinding, Hall et al (13) cite the design and speed of plates, the wear of plates, the pressure on the burr, the rate of feeding, the material being ground, and the moisture content of the grain. They also state that, for any given modulus of fineness, the power required to grind decreases as the speed of the mill increases; the power requirements decrease to a speed of about 2000 rpm.

Pfost (27), comparing performances of attrition mills and hammermills, stresses the superiority of attrition mills in producing a coarser product, whereas hammermills are more efficient when producing a finer product. It is also believed (13, 27) that attrition mills give a more uniform ground product than do hammermills.

Cutting:

In some size reduction problems, the feed stocks are too tenacious or too resilient to be broken by compression, impact, or attrition. In this case, mills having a cutting action are used. There are many types of cutters available. Some are precision units that produce a particle of exact size and shape. Others, the non-precision cutters, produce random particle size and shape. The difference between both types is that in precision knife cutters a feeder is synchronized with the knives (26).

Basically, the mechanical action of the cutting machines falls into two groups: 1) where pieces to be cut are thrown or held against a moving knife and 2) where pieces are forced or thrown against stationary knives. In either case, the major problem is to keep the knives sharp, so they cut rather than tear. From a standpoint of energy consumption, Rietz and Schreffler (17) consider the action of cutting machines as one of the most efficient size reduction methods; cutting action is obtained with the minimum amount of energy expanded on friction and deformation of particle size. However, when an attempt is made to produce very small particles by cutting, the use of energy and the cost of the operation approaches or exceeds other methods of grinding.

Miscellaneous Grinding Equipment:

In the mills we have reviewed, several mechanisms are sometimes involved in the grinding operation, but because a certain mechanism is often dominant, the grinding operation was designated accordingly as compression, impact, attrition, or cutting. This is not the case of those mills, known as tumbling mills, where the particle size reduction is due to the simultaneous action of compression, impact, and friction, in almost equal proportion. Snow et al (26) gives an exhaustive description of these mills which include ball, pebble, rod, tube, and compartment mills. Most of these have not found their way in the food industry. But, evidence exists that ball mills have had some applications. Schlesinger (31) reports a study of ball mill action on buhler experimentally milled flour. D'Appolonia and Gilles (9) conducted tests on flour damaged by ball milling and roller milling to determine the effect of overgrinding on protein structure. Lorenz and Johnson (22) investigated the effect of starch damaged by ball milling on dough properties and quality of continuous-mix bread. More recently, the introduction of a new ball mill as a laboratory grinder for grain is reported (41); it is called the Retsch Centrifugal grinder.

Ball mills may be cylindrical or conical. They employ steel balls as grinding medium and have metal linings (33). As the mill rotates, the balls tend to be carried up the side of the mill and then fall down. The tumbling action of the balls produced by the rotation of the mill is responsible for the grinding of the particles of material. Size reduction occurs by compression and attrition as the material is rubbed around in the ball chamber and, also, by impact of the balls falling from the upper part of the mill. Grinding continues all the time that the mill is rotated at a speed below that at which centrifuging of the balls occurs. When this happens, the balls are held against the shell as it turns; there is no tumbling action and, in consequence, no grinding. This critical speed is a function of the mill diameter (18). Brennan et al (7) show how speed of rotation of the mill affects the grinding operation and suggest that the mill be operated at about 75% of the critical speed for optimum grinding efficiency. With the speed of the mill, Doris et al (42) include also ball size and loading, ratio of different ball sizes, size of the feed, hardness of the material being ground, moisture content, and feed rate among the factors that determine capacity and fineness of the ground material.

Particle Size and Particle Size Measurement Methods

Particle size plays an important part in the processing of most food, both in the finished product and in the basic ingredients. Therefore, it is not surprising that literature on the subject has been voluminous. Here, we ask a question: What is particle size?

Irani (16) defines the size of a particle as that dimension which best describes its degree of subdivision. For a spherical particle, the diameter is that dimension and, therefore, is its size. For a non-spherical particle, the diameter may be defined as any one-dimensional distance between two points on the external surface of the particle which passes through the geometric center of the particle. For a particle with an irregular shape, what is referred to as the size is the average of a large number of diameters as defined for a non-spherical particle.

A complete description of a ground product should include its particle size distribution. This can be plotted in terms of cumulative percent oversize or undersize in relation to the diameters of particles, or it can be plotted as a distribution of the amounts present in each unit of diameter against the several diameters (26).

For ground grains the particle size distribution is found to be skewed or non-normal (28). However, if the weight distribution is replotted using the logarithm of the particle size to the base-10, the asymmetrical or skewed curve is transformed into a symmetrical or bell-shaped curve. In this form, the distribution is amenable to all statistical procedures developed for the normal distribution (35). Two parameters, the geometric mean particle size or diameter by weight of the distribution, representing the single central tendency, and the geometric standard deviation measuring the dispersion about the central tendency, completely define the log-normal distribution. The value of these two parameters may either be obtained by calculation or, graphically, by plotting the log-normal particle size distribution curves on log-probability paper (4). In this case, the plotting of cumulative data along the probability scale in ordinate versus the logarithm of particle size along the abscissa yields a linear relationship. A completely uniform material, all particles the same size, would show up as a horizontal line and have a standard geometric deviation of 1.0. A completely heterogeneous material would be represented by a vertical line, which would have a standard geometric deviation of infinity (19).

In many cases, it is also desirable to know the total exposed surface area of the ground product, which represents the sum of the individual grain surfaces. This parameter is also determined by using the log-normal distribution by weight (28). However, with the particle size distribution it is also necessary to know the shape factor of the particles. For a cube or a sphere, the shape factor equals unity. For particles of irregular shape, it has been found experimentally that the shape factor is approximately 1.75 (10, 24).

To obtain particle size distribution curves, particle size measurement methods are generally used. These methods are discussed by many workers (16, 26, 40). Whitby (40) makes a classification of these methods into three categories:

- geometric, the best known being microscopic and sieve sizing methods,
- fluid drag, which regroup elutriation and sedimentation methods,
- and miscellaneous methods.

Unlike the microscopic techniques, most of these methods do not measure size directly, but measure a property of the particle and then, through an equation, calculate the "size" (16). In the pipette method, a variation in concentration of particles and medium occurs at a fixed depth below the surface, thus the particle size distribution is calculated from the measured concentration changes. In permeability techniques, size characteristics can be inferred from the resistance offered to the flow of a fluid through a pressed plug of powder (26).

Furthermore, Whitby points out that the various methods of particle size analysis yield different moments and weightings, so this makes it necessary to accompany particle size data with a clear statement as to which of the weightings and moments are being used. The distribution weighting is the variable that is summed, i.e., weighting by number, weighting by area, or weighting by volume or weight. The distribution moment, on the other hand, refers to the power of the distribution variable. There are also three moments: size is the first moment, area represents the second moment, and volume the third. For example, sieving yields the size, a first moment, weighted by volume.

Another way to express particle size is in terms of modulus of fineness and modulus of uniformity (28). The standard method for determining the fineness of the ground material is the modulus or index system as adopted by the American Society of Agricultural Engineers (ASAE) in 1930 (3). This method has had extensive use among mill manufacturers and others. Basically, the modulus of fineness is a means of giving a numerical value to the average size of particles in a representative sample. The determination of the fineness modulus involves the use of a series of seven screens: 3/8-, 4-, 8-, 14-, 28-, 48-, and 100-mesh. Starting from the smallest screen and going to the next larger, each succeeding screen has exactly twice as large an opening as the previous screen. A 250-gram sample of ground feed is sifted for five minutes on a Ro-Tap shaker. The percent of material remaining on each screen and in the pan is then calculated and multiplied by a coefficient between 0 and 7 (0 is the coefficient affected to the pan, and 7 is the one affected to the coarsest screen). The sum of all the figures obtained, divided by 100, gives the modulus or index of fineness. A low value of this index means a fine grinding; a large number indicates a coarse grinding.

The quality of a product also includes the uniformity in size of the ground particles. In 1937, a Modulus of Uniformity was proposed by the American Society of Agricultural Engineers and the American Society of Animal Production (3). The basis of determination of this modulus is the same as for the Modulus of Fineness. Three figures, representing coarse, medium, and fine particles, the sum of which must equal 10, are used to describe the degree of uniformity of the ground sample. In this definition, the coarse fraction represents the material remaining on the 3/8-, 4-, and 8-mesh screens, the medium fraction that remaining on the 14-, and 28-mesh screens, and the fine part is the material that passes through the 28-mesh screen.

It should be noted, however, that the ASAE recommendation concerning the method of expressing particle size by means of the moduli of fineness and uniformity was discontinued in 1973.

Research in the Field of Laboratory Grinding

Williams (41) describes grinders which have been the object of a survey conducted by the Canadian Grain Commission. He reports that feed rate is critical in many grinders, particularly high speed hammermills and impeller grinders. For the grinding of Hard Red Spring Wheat with a hammermill, a reduction in rpm from 11,500 to 10,000 increased the mean particle size by 10 microns. A further reduction to 8500 rpm saw a continued increase of 24 microns.

As far as maintenance and repair of laboratory grinders is concerned, Williams opposes belt driven grinders to direct-drive grinders, the latter being more prone to loss of rpm due to overload than are belt-driven grinders. He also reports that grinders equipped with screens give more reproductible grinds than those with no screens, such as most burr mills.

The effect of fiber content is also noted: barley, millet, and oats generally display more variability in both mean particle size and particle size distribution than do wheat, rye, and corn.

Other factors investigated through this survey include grinder clean-up time, working conditions, dust problems, heating up of grinders, and commercial availability.

In another case, a study of the effect of type of grinder on protein values of Hard Red Winter Wheat when analyzed by Infrared Reflectance devices is reported (15). The grinders involved in this study were three Wiley mills, two equipped with an 18-mesh screen and one with a 40-mesh screen, two Norris mills, and two Udy-Cyclotec mills. The conclusion drawn from the study shows the Udy grinder as the most suitable for Infrared Reflectance measurements of Hard Red Winter Wheat in terms of self-cleaning, rapid throughput, and minimum variability, in mean particle size and particle size distribution.

A recent article (11) covers a range of common grinders in use in the United Kingdom and points out to the situation governing the sampling of grinders for the British Market.

A paper by Black et al (6) describes two laboratory research mills with roll diameters of 6 inches and 10 inches. They are claimed to be very flexible and to have a wide range of selections for feed rate, roll gap, roll speed, and roll differential. A mill comparison study showed them to be comparable in performance to the Allis-Chalmers laboratory mills.

Another investigation for variation in modulus of fineness, modulus of uniformity, number of particles, and total surface area was conducted on wheat samples prepared with different grinding procedures. The results of the survey which covered several countries are compiled in a paper by Ward, Shellenberger, and Wetzel (39).

A laboratory procedure for milling small samples of sorghum into grits, flour, germ, and bran fractions is described by Rooney and Sullins (30). However, there is no information available concerning the reliability of this method to consistently indicate differences in milling properties that are related to commercial milling performance of sorghum.

Nishita and Bean (25) describe tests run on different grinders using rice and show how flour particle size and functional properties are affected by the different grinding methods.

All these efforts in the field of laboratory grinding mean that more knowledge, better experimental techniques, and improved laboratory milling equipment are continually needed.

MATERIALS AND METHODS

Kind of Grain Being Ground

Dry Hard Red Winter Wheat was used to run all the tests. The characteristics of this wheat were as follows:

moisture content	= 11.3%
test weight	= 61 lbs/bushel
weight per hectoliter	= 78.6 kg/hectoliter
density	= 1.45 gm/cc
pearling value	= 73%
theoretical yield	= 76.42%
1000 kernel weight	= 32.28 gm

Grinders

Five laboratory grinders were tested for particle size and energy consumption. The choice of these grinders was based on the principle of grinding employed by each one of them; these grinders are the Brabender Quadrumat Junior (compression), The Hobart Coffee Grinder Model 275 (attrition), the Weber Laboratory Pulverizing Mill Model 22 (impact of particles against swinging hammers), the Udy Cyclotec grinder (impact of particles against the carborundum-impregnated wall), and the Wiley Mill Model 4 (cutting action).

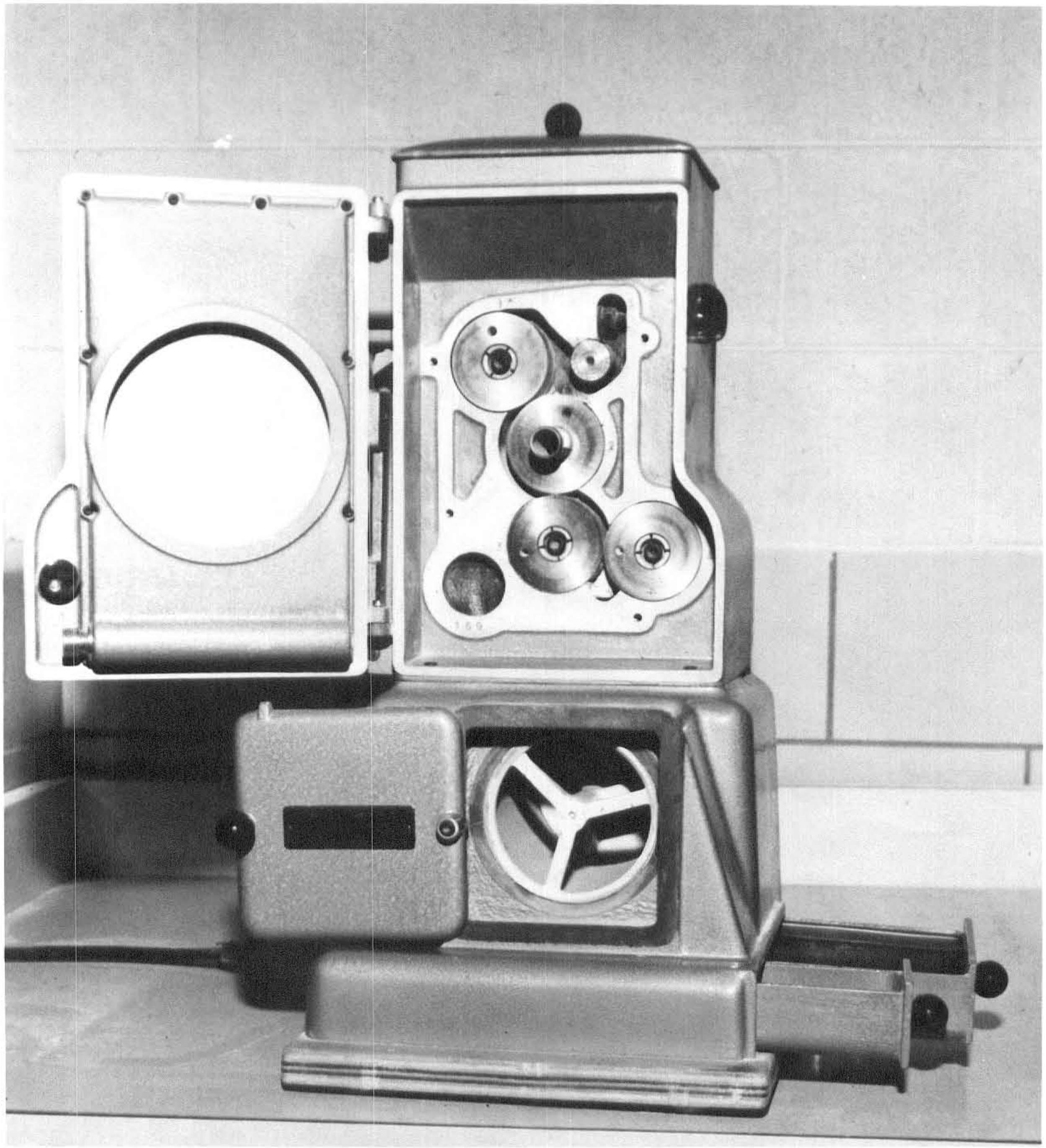
Brabender Quadrumat Junior:

The Brabender Quadrumat Junior is a precision laboratory roller mill. The principle of size reduction employed is that of multiple grinding with corrugated rolls made of special steel. Four 3-inch diameter rolls make three grinding steps. This is achieved by a unique positioning of the rolls: two of them, the second roll and the third, do double service (Fig-1).

Normally, the mill is equipped with a feeder roll and a rotating sifter reel. For the purpose of this experiment both were removed: the feeder was replaced by a vibratory feeder independent of the mill to allow for feed rates higher than 60 grams per minute, and the sifter reel was removed because the study was based on the analysis on the whole ground product, and there was no need for separating the flour from the bran.

A flow diagram will show that the grain flows from the vibratory feeder to the first break rolls. From here grain flows directly to the second break rolls without intermediate sifting. Again, without intermediate sifting, the stock flows directly to the middlings reduction rolls where the final grinding operation is done by rolls with extremely fine corrugations.

Plate I. Photograph of the Brabender Quadrumat Junior



roll	rpm	corrugation
1	1240	12
2	540	25
3	1200	37
4	540	40

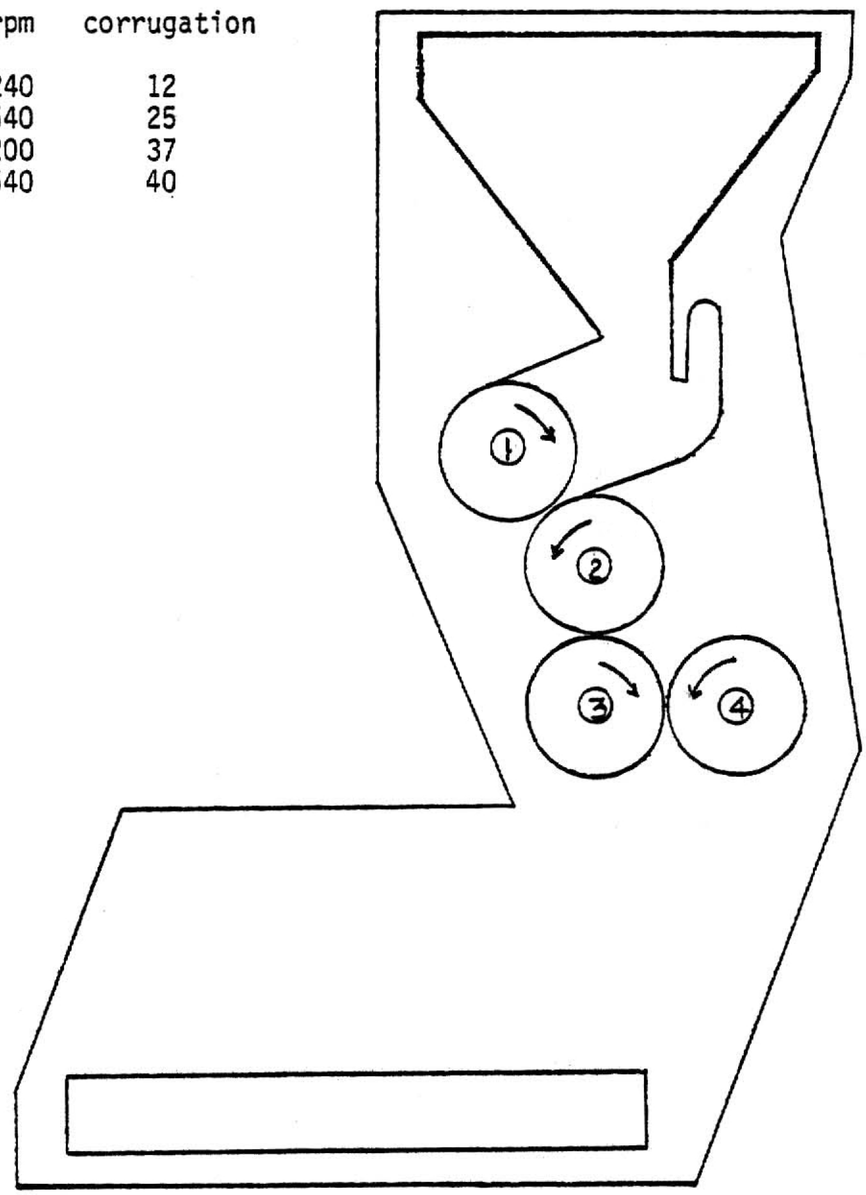


Figure 1. Quadrumat Junior. Cross-Section
(feeder and sifter reel removed)

Following the last grinding step, the stock (bran and flour) drops into the same drawer. The rolls have fixed settings. This arrangement makes it impossible to damage the rolls by improper settings.

An interesting feature of the mill is the complete aspirator system, consisting of a blower, adjustable air valve, filter, and filter flour collector. This aspiration system prevents excessive heating of the rolls during continuous operation. (1)

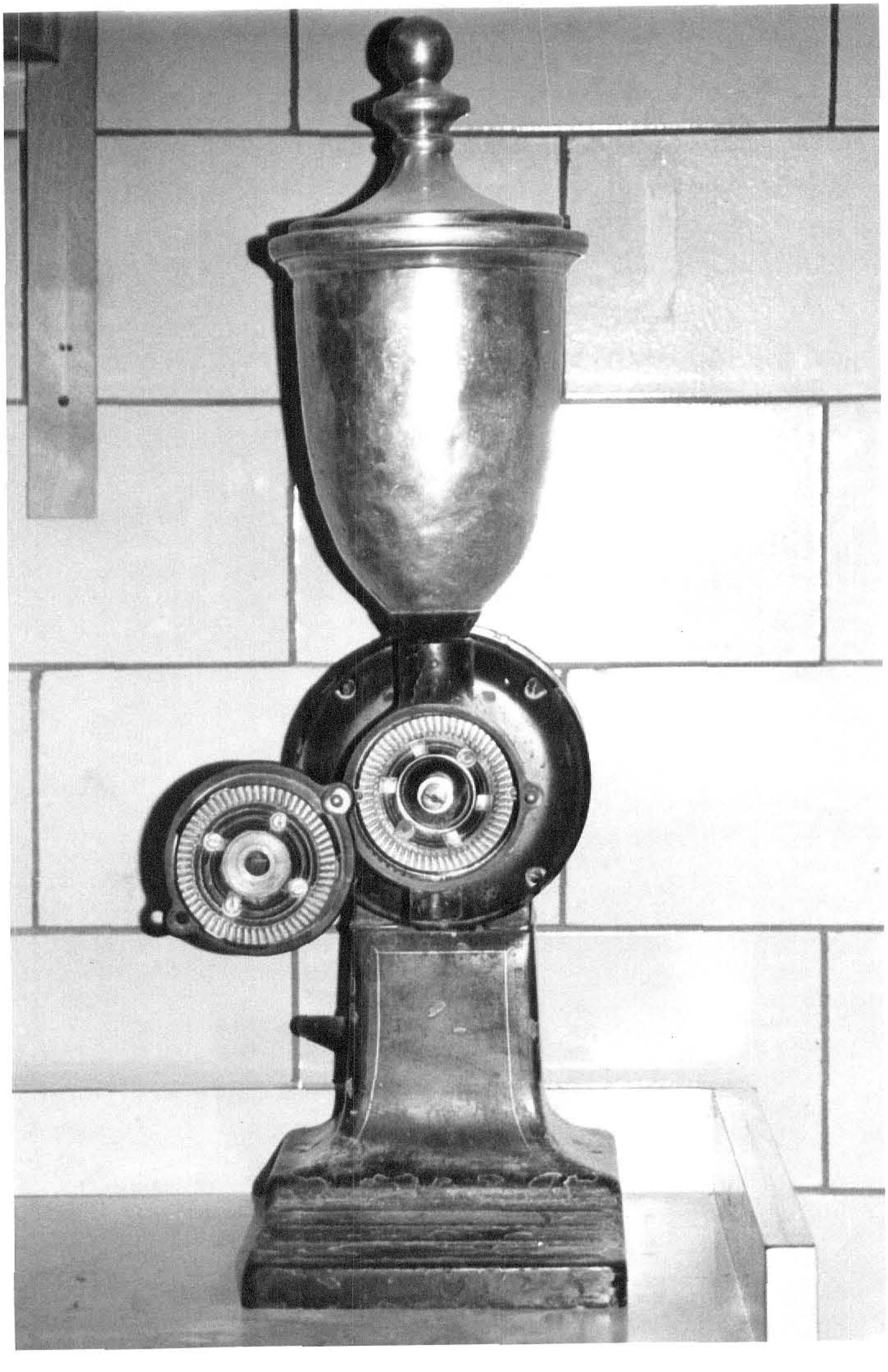
Hobart Coffee Grinder Model 275

The Hobart Grinder Model 275 is a grinding unit known as an attrition mill because of the rubbing action which takes place between two discs operating in the vertical plane (Fig-2.1). The mill is driven by a shaft-mounted motor and is designed to operate at a speed of 1725 rpm. One burr, which rotates, is fastened to one end of the main drive shaft; the other is held to the body of the mill and does not revolve. The surface of both discs is provided with grooves at the periphery to help in the rubbing action (Fig-2.2). The mill is also equipped with a knob-like device with settings from "very fine" to "extra coarse," to adjust the clearance between the discs.

The material enters through the center of the stationary disc, makes its way to the periphery where it is ground between the two corrugated surfaces, and then is thrown free to the discharge located at the bottom of the grinding chamber.

Particle size is controlled by adjustment of the distance between the burrs and by the feed rate. The sharpness of the burrs also plays a role, and excessive wear will result in a very coarse grinding. On the other hand, since the design and mode of operation do not give a grinding action capable

Plate II. Photograph of the Hobart Coffee Grinder Model 275.



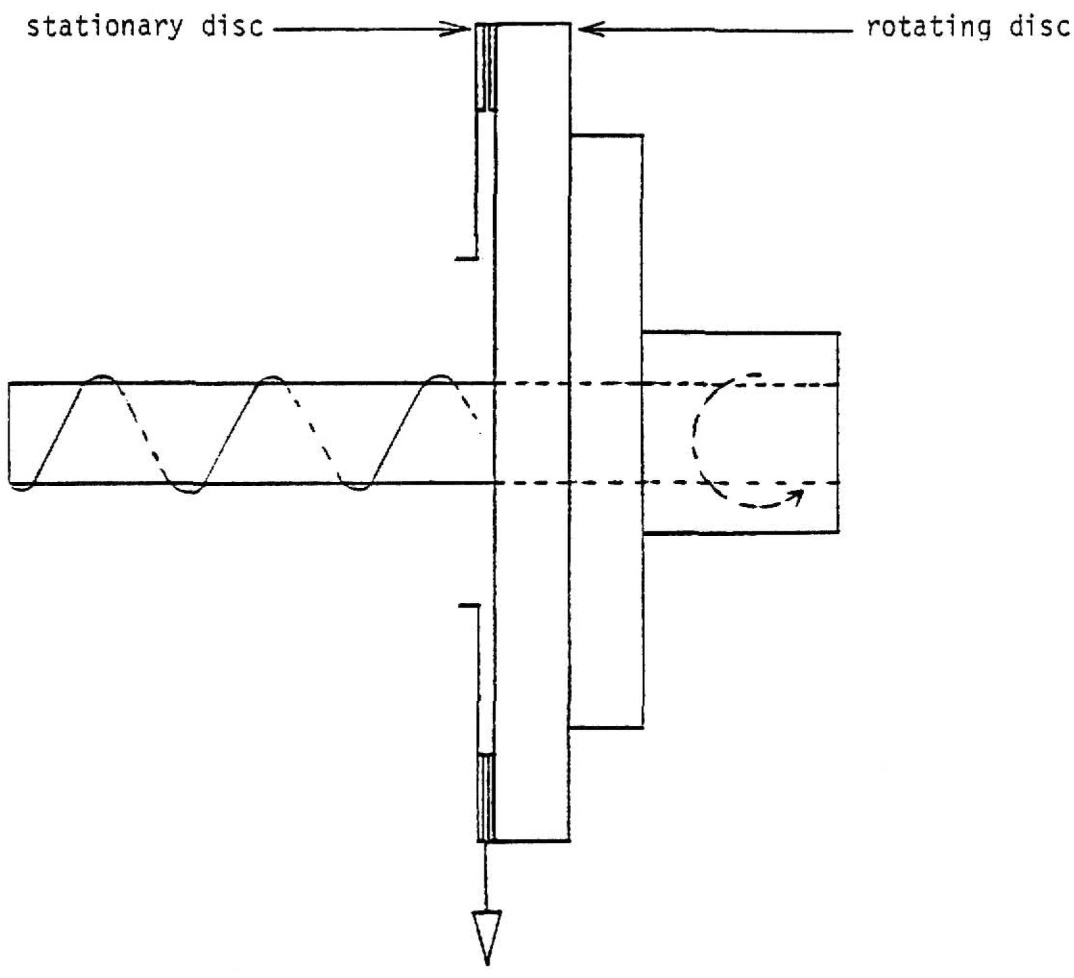


Figure 2-1. Hobart Grinder. Working Parts

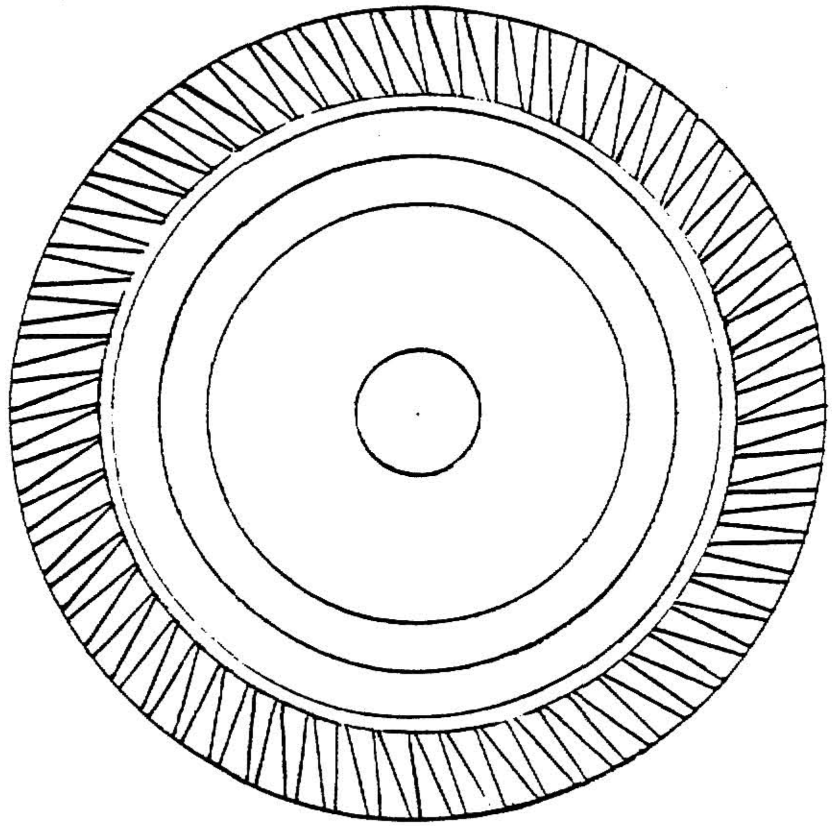


Figure 2.2.1. Rotating Disc of the Hobart Grinder

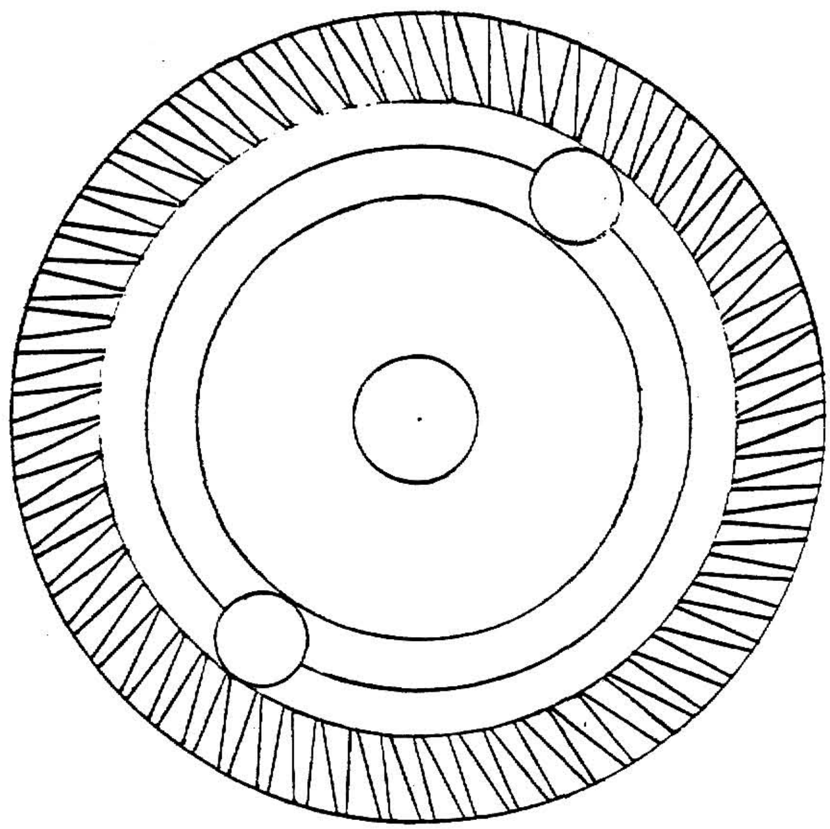


Figure 2.2.2 Stationary Disc of the Hobart Grinder

of forcing the material through a screen, there is no screen to regulate mean particle size.

Weber Laboratory Pulverizing Mill Model 22

The mill consists of a rotor made up of several plates keyed to the main shaft. Pins through these plates, near the edge, carry the hammers which are attached to them. There are eighteen hammers. Outside the rotating cylinder is a perforated screen. The perforations on this screen may be as small as .008" or as large as .050". The screen may be readily changed by removing the hammer chamber plate. A row of six hammers and the screen are shown on the cross section of the mill in Figure 3.

Material is fed to the mill through the funnel type intake at the top. The impact of the eighteen hammers rotating at high speed quickly pulverizes the material, which is then forced through the screen into a cyclone attached to the grinder. From there, the material is discharged into a collector.

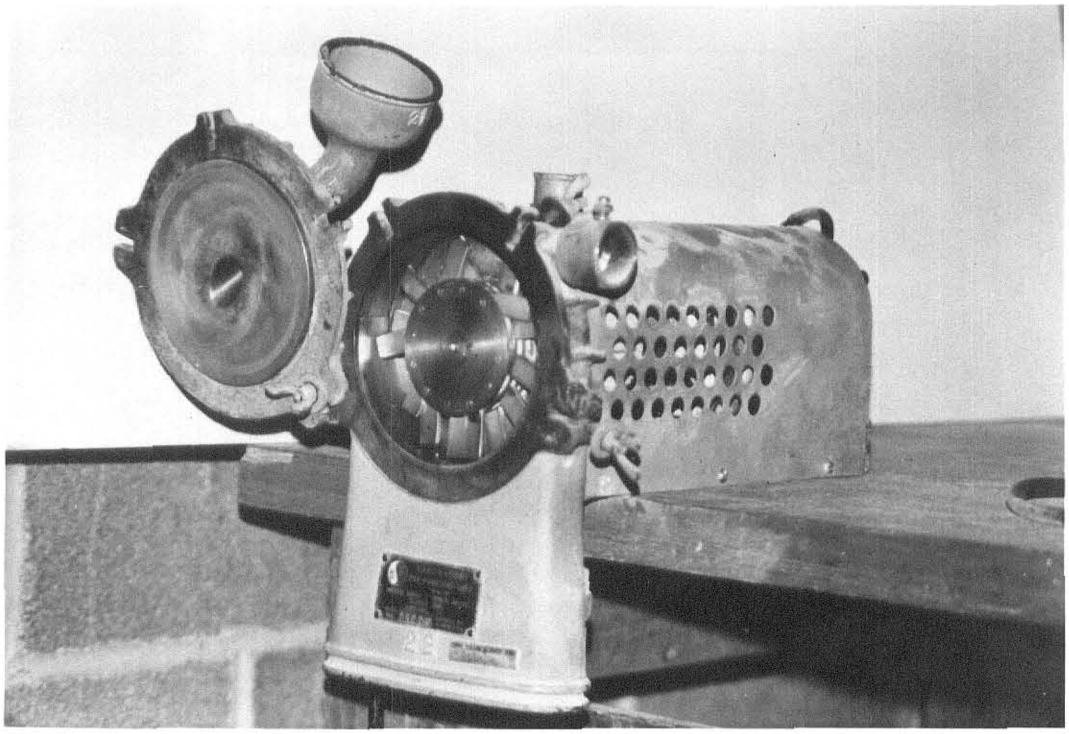
This type of grinder generates a considerable volume of air which has to be dissipated to avoid excessive loss of ground sample. This is taken care of by the vacuum source coupled to the cyclone, which, not only contributes to the transport of material from the grinding chamber into the feed collector, but also neutralizes the air generated without drawing off the fine particles (41).

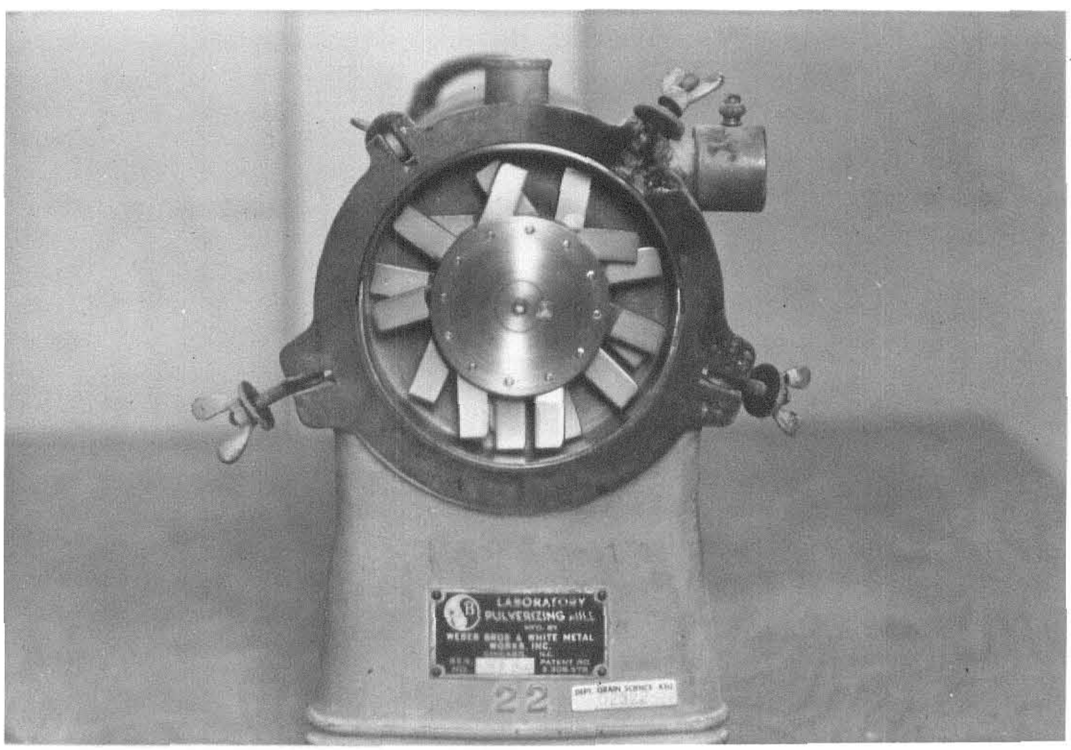
Udy Cyclotec Grinder:

This grinder is a marriage of convenience between a hammermill and an impeller mill. The grinder is belt driven and operates at a speed of about 13,000 rpm. Size reduction is the result of impact; as the material drops into the grinding chamber, it is struck by the impellers and projected against the carborundum abrasive surface liner of the circular grinding

Plate III. Photograph of the Weber Laboratory Pulverizing Mill

Plate IV. Photograph showing the Working Parts of the Weber Laboratory Pulverizing Mill




LABORATORY
PULVERIZING MILL
WEBER BROS & WHITE METAL
WORKS, INC.
22

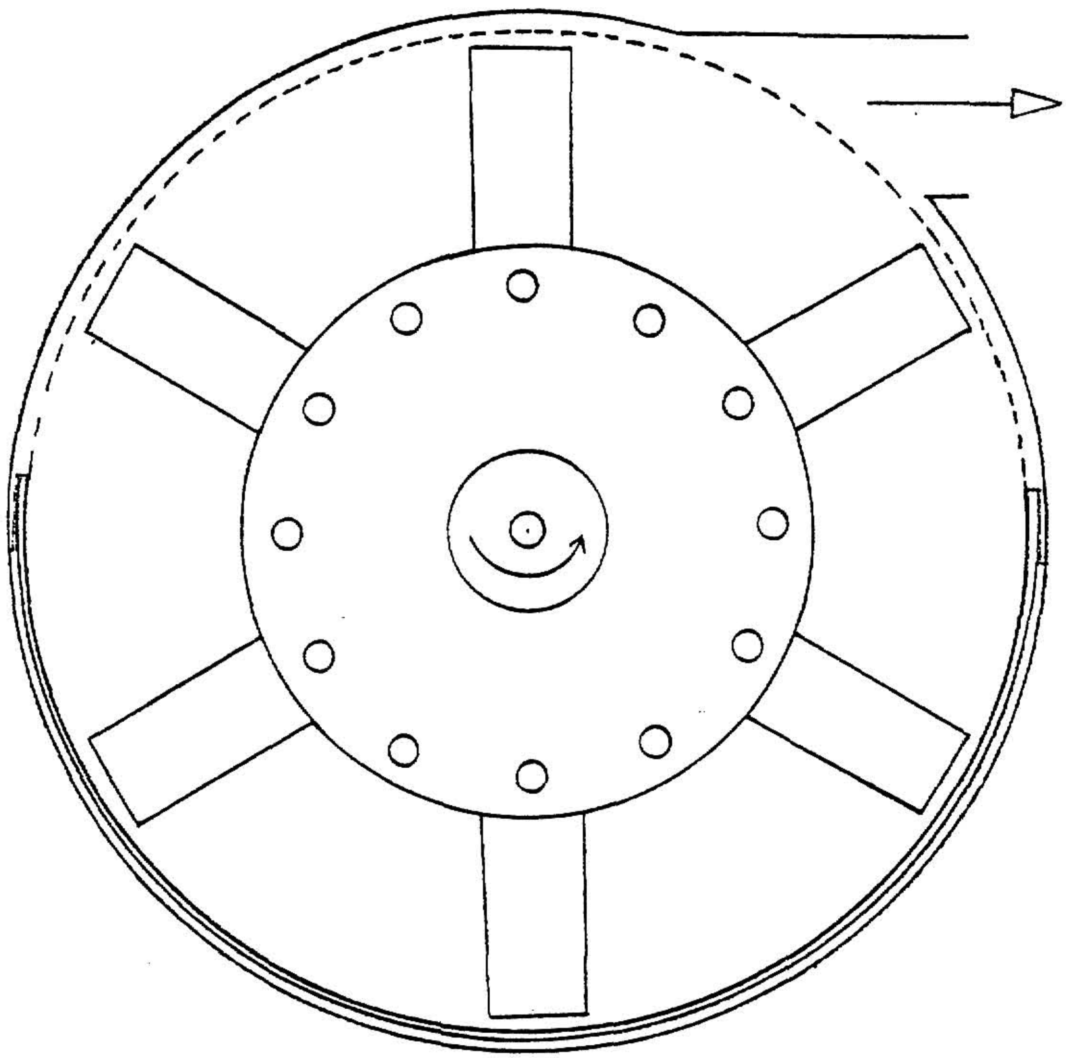
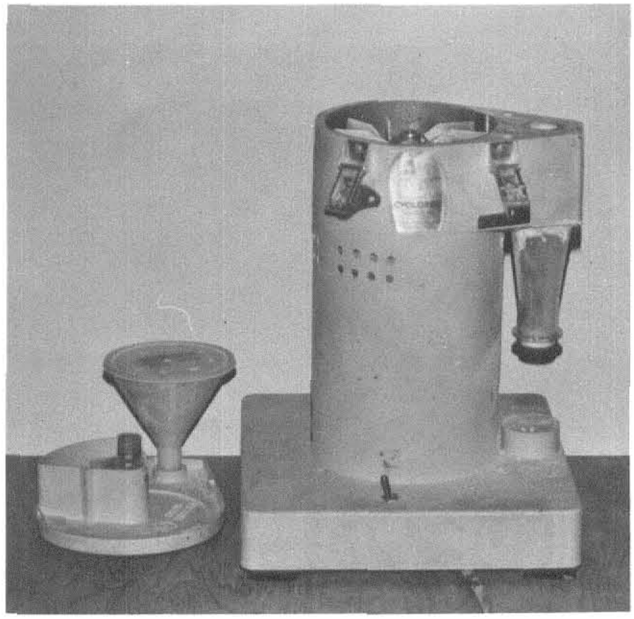
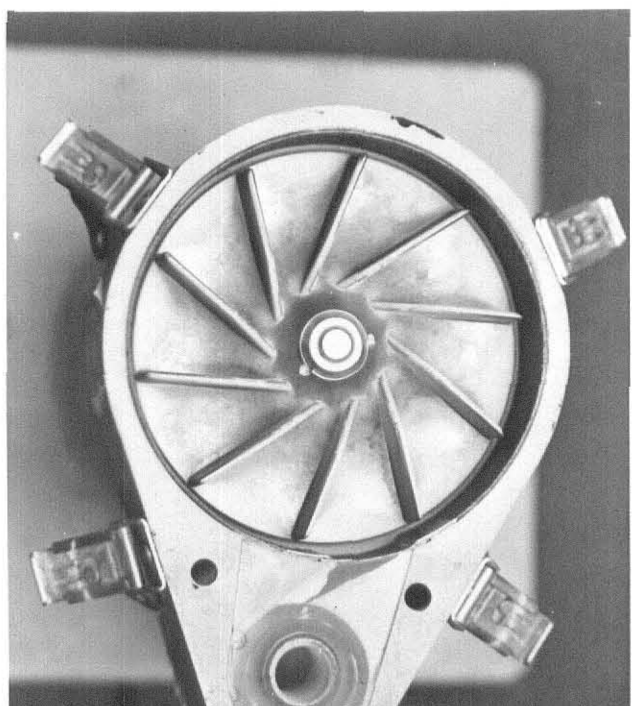


Figure 3. Weber Mill. Cross-Section

Plate V. Photograph of the Udy Cyclotec Grinder

Plate VI. Photograph Showing the Working Parts of the Udy Cyclotec Grinder





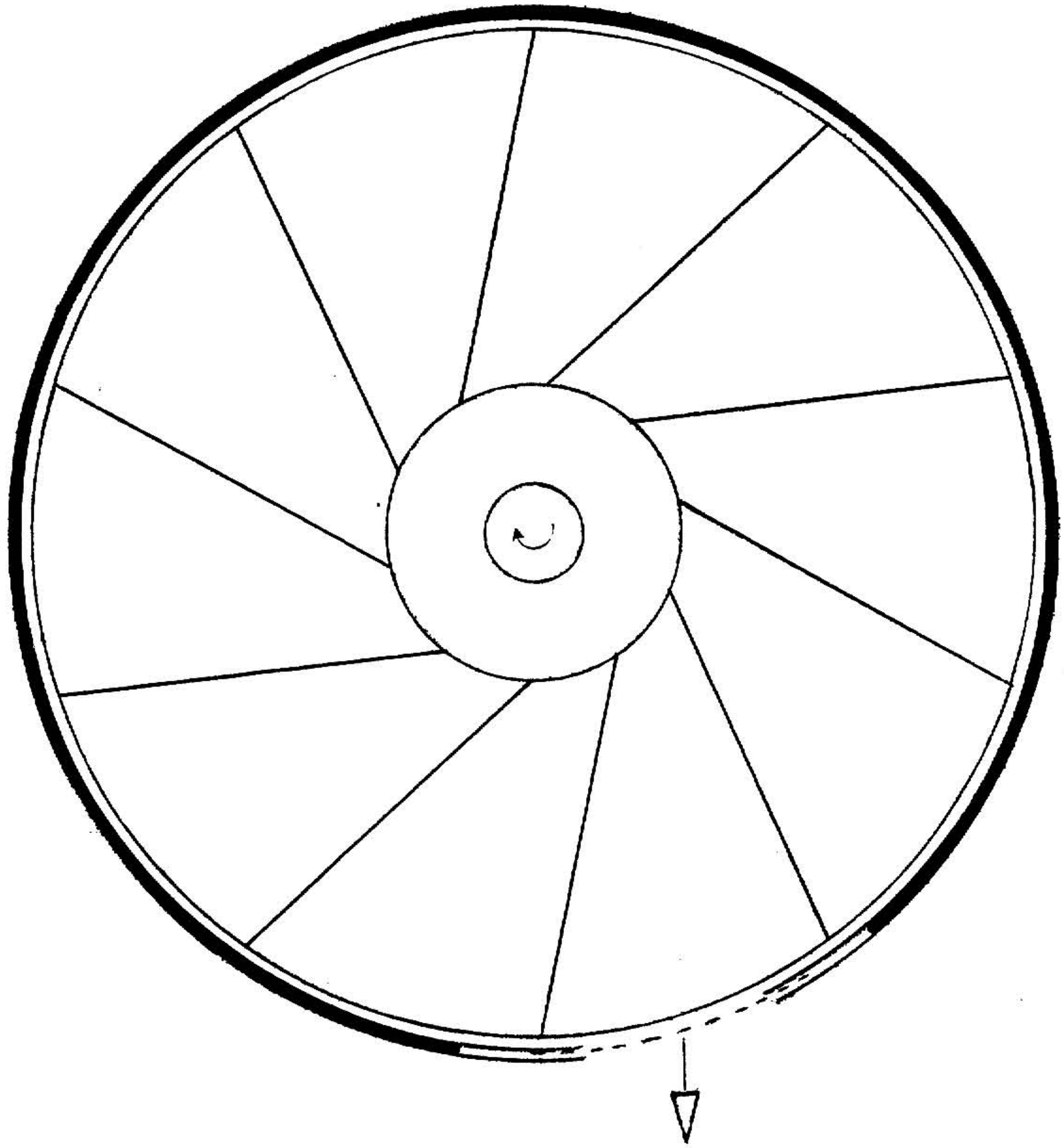


Figure 4. Udy Mill. Cross-Section

chamber (Fig-4). The air generated by the grinder is employed to drive the sample through a screen and is then further used to create a strong down-draught by means of a plastic cyclone. This forces the sample downwards into the collector. Excess air disappears up through the center of the cyclone and into the atmosphere via a dust-trap.

Screens are easily interchangeable; there are three sizes: .4mm, .5mm, and 1mm. The feed rate is a critical factor. If grain is fed at too high a rate, the rpm falls, which affects mean particle size and may even result in broken driving belts.

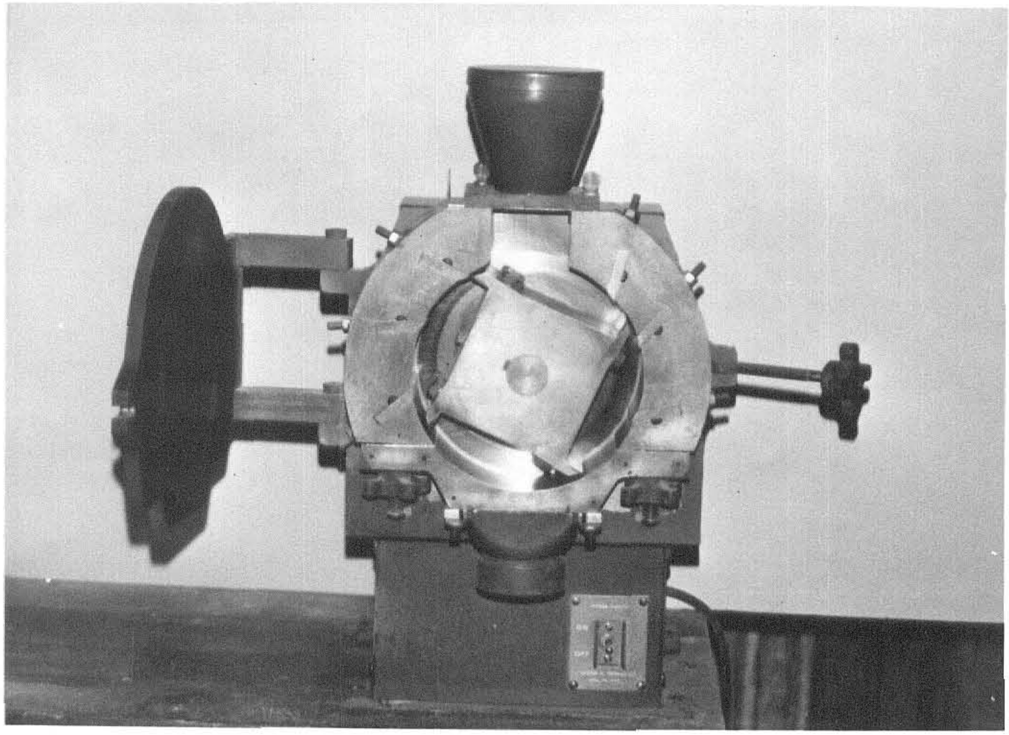
This grinder is claimed to grind samples up to 15% moisture content and 20% oil content, but Williams (41) reports that this grinder is not suitable for grinding material above eight percent in oil.

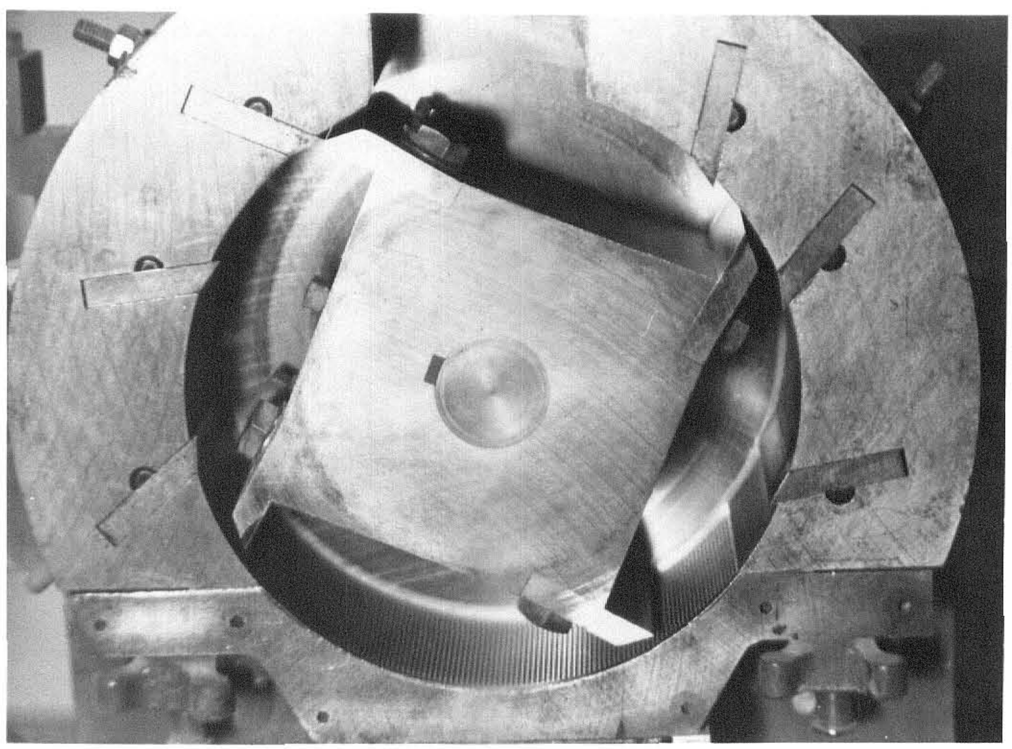
Wiley Mill, Model 4:

This grinder, unlike the previous ones, was fed batchwise. The mill is belt driven and designed to run at a speed of 800 rpm. The batch sample is introduced through a hopper. During milling, four robust knife blades, rotating in counterclockwise direction, chop the material against six stationary knives bolted into the casing of the grinding chamber (Fig-5). The knives are made of hardened steel to ensure durability and optimum cutting. The distance between fixed and rotating knife blades is adjustable. The milled sample is then forced through a screen which fits tightly against the top of the delivery chute. Screens are interchangeable to generate meal of different particle size. The screen sizes available include .5mm, 1mm, and 2mm screens. The delivery end of the chute is such that it permits direct attachment of a machine-made glass jar where the ground feed is collected.

Plate VII. Photograph of the Wiley Mill Model 4.

Plate VIII. Photograph showing the Working Parts of the Wiley Mill Model 4.





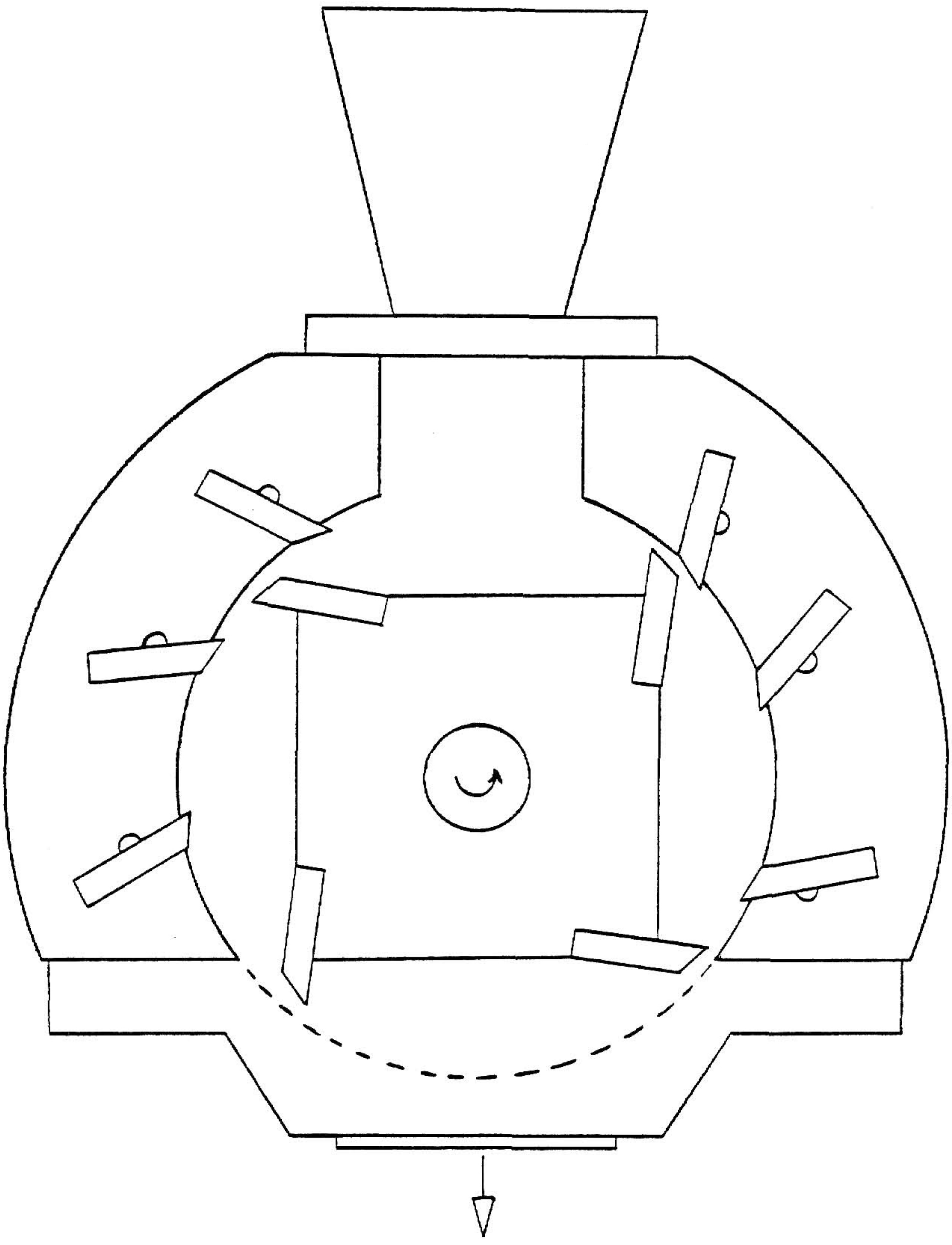


Figure 5. Wiley Mill. Cross-Section

The Wiley laboratory mill is reported to operate at up to 20% moisture content in cereals (41). It heats up to only a slight degree and thus causes a minimal moisture loss during grinding. A big disadvantage, however, with this mill is that it requires thorough cleaning out between samples.

Feed Rate

A vibratory feeder placed on a metal base was used to feed the grain to each of the mills, with the exception of the Wiley Mill. Both the amount of vibration delivered by the vibratory feeder and the slope of the metal supporting base were used to regulate the feed rate.

The full capacity tests were secured by increasing the rate of feeding up to the point were the motor started to be overloaded. Feeding was then decreased until the mill operated satisfactorily. The three-quarter, one-half, and one-quarter capacity tests were then figured from the full capacity tests. Table-1 shows the different feed rates used on each grinder.

Table-1

Feed Rates in Grams Per Minute

Grinder	Full Capacity	3/4 Full Capacity	1/2 Full Capacity	1/4 Full Capacity
Quadrumat Junior	240	180	120	60
Hobart	320	240	160	80
Weber	150	110	75	38
Udy Cyclotec	180	135	90	45

For the Wiley mill two batch-sizes were tested: 100-gram batch and 200-gram batch.

Other Tests

For each of the grinders equipped with a screen, different screen sizes were tested, which are:

Weber: .024" (approximately .6mm) and .040" (approximately 1mm)

Udy: .5mm and 1mm

Wiley: .5mm, 1mm and 2mm

For the Hobart grinder, burrs clearance was tested. Two settings were used: "very fine" grind and "medium" grind.

Particle Size Analysis

For each grinder, the grinding tests were run using different combinations of the variables involved. Particle size was first determined by means of a modified modulus of uniformity and a modified modulus of fineness. A Ro-Tap shaker and the following sieve series were used:

US Mesh Number	Tyler Mesh Number	Opening Inches	Opening Microns
16	14	.0460	1190
25	24	.0276	710
40	35	.0165	420
60	60	.0097	250
100	100	.0059	149
170	170	.0035	90
PAN	PAN		

The sieve series is such that, starting with a 14-mesh Tyler screen and going down to the finest screen, the size ratio of a screen and the screen succeeding it equals 1.7. Preliminary tests showed that there was no need to start with a screen coarser than 14-mesh, because, in most grinds obtained, the material contained a very small amount of particles coarser than the size corresponding to this screen.

The determination of the modified modulus of uniformity was based on amount of 100-gram sample of ground wheat remaining on each of the six screens and in the pan following a 2-minute test with the Ro-Tap shaker. The length of sieving time was assessed by running preliminary tests based on the technique of sifting to an end-point. The modified modulus of uniformity is expressed as three figures: coarse, medium, and fine, the sum of which equals ten. The coarse fraction corresponds to the material remaining on the 14- and 24-Tyler screens, the medium fraction is that remaining on the 35- and 60-mesh screens, the fine fraction is the material that passes the 60-mesh screen (see page 96 of the appendix).

For the determination of the modified modulus of fineness, the percent of material remaining on each screen and in the pan is multiplied by a coefficient between 0 and 6 (0 is the coefficient affected to the pan, 6 that affected to the 14-mesh Tyler screen). The sum of the figures obtained for each screen and the pan, divided by 100, is the numerical value of the modified modulus of fineness (see page 95 of the appendix).

However, even though these two moduli are a good indication of the degree of fineness of the ground product, they do not describe completely the particle size of the ground samples. Thus, the log-normal particle size distribution derived from the ASAE recommendation S319 (4) was used to obtain the mean particle size or average diameter of the particles and the standard deviation which, in return, led to the determination of the total surface area of the ground material.

The procedure for the log-normal particle size distribution requires that a minimum of six standard sieves be used (28). Thus, among the fourteen sieves recommended for the particle size distribution method (4), the following sieves were used:

US Mesh Number	Tyler Mesh Number	Opening Inches	Opening Microns
16	14	.0469	1190
30	28	.0234	595
50	48	.0117	297
100	100	.0059	149
140	150	.0041	105
200	200	.0029	74
PAN	PAN		

The particle size distribution, as defined here, is based on amount of material remaining on each screen and in the pan following a 2-minute sifting test of 100 grams of ground sample with the Ro-Tap shaker. The length of sieving time was also obtained from preliminary tests using the end-point sifting technique.

The calculated values of the geometric mean diameter and the geometric standard deviation by weight were obtained as follows (4, 28):

1) $\log d_w = \frac{\Sigma W_i \log d_i}{\Sigma W_i}$, or $d_w = \log^{-1} \left(\frac{\Sigma W_i \log d_i}{\Sigma W_i}\right)$

2) $(\log S_w)^2 = \frac{\Sigma W_i (\log d_i - \log d_w)^2}{\Sigma W_i}$, or

$$S_w = \log^{-1} \left[\frac{\Sigma W_i (\log d_i - \log d_w)^2}{\Sigma W_i}\right]^{1/2}$$

Where: W_i = weight fraction on i'th sieve.

d_i = geometric mean diameter of particles on i'th sieve.

d_w = geometric mean diameter by weight distribution.

s_w = geometric standard deviation by weight distribution.

log = indicates logarithm to base 10.

Total Surface Area

The total surface area of the ground material was calculated by solving the following equation:

$$A_{st} = \frac{6\lambda W_t}{\rho} \exp(.5\, Ln^2 \sigma_w - Ln \mu_w)$$

Where: λ = shape factor of the particles

W_t = total sample weight (grams)

ρ = specific weight of ground sample (grams per cm^3)

σ_w = geometric log-normal standard deviation of parent population by weight distribution.

μ_w = diameter of parent population by weight distribution (cm)

L_n = indicates logarithm to base e.

The equation for total surface area given here is derived from the equation given by Pfost and Headley (28), as shown in page 99 of the appendix.

The standard recommendation for particle size analysis, ASAE S319, applies to reduction processes which yield particles which are essentially spherical or cubical (4). The shape factor for such particles is unity (see page 98 of the appendix).

Note: The total number of particles which is a good indication of the degree of subdivision of a ground product was not calculated because of some considerations relative to the value of β_v, the volume shape factor of the particles (see page 132 of the appendix).

Energy Consumption

The determination of the energy consumed for grinding was based on the difference between the energy consumed by the grinder when loaded and the energy consumed by the grinder when running empty.

Three watthour meters were used to make the energy measurements on the different grinders. The specifications for each meter were as follows:

- Watthour meter used with the Quadrumat Junior:

  phase = 3

  volts = 240

  amps = 15

  Hz = 60

  K_h = 14.4

- Watthour meter used with the Hobart grinder:

  phase = 1

  volts = 240

  amps = 3-100

  Hz = 60

  K_h = 7.2

- Watthour meter used with the Weber, Udy, and Wiley mills:

  phase = 1

  volts = 120

  amps = 5

  Hz = 60

  K_h = .6

The K_h factor represents the number of watthours per revolution of the disc counter. For all the grinders, except the Hobart grinder, the disc revolutions were carefully counted during each test. The energy consumption in watthours was then obtained by multiplying the number of revolutions of the disc by the corresponding K_h value.

For the Hobart grinder, the meter used was equipped with a dial reading, thus there was no need to count the disc revolutions.

RESULTS AND DISCUSSION

Modified Modulus of Uniformity

For all the grinders, the results given in the following tables are average values of four trials. The data for modified modulus of uniformity are shown in Tables 2-1 to 2-5. Noticeable from the beginning is that the Brabender Quadrumat Junior, the Weber hammermill, and the Udy mill grind fine, whereas the Hobart grinder gives about equal proportions of "fine" and "medium" when the burr-clearance is set at "very fine," and a rather coarse product when the burrs are set farther apart in the "medium" position. On the other hand, the product ground on the Wiley mill was characterized by a high concentration of particles of the medium range when a 1-mm screen was used, but when a 2-mm screen was used, the product was definitely coarse.

At this point, it should be mentioned that for comparison purposes between the Weber, the Udy, and the Wiley mills, it would have been preferable to use the same screen sizes for all three mills. In fact, the tests were run at first with two screen sizes, .5-mm and 1-mm screens. For the Weber hammermill the screen size is expressed in inches; the two sizes used were .024 inch and .040 inch, which respectively correspond to .6-mm and 1-mm. In the case of the Wiley mill, the size reduction process happened to be so slow that the use of the .5-mm screen resulted in a very inefficient operation.

When a 100-gram batch was tested, a recovery of 96.5 percent of the product required 45 minutes. Thus, for this grinder, the .5-mm screen had to be abandoned. However, the need for testing the effect of screen size on particle size and energy consumption led to the selection of a second size, the 2-mm screen.

By observing the data in Tables 2-1 to 2-4, it may also be noted that, in general, an increase in the feed rate is accompanied by a decrease in the production of fines. In the case of the Wiley mill, a change in the batch size from 100 grams to 200 grams did not affect the modified modulus of uniformity when a 1-mm screen was used but did result in an increase of the proportion of coarse particles when the 2-mm screen was tested (Table 2-5).

The next noticeable fact, when examining these tables, is the similarity between the results obtained with the Weber hammermill and those obtained with the Udy mill. This similarity is such that a question may be asked: Could it be that these two grinders grind to the same degree of fineness? An answer to this question, or even an attempt to classify different grinders which grind in the same range of fineness on the basis of the ratio of uniformity, would be inappropriate. The numbers, in the ratio of uniformity representing the coarse and medium fractions, refer to the product remaining on two sieves; the third number, representing the fine fraction, refers to the product remaining on the last two sieves and in the pan. It is, therefore, obvious that the sum of the overs of two sieves in one case, and the sum of the overs of the same sieves in another case, could be identical but the repartition of the product between the two sieves different from one case to another. Thus, the same number affected to the same fraction in two different grinds would not mean that the two fractions are identical in fineness.

Table 2-1. Quadrumat Junior. Effect of Rate of Feed on the Uniformity of the Material.

Feed Rate (gm/mn)	Modified Modulus of Uniformity Coarse : Medium : Fine C : M : F
60	1 : 2 : 7
120	2 : 2 : 6
180	2 : 2 : 6
240	2 : 3 : 5

Table 2-2. Hobart Grinder. Effect of Rate of Feed and Burrs Clearance on the Uniformity of the Material.

Feed Rate (gm/mn)	Setting at "Very Fine"	Setting at "Medium"
	C : M : F	C : M : F
80	2 : 4 : 4	6 : 3 : 1
160	2 : 4 : 4	6 : 3 : 1
240	2 : 4 : 4	6 : 3 : 1
320	2 : 5 : 3	7 : 2 : 1

Table 2-3. Weber Mill. Effect of Rate of Feed and Screen Opening on the Uniformity of the Material.

Feed Rate (gm/mn)	.024" screen	.040" screen
	C : M : F	C : M : F
38	0 : 3 : 7	0 : 3 : 7
75	0 : 3 : 7	0 : 4 : 6
110	0 : 3 : 7	0 : 4 : 6
150	0 : 4 : 6	0 : 4 : 6

Table 2-4. Udy Mill. Effect of Rate of Feed and Screen Opening on the Uniformity of the Material.

Feed Rate (gm/mn)	.5mm screen	1mm screen
	C : M : F	C : M : F
45	0 : 3 : 7	0 : 3 : 7
90	0 : 3 : 7	0 : 3 : 7
135	0 : 4 : 6	0 : 4 : 6
180	0 : 4 : 6	0 : 4 : 6

Table 2-5. Wiley Mill. Effect of Size of Batch and Screen Opening on the Uniformity of the Material.

Batch Size (gm)	1mm screen	2mm screen
	C : M : F	C : M : F
100	0 : 8 : 2	5 : 4 : 1
200	0 : 8 : 2	6 : 3 : 1

Furthermore, considerable difference of opinion exists relative to what constitutes coarse, medium, or fine grinding. One man's idea of medium grinding may be another man's idea of coarse grinding. To illustrate this, an example is given on page 97 of the appendix showing a definition of "coarse," "medium," and "fine," looking at the material from yet another viewpoint.

Modified Modulus of Fineness

The results of tests run to determine the modified modulus of fineness are presented in Tables 3-1 to 3-5. The smaller the value of this index, the finer the product. The first noticeable fact is the relationship between capacity and fineness of grinding: as the feed rate increased, the product fineness dropped. This response of the modified modulus of fineness to the change in the rate of feed was most observable when grinding was done with the Quadrumat Junior. It is believed that the variation in load is one of the most important factors that affect the percent extraction of a pair of break rolls. The load to the rolls changes the flow of stock in the grinding zone and causes the rolls to increase or decrease their grinding actions. Heavy loads will result in coarse grinding.

For the Hobart, the Weber, and the Udy grinders, even though an increasing rate of feed is associated with a coarser product, other factors rather than the feed rate determine the quality of the ground material; this will be true as long as the load remains within the limits of the mill capacity so that the rpm will not fall due to a too high rate of feed. These other factors are burr-clearance in the case of the Hobart grinder; peripheral speed or speed of the hammer tips and clearance between the hammer tips and the casing or screen in the case of the Weber hammermill; and for the Udy Cyclotec grinder, rotor speed.

As far as the Wiley mill was concerned, the size of the batch seemed to act like the feed rate, since an increase in the load of the mill from 100 grams to 200 grams resulted in a coarser product. However, the difference was very slight, barely noticeable, probably because in determining product fineness for the Wiley mill, the prime factors are screen size and gap between fixed and rotating knife blades.

Considering the effect of screen opening on particle size, it is a well-known fact that the larger the screen opening the coarser the ground material, due to the fact that the retention time of the product in the grinding chamber is less with a coarse screen than with a fine screen. But, it should also be stressed that the screen size can often be materially increased without appreciably affecting the fineness of the end product. This fact is well illustrated through the results obtained with the Weber and the Udy mills (Tables 3-3 and 3-4). In the case of the Wiley mill, which has a slow grinding action, the doubling of the screen size resulted in a very significant variation of the modified modulus of fineness (Table 3-5), but for the Weber and the Udy grinder, both equipped with a high rotor speed, the change in product fineness was only minor. Some workers (36, 42) attribute this peculiarity to the fact that, at very high rotor speeds, the material tends to strike the screen at a tangent so that the effective screen opening is actually smaller than the designated perforation.

As for the Hobart (Table 3-2), changing the burr-clearance from the "very fine" setting to the "medium" setting did affect the particle size to a great extent.

At this point, if a classification of the various grinders was to be made on the basis of the fineness of the grind, the Weber and the Udy mills

Table 3-1. Quadrumat Junior. Effect of Rate of Feed on Fineness of Grinding.

Feed Rate (gm/mn)	Modified Modulus of Fineness
60	2.29
120	2.39
180	2.50
240	2.73

Table 3-2. Hobart Grinder. Effect of Rate of Feed and Burrs clearance on Fineness of Grinding.

Feed Rate (gm/mn)	Setting at "Very Fine"	Setting at "Medium"
80	2.75	4.39
160	2.81	4.44
240	2.87	4.50
320	2.96	4.63

Table 3-3. Weber Mill. Effect of Rate of Feed and Screen Opening on Fineness of Grinding.

Feed Rate (gm/mn)	.024" screen	.040" screen
38	2.00	2.18
75	2.07	2.26
110	2.10	2.27
150	2.16	2.31

Table 3-4. Udy Mill. Effect of Rate of Feed and Screen Opening on Fineness of Grinding.

Feed Rate (gm/mn)	.5mm screen	1mm screen
45	2.11	2.19
90	2.16	2.26
135	2.25	2.33
180	2.31	2.40

Table 3-5. Wiley Mill. Effect of size of Batch and Screen Opening on Fineness of Grinding.

Batch size (gm)	1mm screen	2mm screen
100	3.31	4.15
200	3.38	4.26

on one hand, and the Quadrumat Junior within certain limits, will be the fine grinders, whereas the Hobart and the Wiley will be considered coarse grinders. Furthermore, the Weber will rank first, followed by the Udy, the Quadrumat Junior, the Hobart, and the Wiley, in that order.

Particle Size Distribution Data and Total Surface Area

The data for particle size distribution and surface area per unit weight of ground material are shown in Tables 4-1 to 4-9. The calculated values of the geometric mean diameter (d_w) and the geometric standard deviation (S_w) by weight were obtained as shown on pages 100 to 131 of the appendix. These values, in return, led to the determination of total surface area per unit weight (A_{st}) of the ground material, using the equation given in "Materials and Methods" section and assigning a value of unity to λ, the shape factor of the particles. Some of the observations made previously when the modified moduli were used, were confirmed by the present method. First, for all the grinders tested, the lowest value for the mean diameter was obtained with the lowest feed rate. Second, the effect of feed rate on the average size of particles was again more noticeable when the product was ground with the Quadrumat Junior than with the Weber, Udy, or Hobart grinders. The differences between maximum and minimum values of the mean diameter were as follows: Quadrumat Junior, 40 microns; Hobart (very fine), 20 microns; Weber (.024-inch screen), 15 microns; Udy (.5-mm screen), 27 microns. However, when the burrs were set at "medium" in the case of the Hobart grinder, the effect of feed rate on the average size of the particles was more important than in the case of the Quadrumat Junior.

The other interesting fact that should be stressed deals with uniformity of the product. This, as reported earlier, is expressed by the standard deviation.

Table 4-1. Quadrumat Junior. Particle size distribution and total surface area of the ground material obtained with various feed rates.

Feed Rate (gm/mn)	d_w (μ)	d_w (cm)	s_w	A_{st} (cm^2/gm)
60	173	.0173	2.13	318
120	182	.0182	2.15	305
180	191	.0191	2.12	287
240	213	.0213	2.20	265

Table 4-2. Hobart Grinder. Particle size distribution and total surface area of the ground material obtained with various feed rates when burrs clearance is set at "very fine."

Feed Rate (gm/mn)	d_w (μ)	d_w (cm)	s_w	A_{st} (cm^2/gm)
80	214	.0214	2.08	253
160	220	.0220	2.08	246
240	231	.0231	2.05	232
320	234	.0234	2.06	230

Table 4-3. Hobart Grinder. Particle size distribution and total surface area of the ground material obtained with various feed rates when burrs clearance is set at "medium."

Feed Rate (gm/mn)	d_w (μ)	d_w (cm)	s_w	A_{st} (cm^2/gm)
80	488	.0488	2.15	114
160	501	.0501	2.11	109
240	522	.0522	2.03	102
320	536	.0536	1.96	96

Table 4-4. Weber Mill. Particle size distribution and total surface area of the ground material obtained with various feed rates when a .024"-screen is used.

Feed Rate (gm/mn)	d_w (μ)	d_w (cm)	s_w	A_{st} (cm^2/gm)
38	155	.0155	1.49	289
75	160	.0160	1.52	282
110	160	.0160	1.51	281
150	170	.0170	1.51	265

Table 4-5. Weber Mill. Particle size distribution and total surface area of the ground material obtained with various feed rates when a .040"-screen is used.

Feed Rate (gm/mn)	d_w (μ)	d_w (cm)	s_w	A_{st} (cm^2/gm)
38	168	.0168	1.66	280
75	175	.0175	1.73	275
110	175	.0175	1.71	273
150	182	.0182	1.73	264

Table 4-6. Udy Mill. Particle size distribution and total surface area of the ground material obtained with various feed rates when a .5mm-screen is used.

Feed Rate	d_w		s_w	A_{st}
(gm/mn)	(μ)	(cm)		(cm^2/gm)
45	159	.0159	1.47	280
90	162	.0162	1.48	276
135	173	.0173	1.47	258
180	186	.0186	1.48	240

Table 4-7. Udy Mill. Particle size distribution and total surface area of the ground material obtained with various feed rates when a 1mm-screen is used.

Feed Rate	d_w		s_w	A_{st}
(gm/mn)	(μ)	(cm)		(cm^2/gm)
45	162	.0162	1.52	279
90	168	.0168	1.52	269
135	180	.0180	1.54	252
180	190	.0190	1.54	239

Table 4-8. Wiley Mill. Particle size distribution and total surface area of the ground material obtained with two batch sizes when a 1mm-screen is used.

Batch Size (gm)	d_w (μ)	d_w (cm)	s_w	A_{st} (cm^2/gm)
100	292	.0292	1.56	157
200	305	.0305	1.59	151

Table 4-9. Wiley Mill. Particle size distribution and total surface area of the ground material obtained with two batch sizes when a 2mm-screen is used.

Batch Size (gm)	d_w (μ)	d_w (cm)	s_w	A_{st} (cm^2/gm)
100	428	.0428	1.82	115
200	456	.0456	1.78	107

The farther the value of this parameter from unity, the more heterogeneous the product. The results showed that the Weber hammermill and the Udy mill give a more uniform grind than do the Quadrumat Junior and Hobart grinders. In addition, it can be noted that grinds obtained with the Weber and the Udy mills are much alike in uniformity, and this also holds good for the products ground on the Quadrumat Junior and the Hobart. The value of the standard deviation, obtained with the first pair of grinders when the fine screens were used, was approximately 1.5; the value obtained with the second pair was approximately 2.1. In the case of the Quadrumat Junior, the lack of uniformity of the ground product was expected because of the well-known action of the rolls which tend to separate the bran, or coarse fraction, from the flour which is made up of very fine particles.

From the standpoint of total surface area of the ground product, the data in Tables 4-1 to 4-9 revealed that the finest grind was obtained with the Quadrumat Junior, while understanding that the higher the value of total surface area the finer the product. Furthermore, it was noted that the Weber ranked second, the Udy third, the Hobart fourth, the Wiley being the last. This classification was based on the conditions of the experiment that resulted in the finest grind from each mill. It should also be pointed out that the conclusions, drawn during the study of the modified moduli relative to the effect of screen size, feed rate, or batch size, can also be drawn from the data obtained for the surface area of the ground material.

If a parallel was to be made between the two methods used to express the particle size, it would be clear that they do not yield exactly the same results. When the modified modulus of fineness method was used, the Weber ranked first (the finest), the Udy second, and the Quadrumat Junior third (Figures 11-1 and 11-2); whereas, when the classification was made on the basis of surface area, the Quadrumat Junior was the finest grinder, followed by the Weber, and the Udy (Figures 17-1 and 17-2). A sound explanation for this is that the modified index of fineness gives no indication on the uniformity of the ground sample. In fact, it is possible to have the same modified modulus of fineness for two distinct samples when the proportionate amounts of different sized-particles are quite dissimilar for each sample. This explains why the modified modulus of fineness should always be accompanied by the modified modulus of uniformity. On the other hand, the method based on total surface area takes into account the average size of the particles and the uniformity of the sample. The Quadrumat Junior, at 60 grams per minute, gave an average particle size of 173 microns; the Weber mill, at 38 grams per minute, yielded an average particle size of 155 microns, yet the surface area of the product ground on the Quadrumat Junior was larger than the surface area of the material ground on the Weber. By examing the equation for total surface area, it is easy to observe that the factors which are subject to variation in the conditions of the study are the mean diameter and the standard deviation. Since the variation in mean diameter is not involved in the result observed (an increase in mean diameter leads to a decrease of surface area), the only factor remaining is the standard deviation, that is, the uniformity of the sample.

Thus, the figures, obtained by the method based on surface area, appear to be more realistic, because they are the result of a combination of both the average size of the particles and the uniformity of the product.

Energy Measurements

The amounts of energy consumed per hour by the different grinders are shown in Tables 5-1 to 5-2. These data were used to plot the curves in Figures 18-1 and 18-2. The conclusions that can be drawn are: first, for all grinders, the energy consumed increases with the capacity. Second, in general, the highest consumption of energy was observed when grinding with the Udy mill, and the least consumption was observed when grinding with the Quadrumat Junior.

The data, relative to energy consumption and energy requirements obtained for the Wiley mill (Tables 5-2 and 6-2), should be considered with some caution. In order to establish a comparison with the other grinders on an hourly basis, the method used to evaluate the energy was purely theoretical. First, to figure out the amount of product ground per hour, preliminary tests were run with different batches and different screens. This was achieved by recording the time necessary for the mill to grind a whole batch of a certain size. It should be noted here, because of the difficulty to know the exact time when there was no more product in the grinding chamber, a tolerance of one percent or less of material remaining in the grinding room was accepted. The number of batches per hour was then determined by simple calculation, assuming that as soon as the whole batch has passed through the screen, another batch was dumped in the grinding chamber.

Second, to determine the amount of energy consumed per hour, the number of watthours used to grind a batch of a certain size were multiplied by the number of batches per hour.

In practice, the operation would probably be conducted differently; if more than one batch is needed, grain, in such amount that it will not overload the mill, will be added before the previous batch has completely left the grinding chamber. The results for particle size and energy consumption would then be completely different from those obtained by the method used for this experiment.

Because the Wiley mill was designed to be fed batchwise, the interest of the study was to test the two batch sizes recommended by the manufacturer from the double standpoint of both particle size and energy consumption. For this reason, preference was given to the theoretical method in evaluating energy consumed per hour. In fact, the most reasonable approach to the problem of energy evaluation would have been to give the energy figures corresponding to a certain batch size and to not express these on an hourly basis. This is shown on page 133 of the appendix.

From the data obtained for energy consumption per hour and grinding capacity, the energy required to grind one pound of wheat was then figured for each grinder. The results, presented in Table 6-1, led to the plotting of curves showing the relationship between energy requirements, capacity and modified modulus of fineness (Figures 6 to 10), and the relationship between energy requirements, capacity and surface area (Figures 12 to 16).

For each grinder, the two methods gave the same relationship between energy, capacity, and fineness of the product. Furthermore, for the Hobart,

Table 5-1. Energy consumed per hour.

Feed Rate		Watthours		
gm/mn	Lbs/hr	Mill empty	Mill under load	Mill under load
			Quadrumat Junior	
60	8	63	43.5	
120	16	--	78.4	
180	24	--	153.4	
240	32	--	283.2	
			Hobart Grinder	
			Very fine setting	Medium setting
80	10.5	150	154.8	75.4
160	21	---	301.8	127.1
240	31.5	---	453.8	181.4
320	42	---	571.6	230.2
			Weber Mill	
			.024" screen	.040" screen
38	5	346	68.1	36.3
75	10	---	108.9	68.9
110	15	---	152.4	92.6
150	20	---	199.6	112.4
			Udy Mill	
			.5mm screen	1mm screen
45	6	364	133.1	108.8
90	12	---	258.8	202.4
135	18	---	381.1	283.1
180	24	---	505.2	357.1

Table 5-2. Wiley Mill. Energy consumed per hour.

Batch Size gm	Lbs ground per hour	Watthours Mill empty	Watthours Mill under load
			1mm screen
100	1.6	203	44.5
200	2.2	---	66.6
			2mm screen
100	9.9	203	62.1
200	13.8	---	103.3

Table 6-1. Energy Requirements.

Feed Rate gm/mn	Feed Rate Lbs/hr	Watthours per pound of ground material	
		Quadrumat Junior	
60	8	5.44	
120	16	4.90	
180	24	6.39	
240	32	8.85	
		Hobart Grinder	
		Very fine setting	Medium setting
80	10.5	14.74	7.18
160	21	14.37	6.05
240	31.5	14.18	5.67
320	42	13.61	5.48
		Weber Mill	
		.024" screen	.040" screen
38	5	13.61	7.26
75	10	10.89	6.89
110	15	10.16	6.17
150	20	9.98	5.62
		Udy Mill	
		.5mm screen	1mm screen
45	6	22.18	18.14
90	12	21.57	16.87
135	18	21.17	15.73
180	24	21.05	14.88

Table 6-2. Wiley Mill. Energy Requirements.

Batch Size gm	Lbs ground per hour	Watthours per pound of ground material
		1mm screen
100	1.6	27.81
200	2.2	30.27
		2mm screen
100	9.9	6.3
200	13.8	7.5

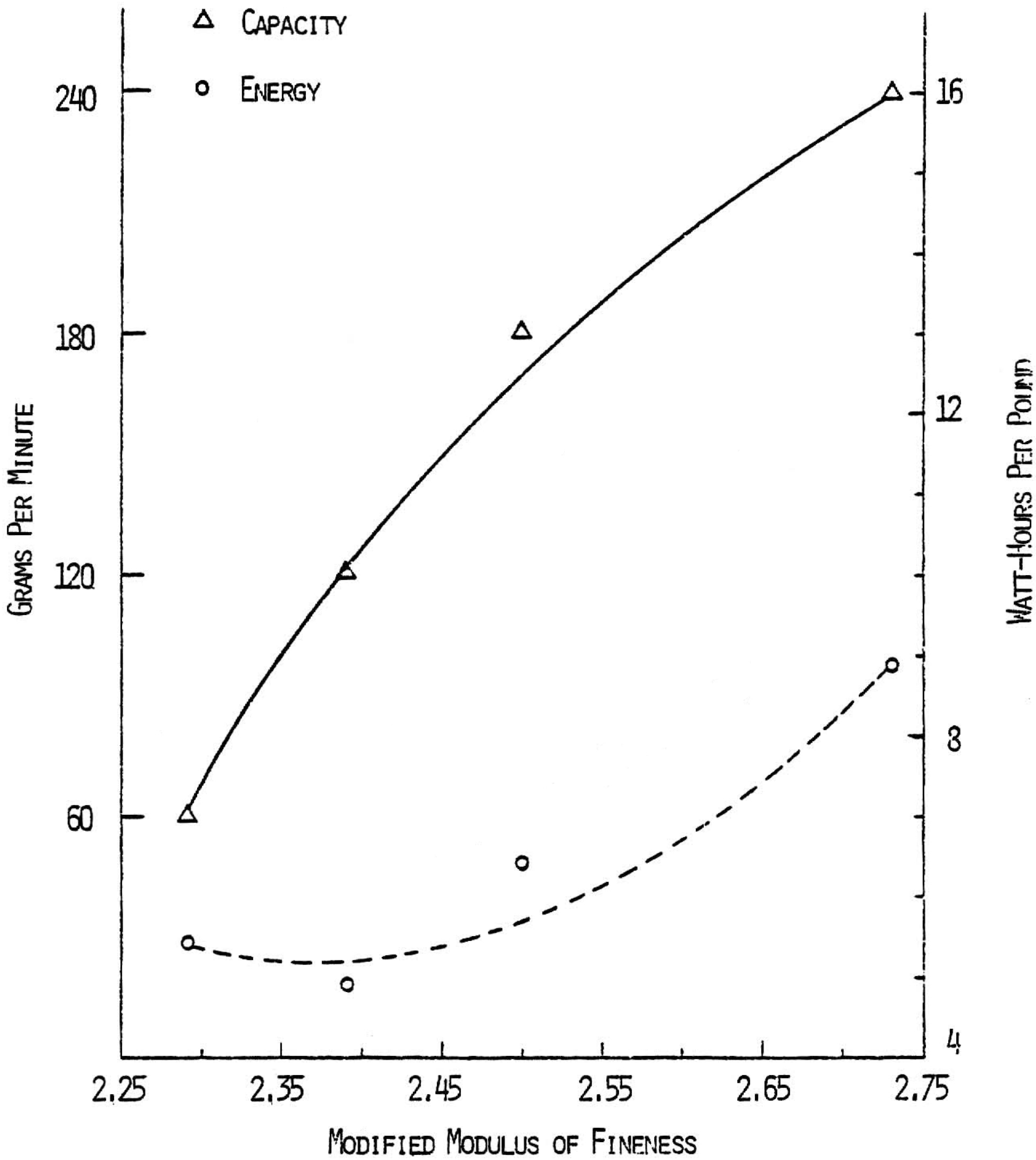


Figure 6. Quadrumat Junior - relationship between capacity energy and modified modulus of fineness.

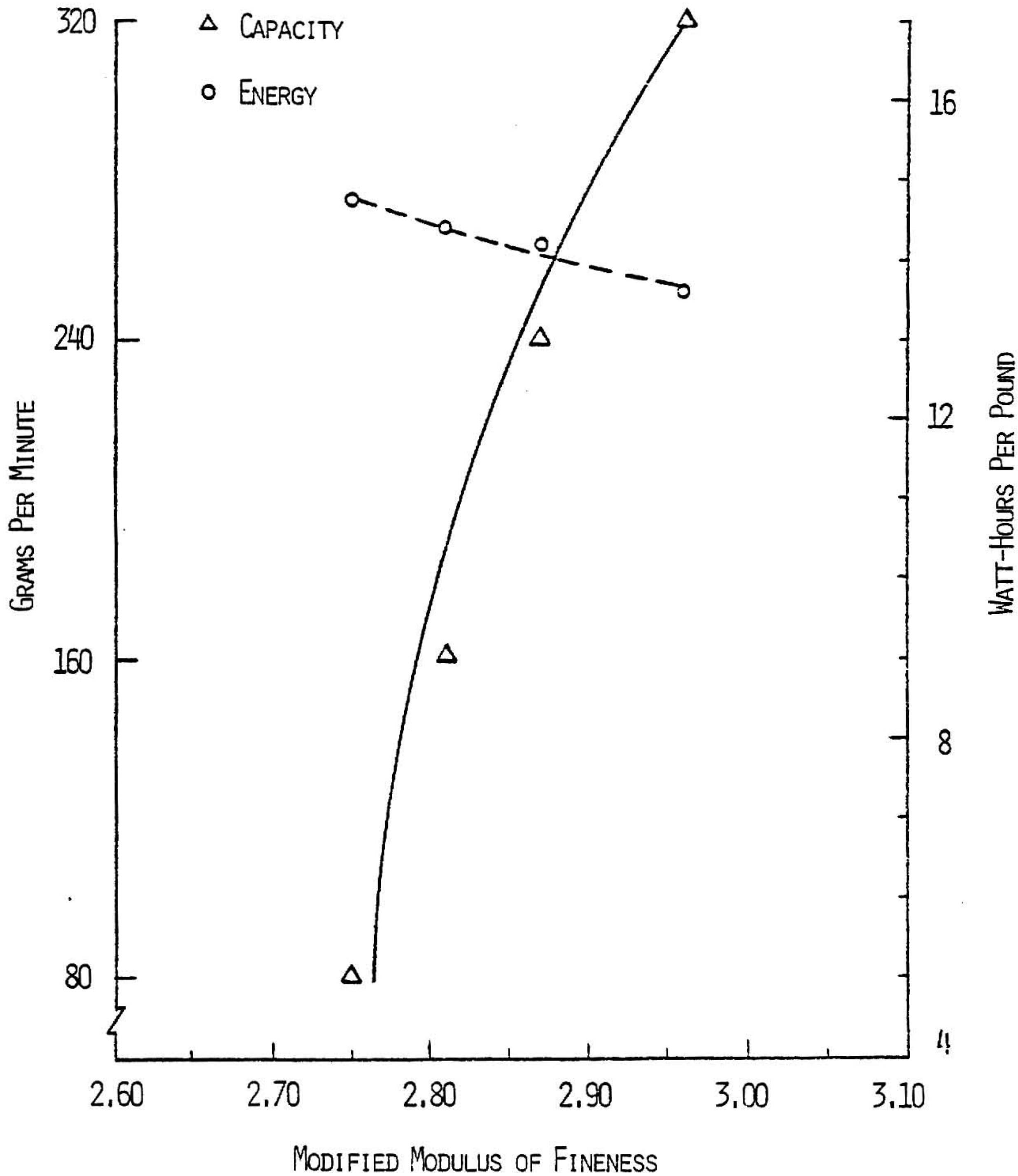


Figure 7-1. Hobart - relationship between capacity, energy and modified modulus of fineness when burr - clearance is set at "very fine".

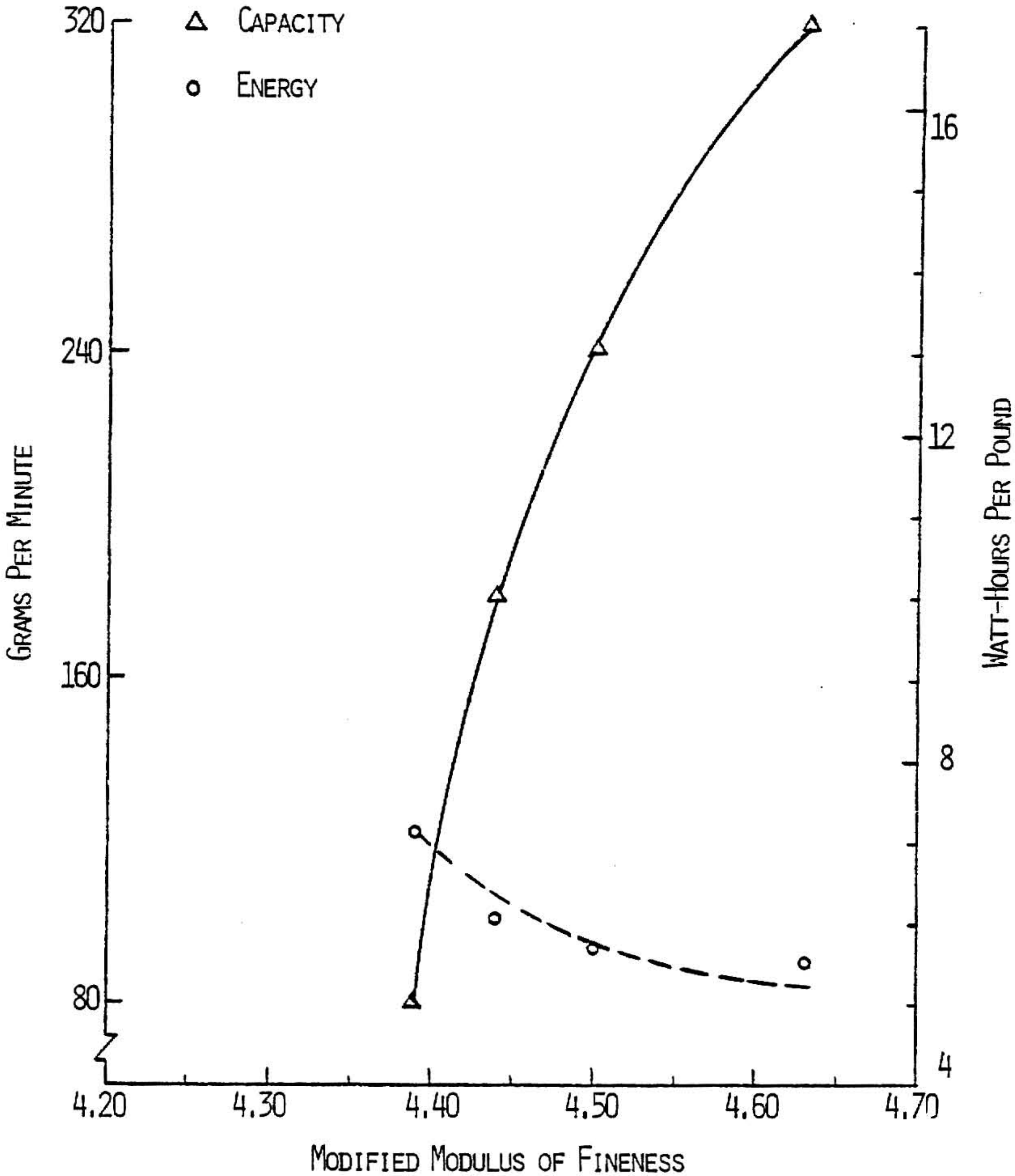


Figure 7-2. Hobart - relationship between capacity, energy and modified modulus of fineness when burr - clearance is set at "medium".

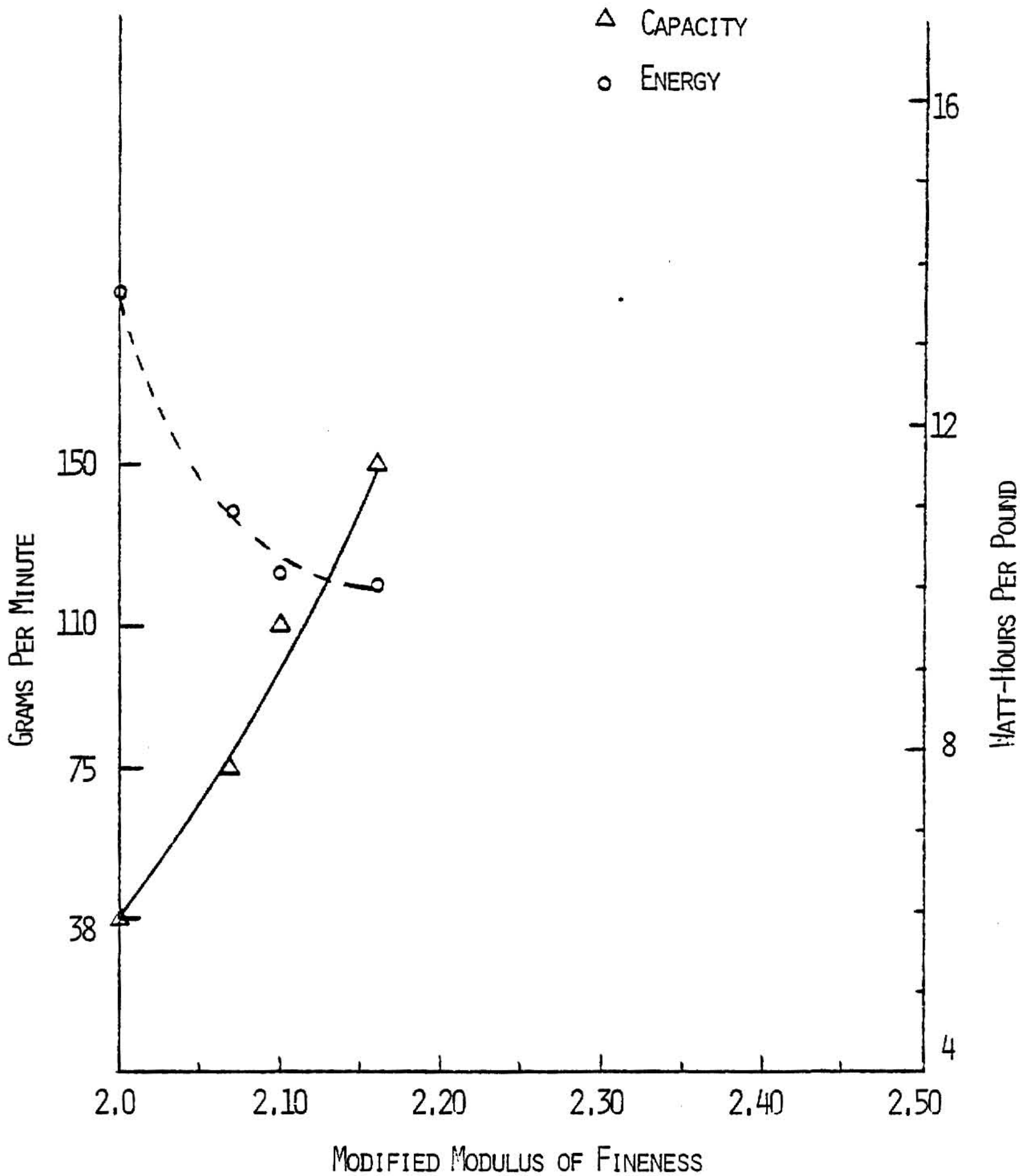


Figure 8-1. Weber - relationship between capacity, energy and modified modulus of fineness when a .024 inch-screen is used.

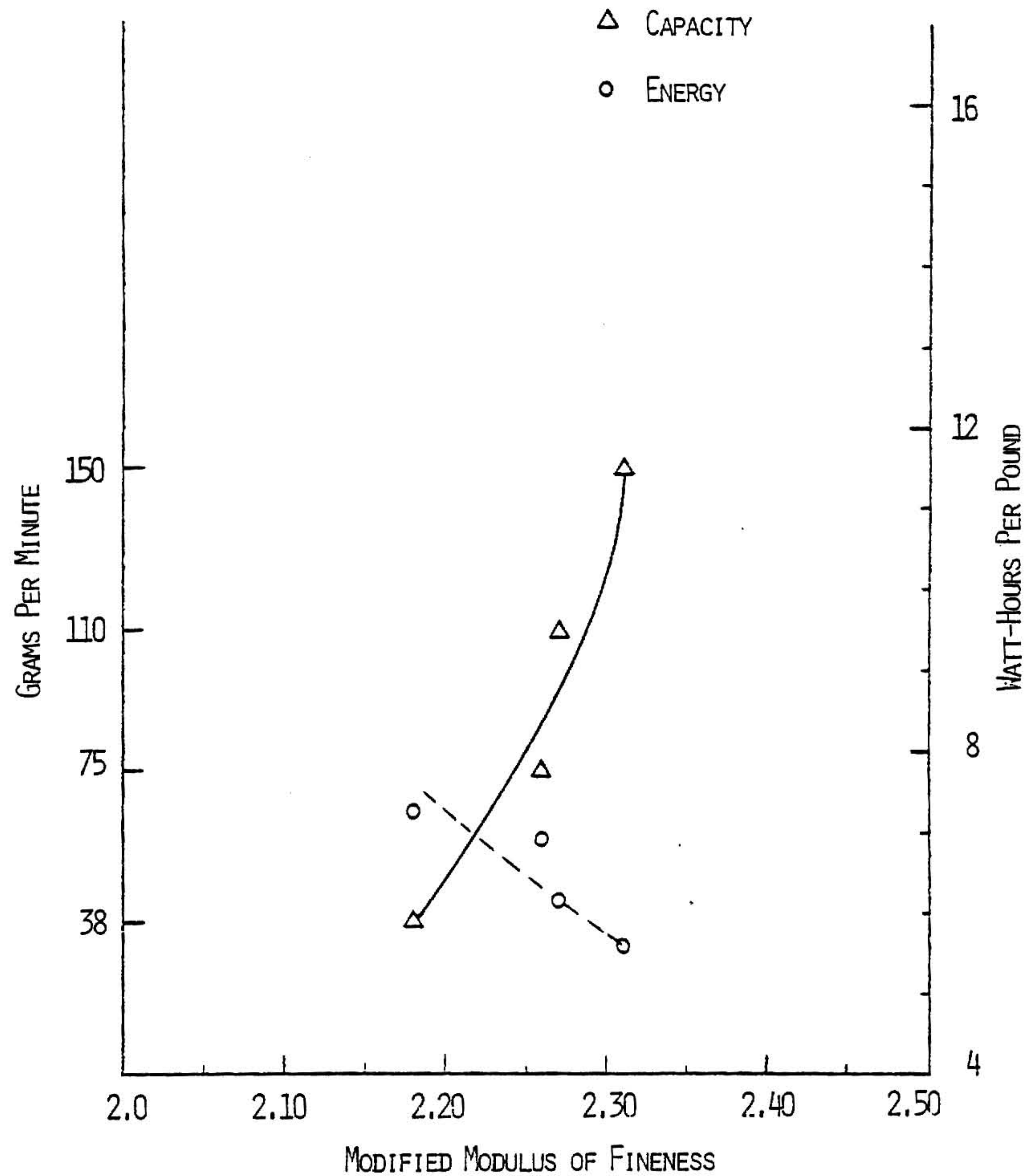


Figure 8-2. Weber - relationship between capacity, energy and modified modulus of fineness when a .040 inch-screen is used.

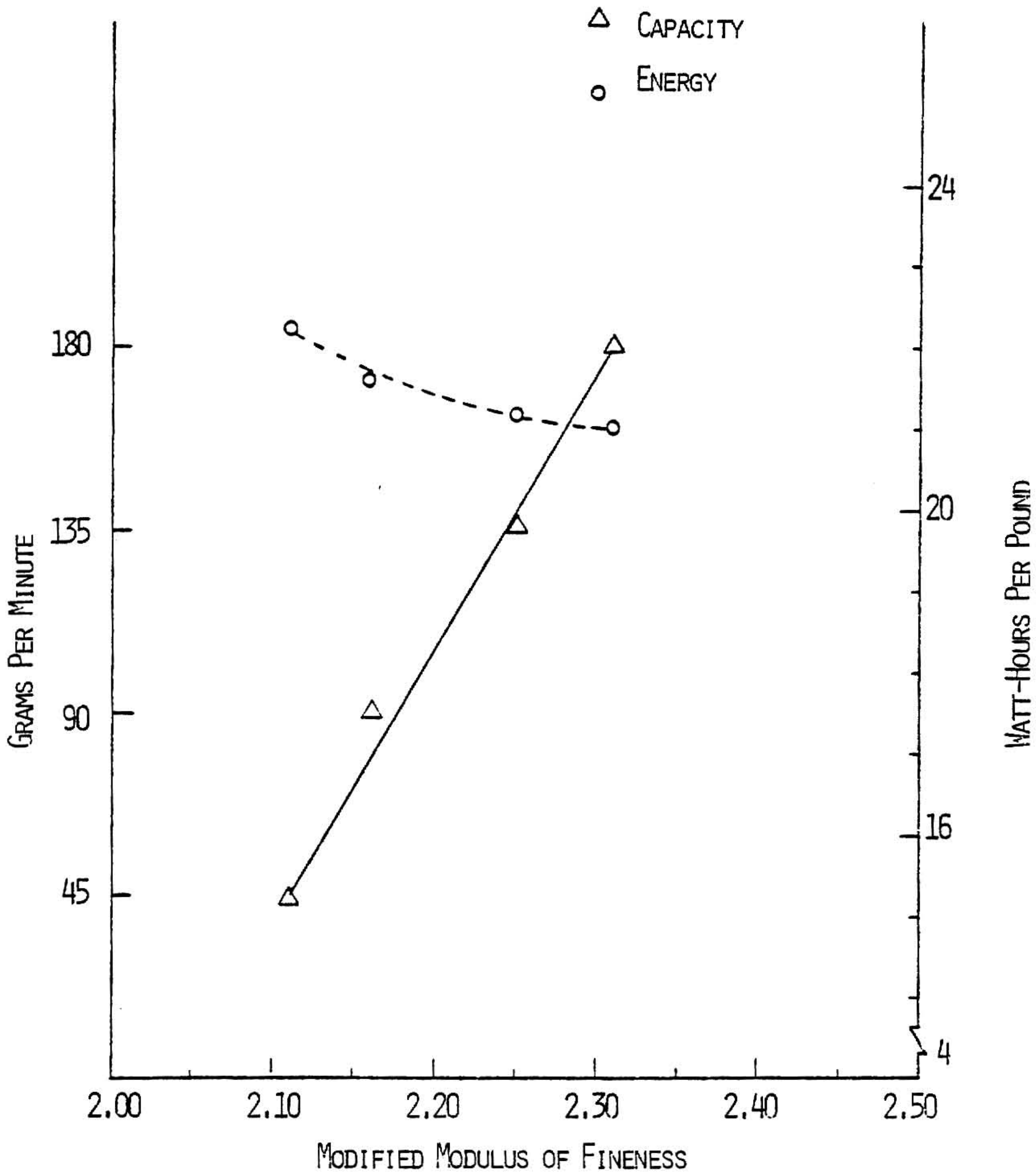


Figure 9-1. Udy - relationship between capacity, energy and modified modulus of fineness when a ½mm-screen is used.

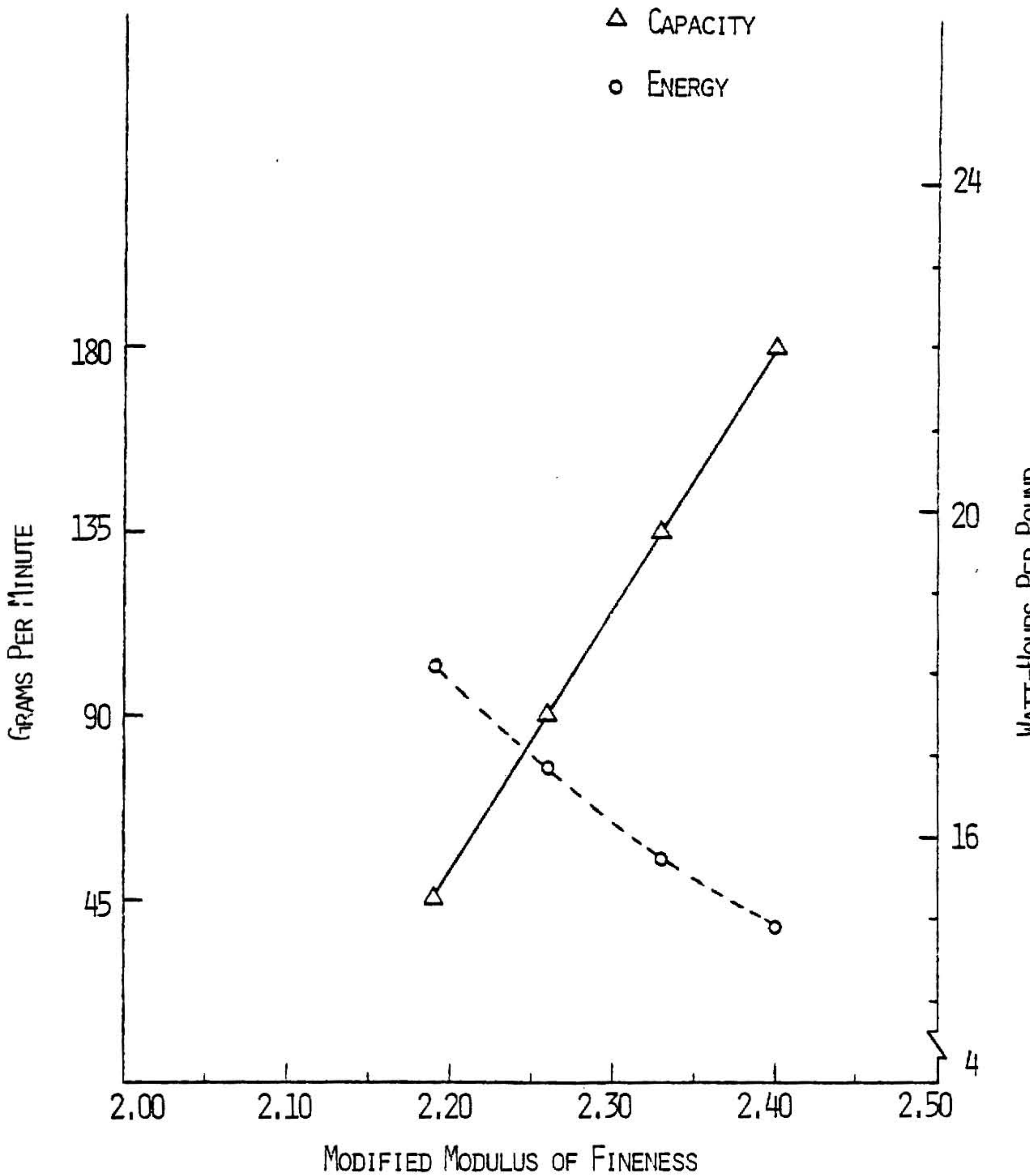


Figure 9-2. Udy - relationship between capacity, energy and modified modulus of fineness when a lmm-screen is used.

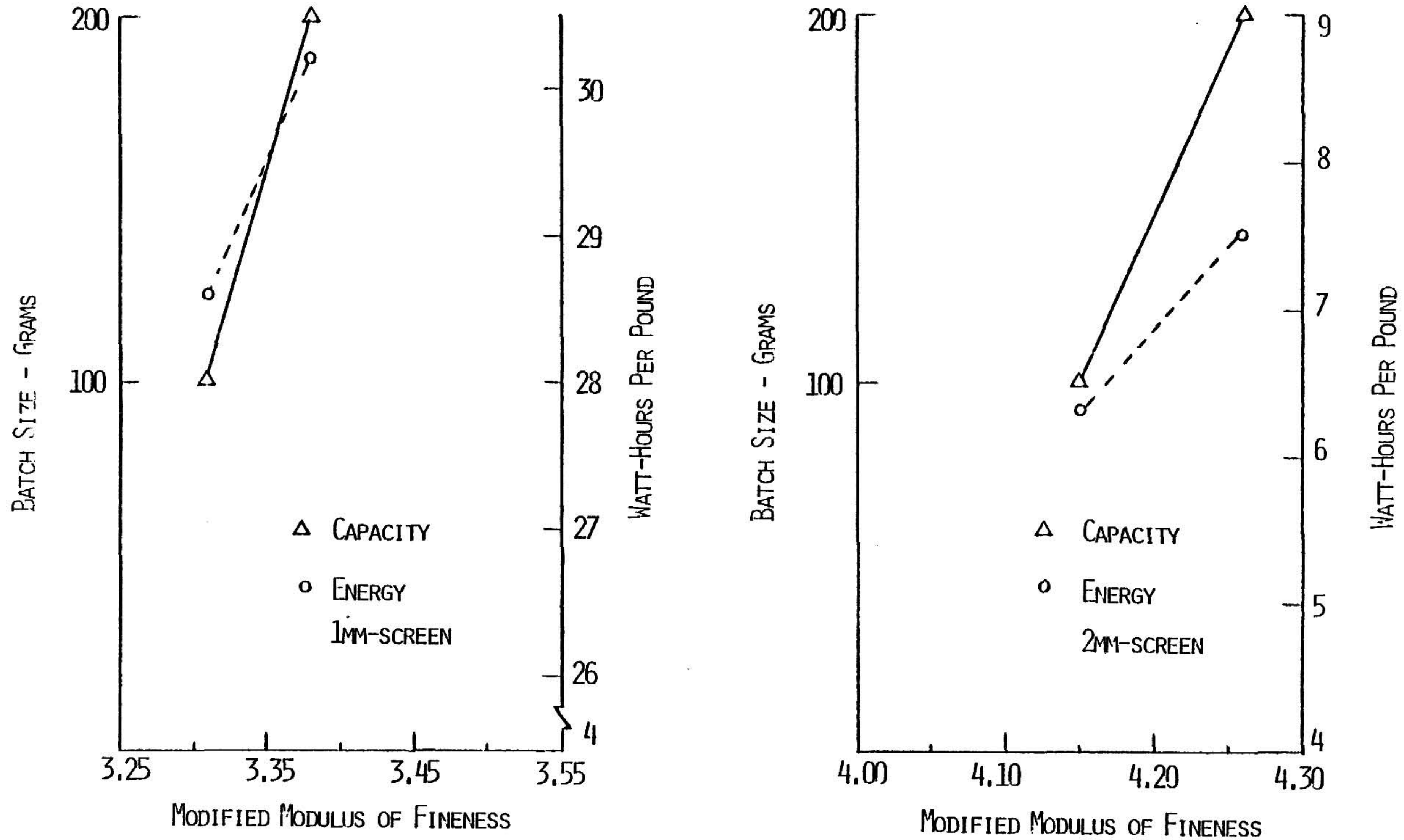


Figure 10. Wiley - relationship between batch size, energy and modified modulus of fineness when two different screens are used.

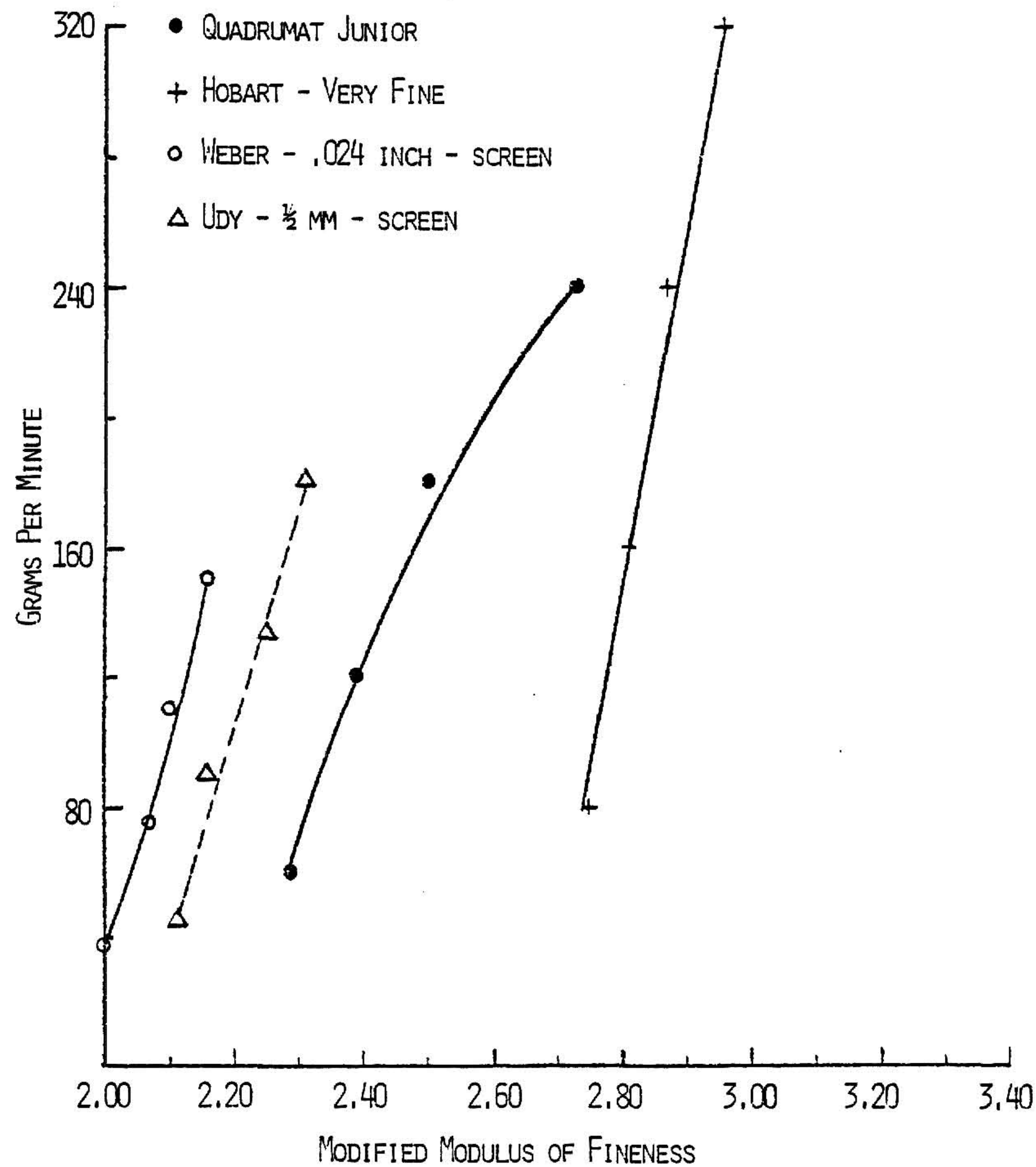


Figure 11-1. Relationship between capacity of grinding and modified modulus of fineness when using different grinders with specifications as shown above.

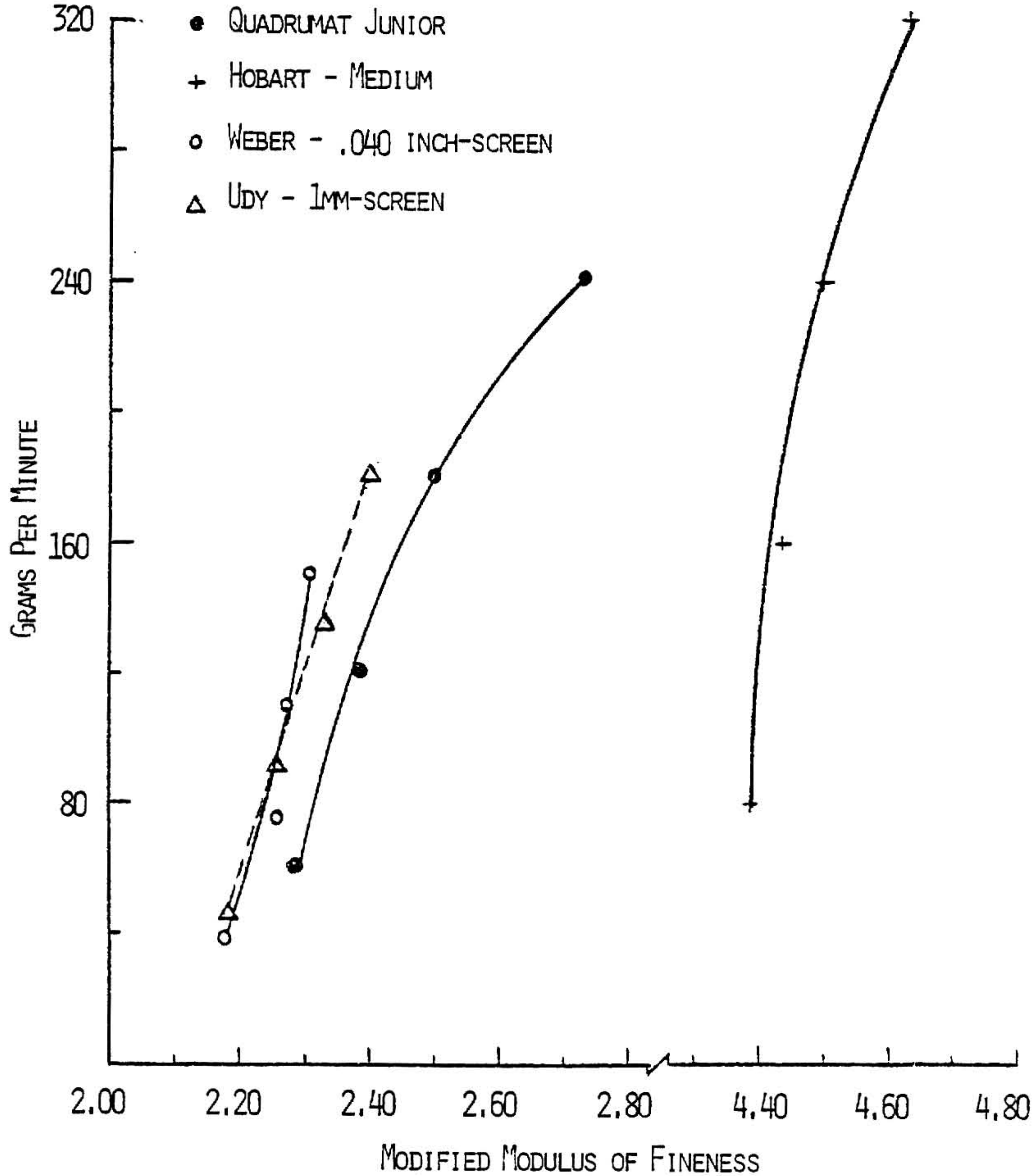


Figure 11-2. Relationship between capacity of grinding and modified modulus of fineness when using different grinders with specifications as shown above.

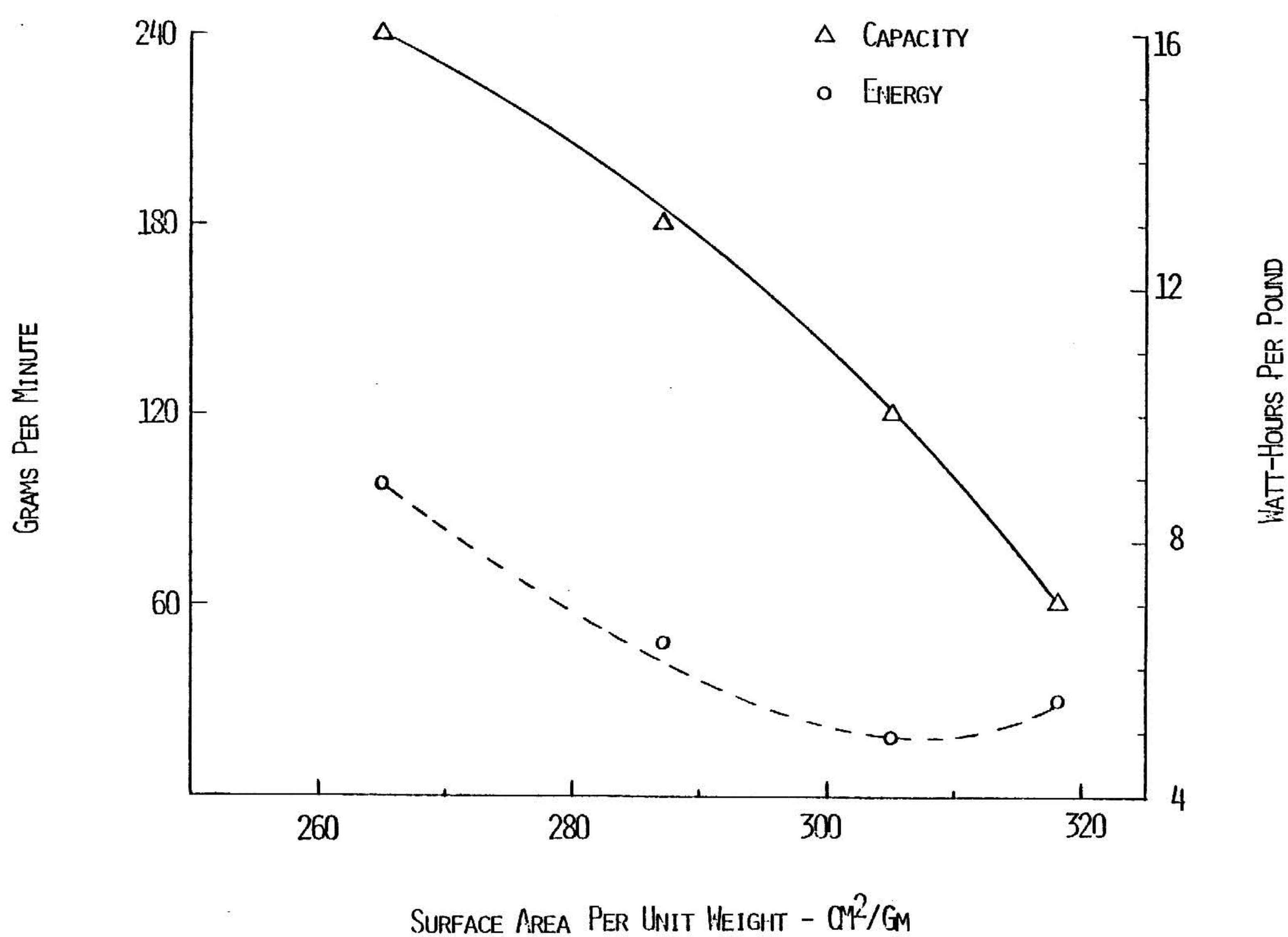


Figure 12. Quadrumat Junior - relationship between capacity, energy and surface area of the ground material.

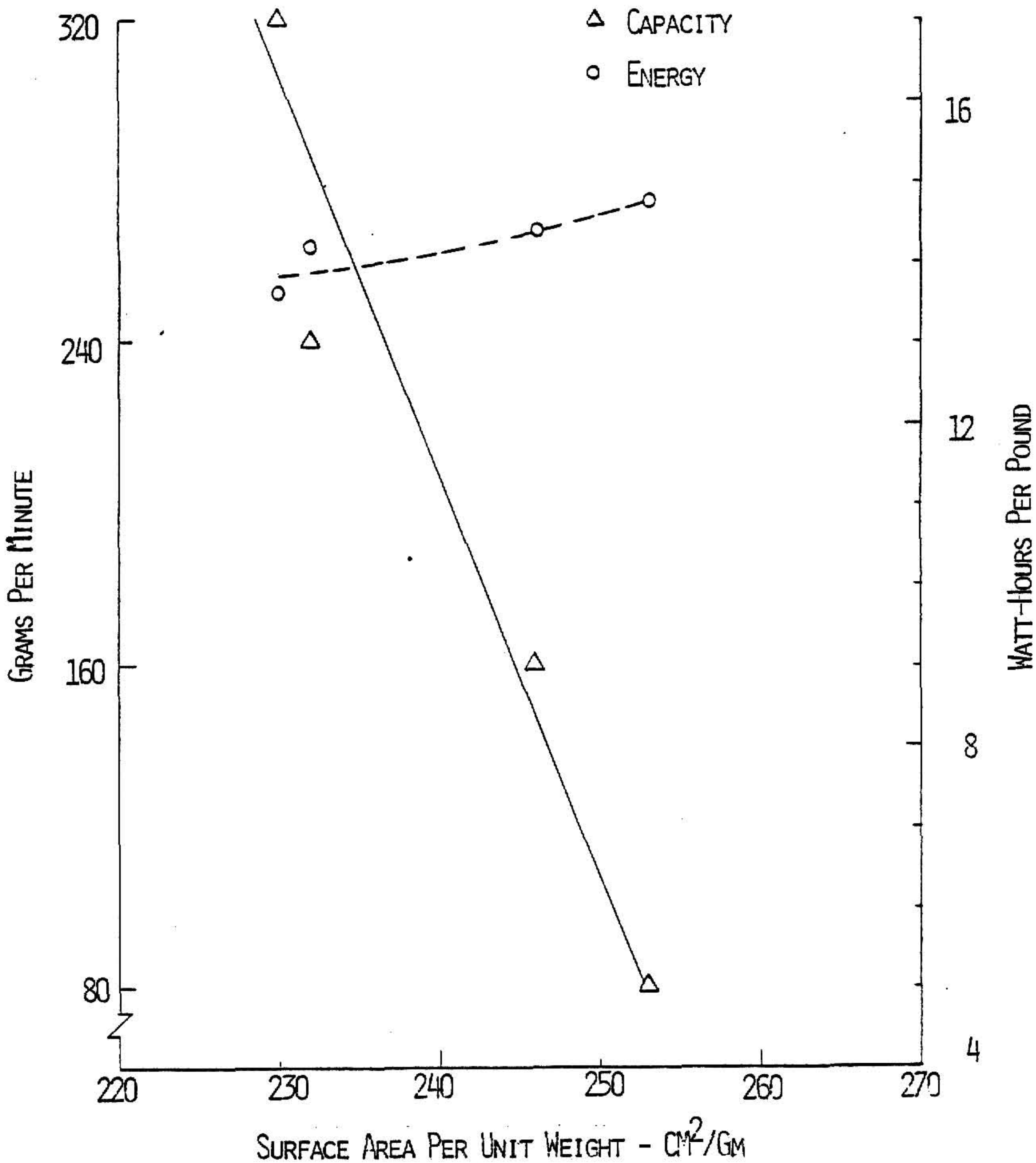


Figure 13-1. Hobart - relationship between capacity, energy and surface area of the ground material when burr - clearance is set at "very fine".

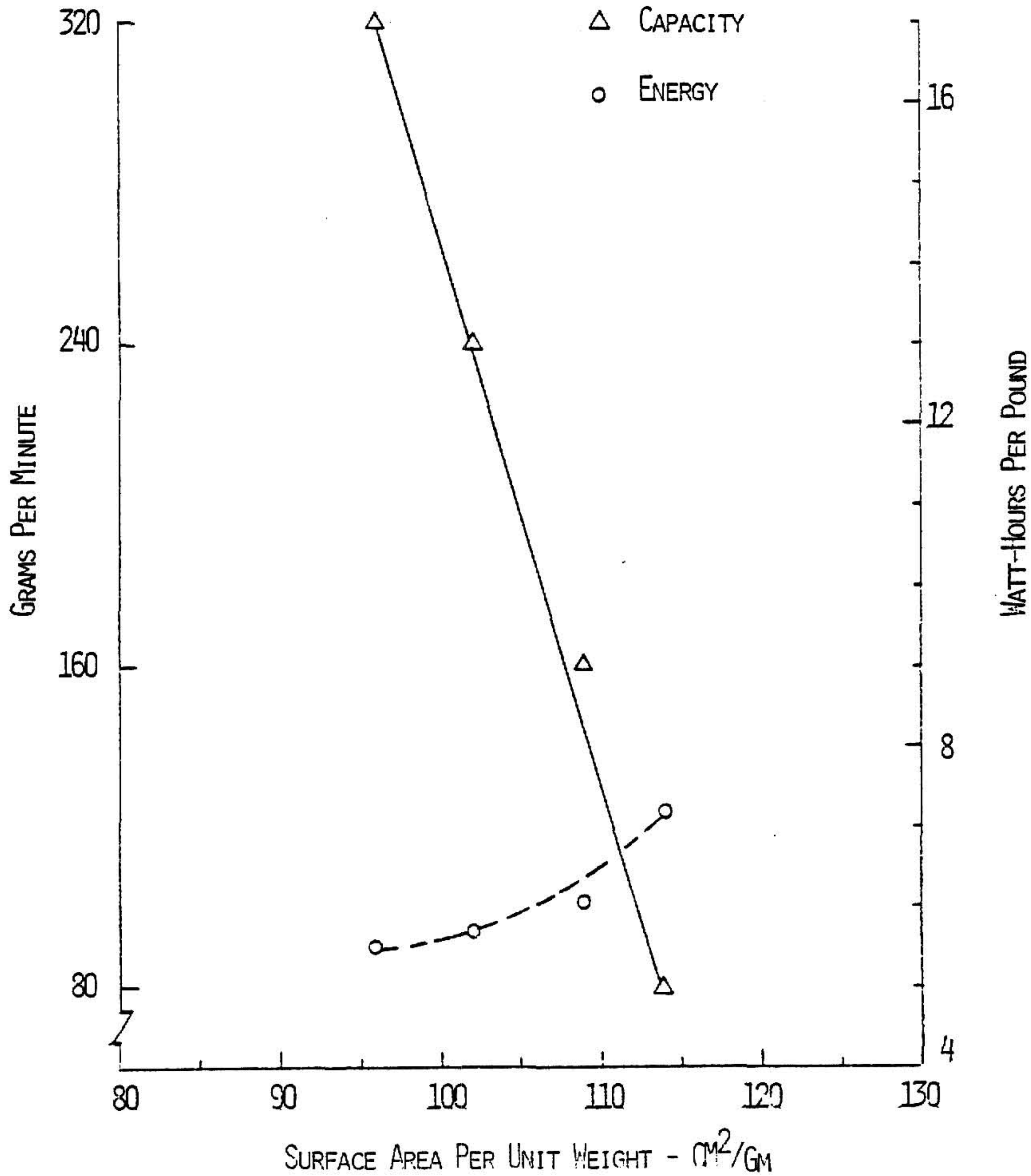


Figure 13-2. Hobart - relationship between capacity, energy and surface area of the ground material when burr - clearance is set at "medium".

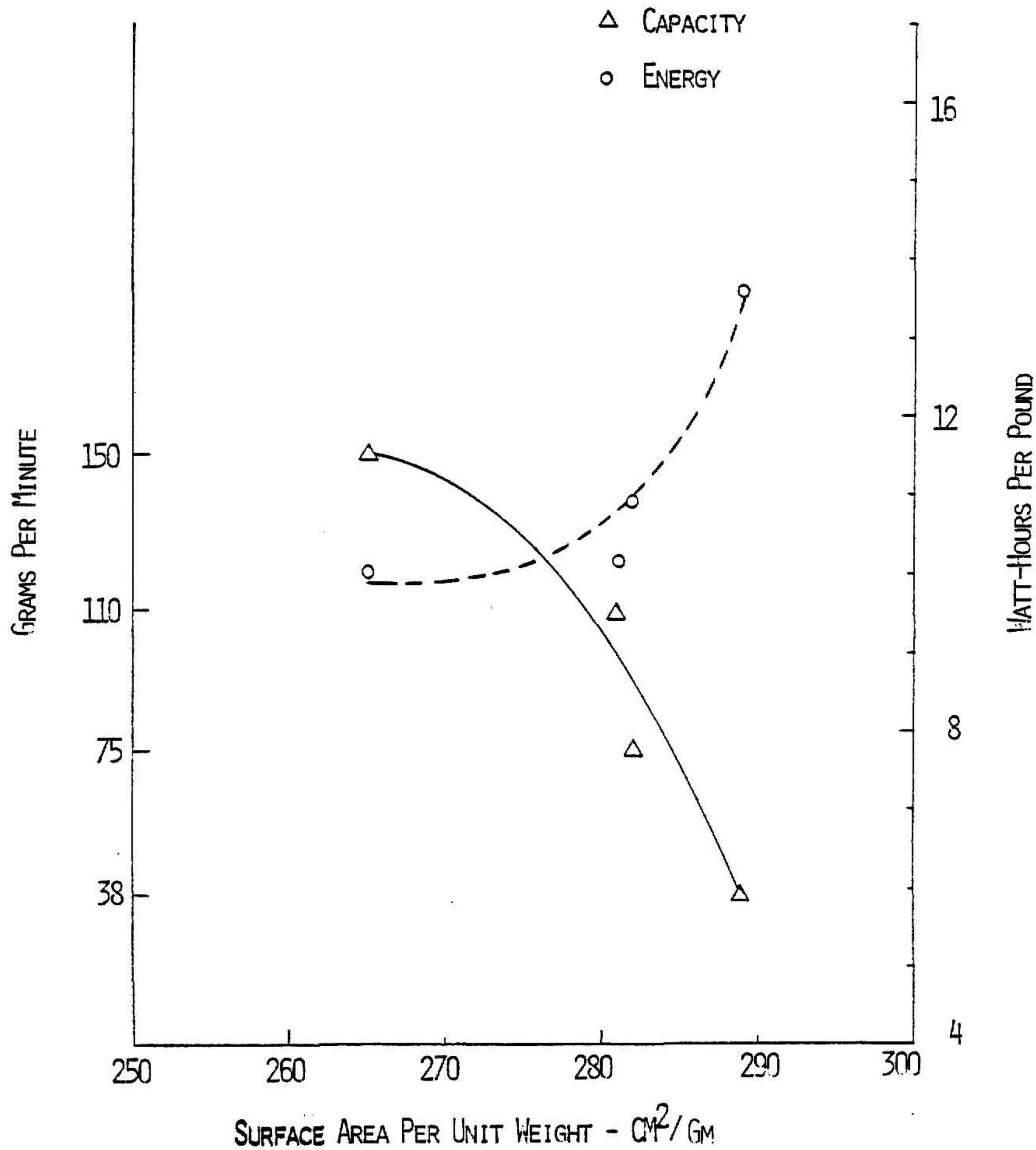


Figure 14-1. Weber - relationship between capacity, energy and surface area of the ground material when a .024 inch-screen is used.

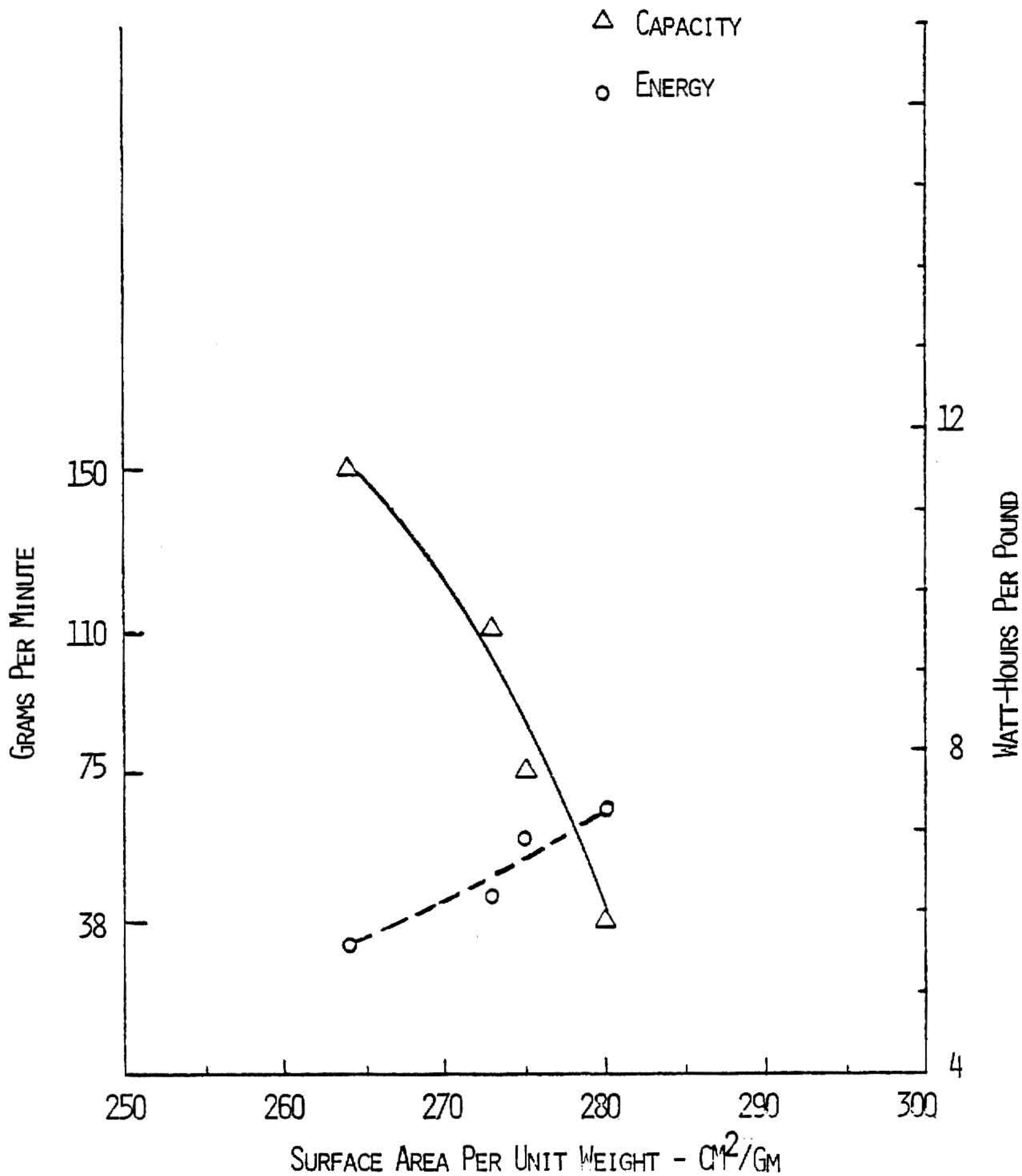


Figure 14-2. Weber - relationship between capacity, energy and surface area of the ground material when a .040 inch-screen is used.

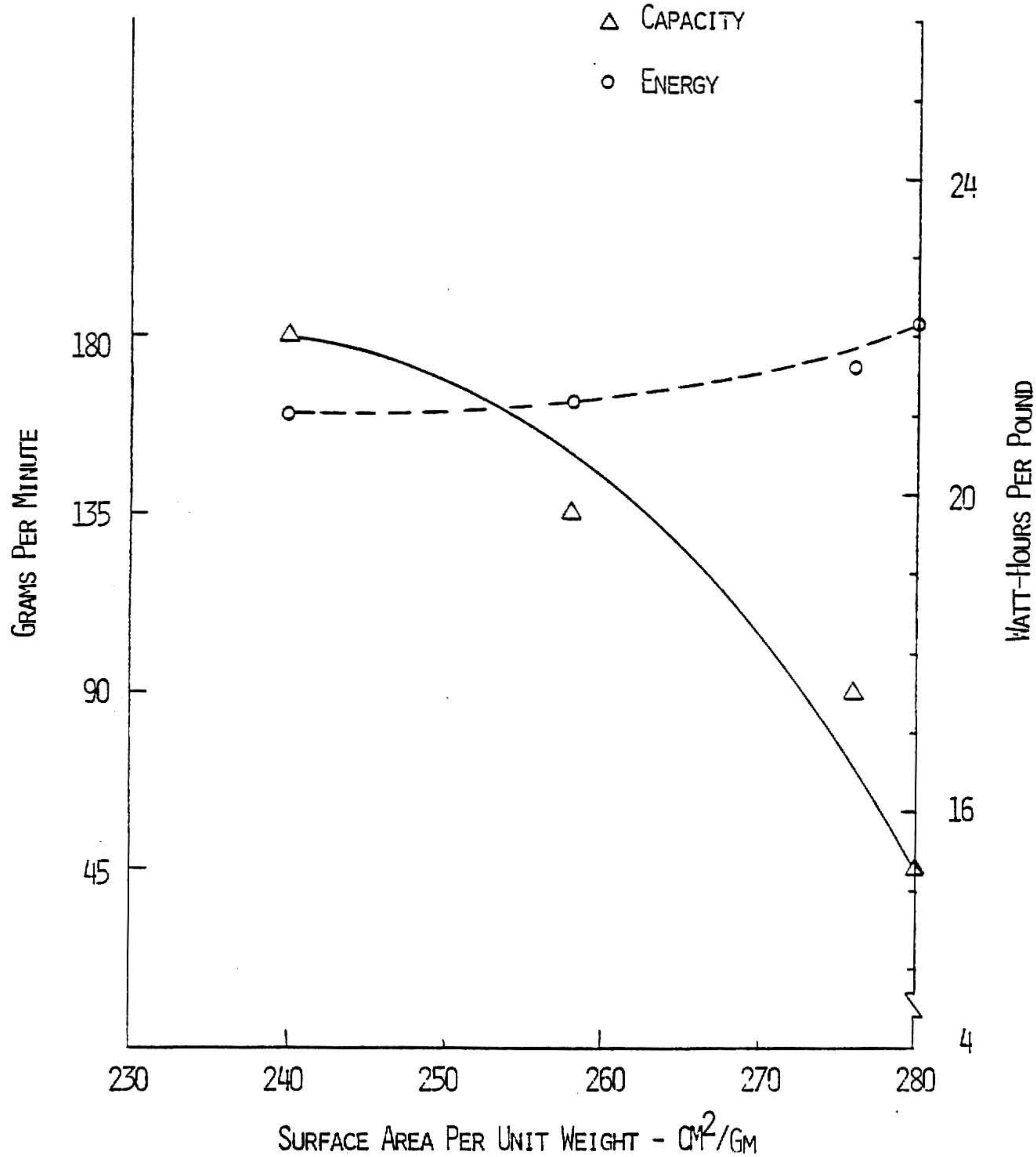


Figure 15-1. Udy - relationship between capacity, energy and surface area of the ground material when a ½mm-screen is used.

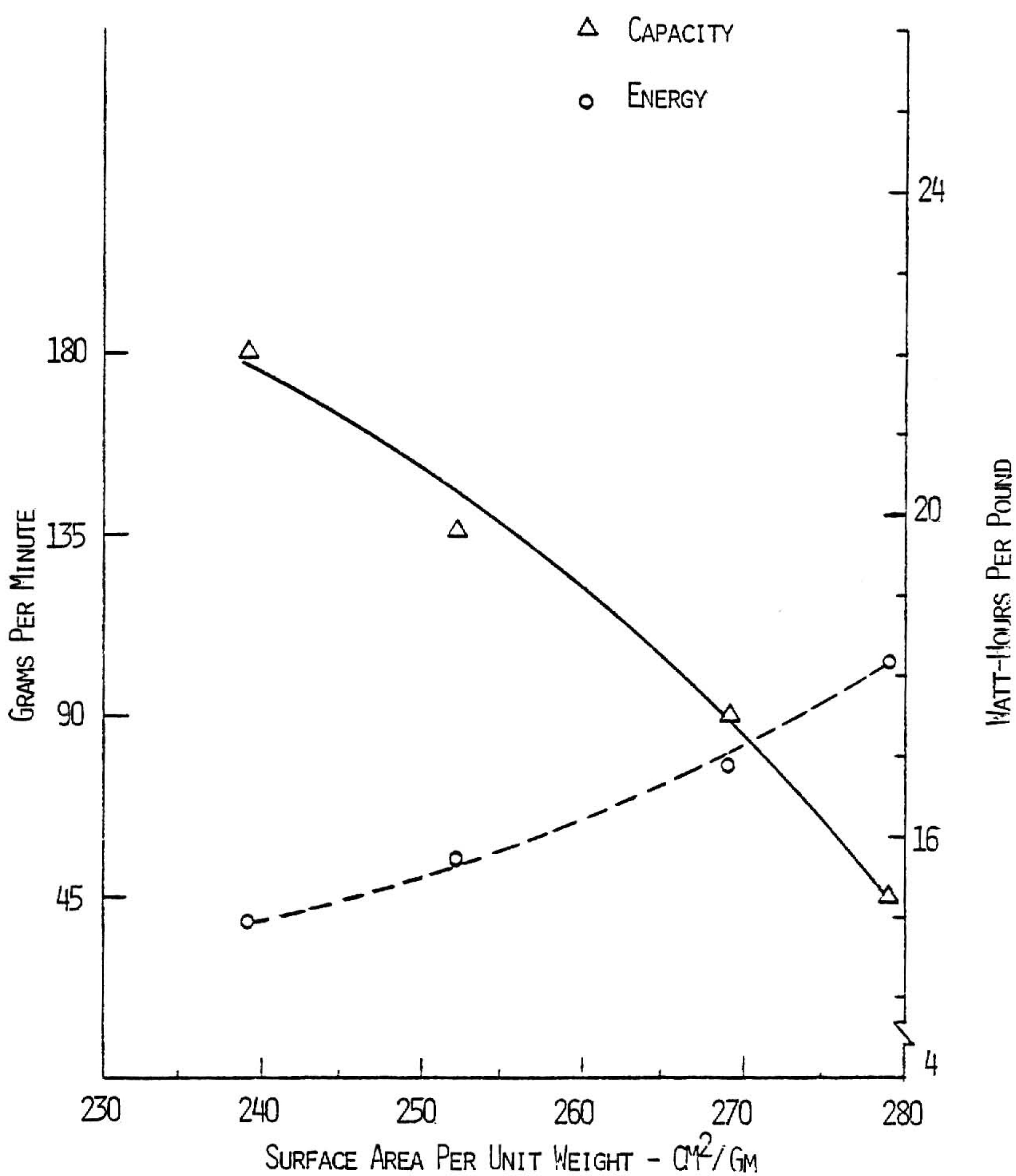


Figure 15-2. Udy - relationship between capacity, energy and surface area of the ground material when a 1mm-screen is used.

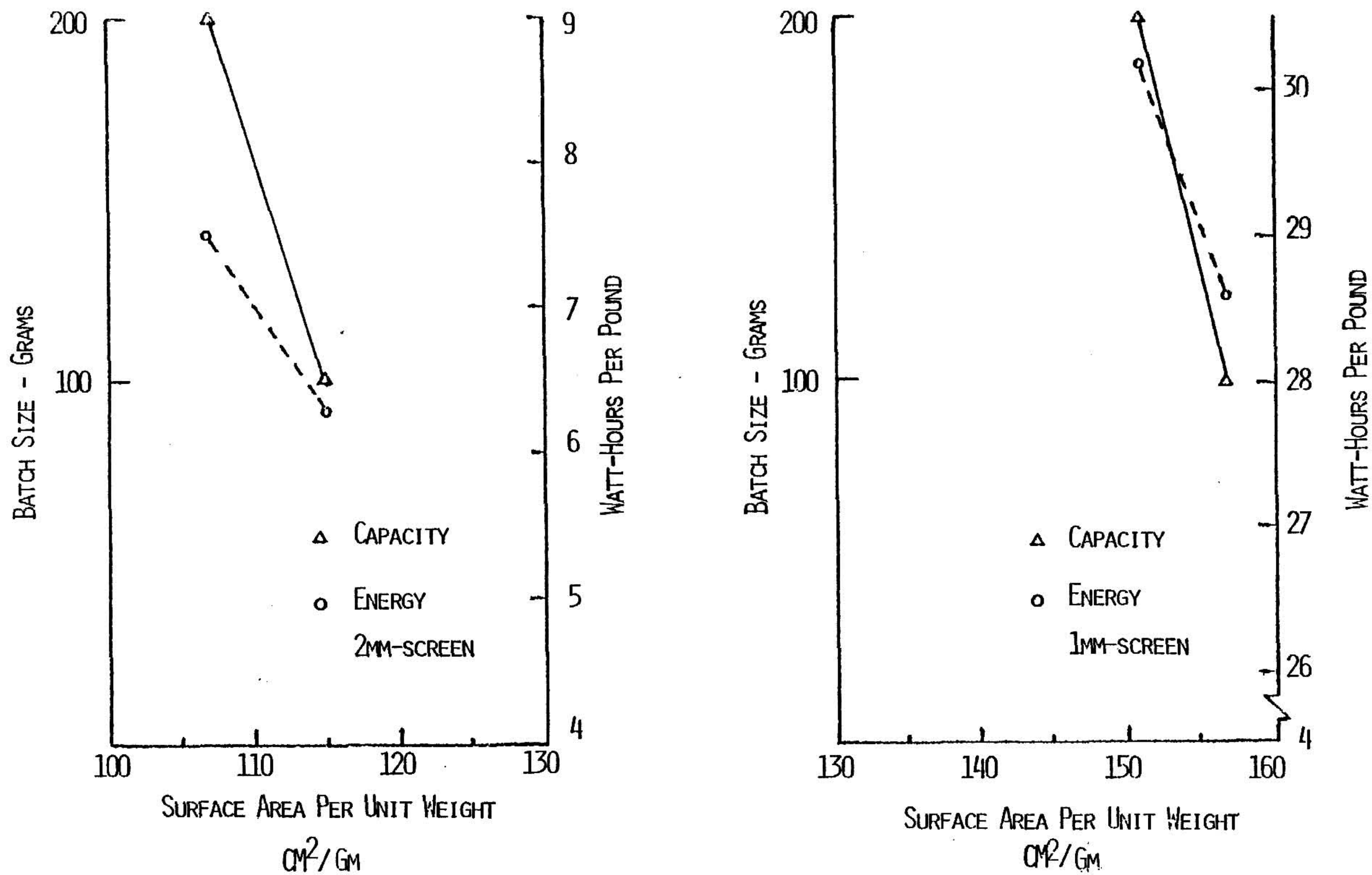


Figure 16. Wiley - relationship between batch size, energy and surface area of the ground material when two different screens are used.

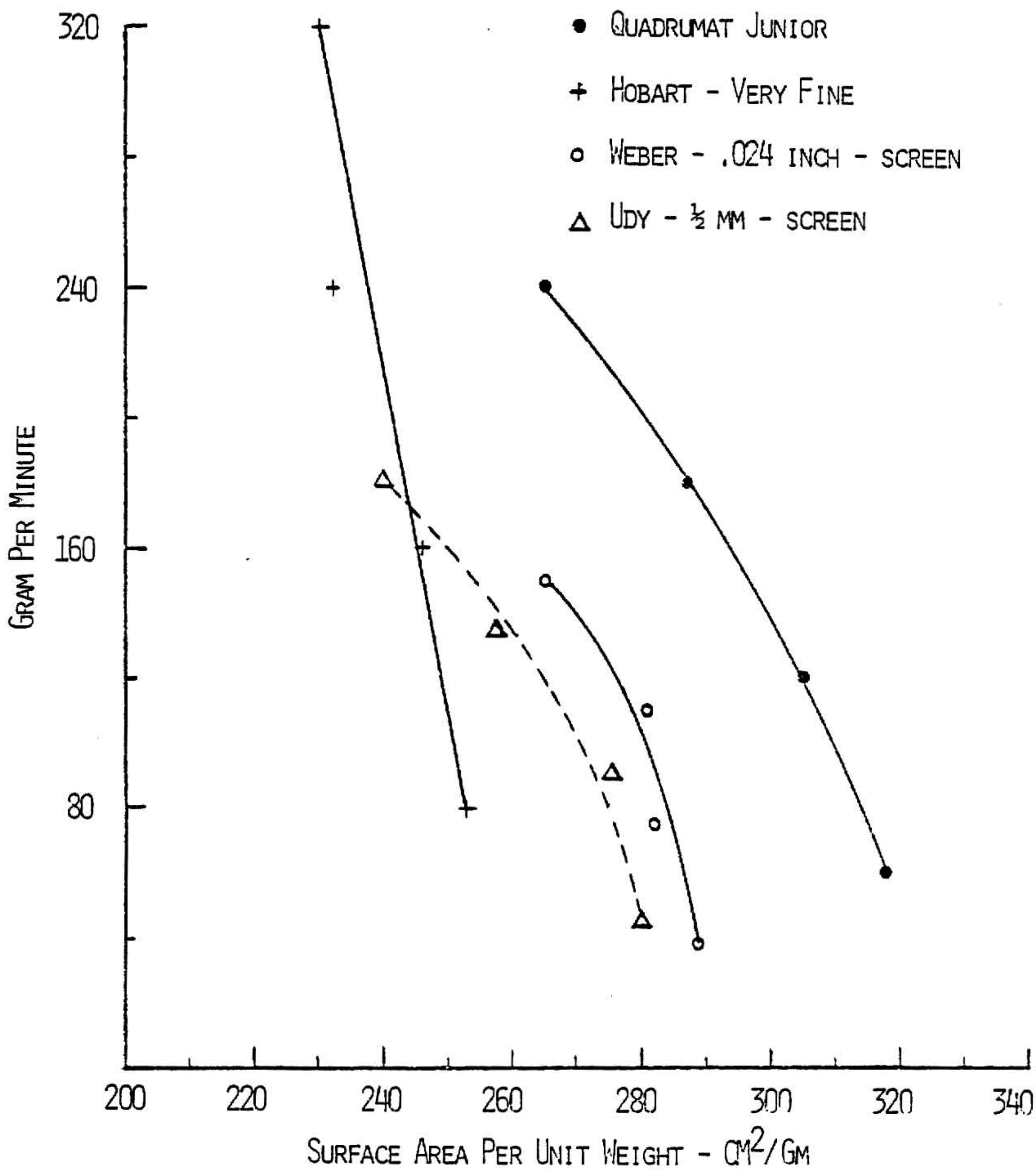


Figure 17-1. Fineness of material ground with the Quadrumat Junior, the Weber equipped with a .024 inch-screen, the Udy equipped with a ½mm-screen, and the Hobart with burr-clearance set at "very fine".

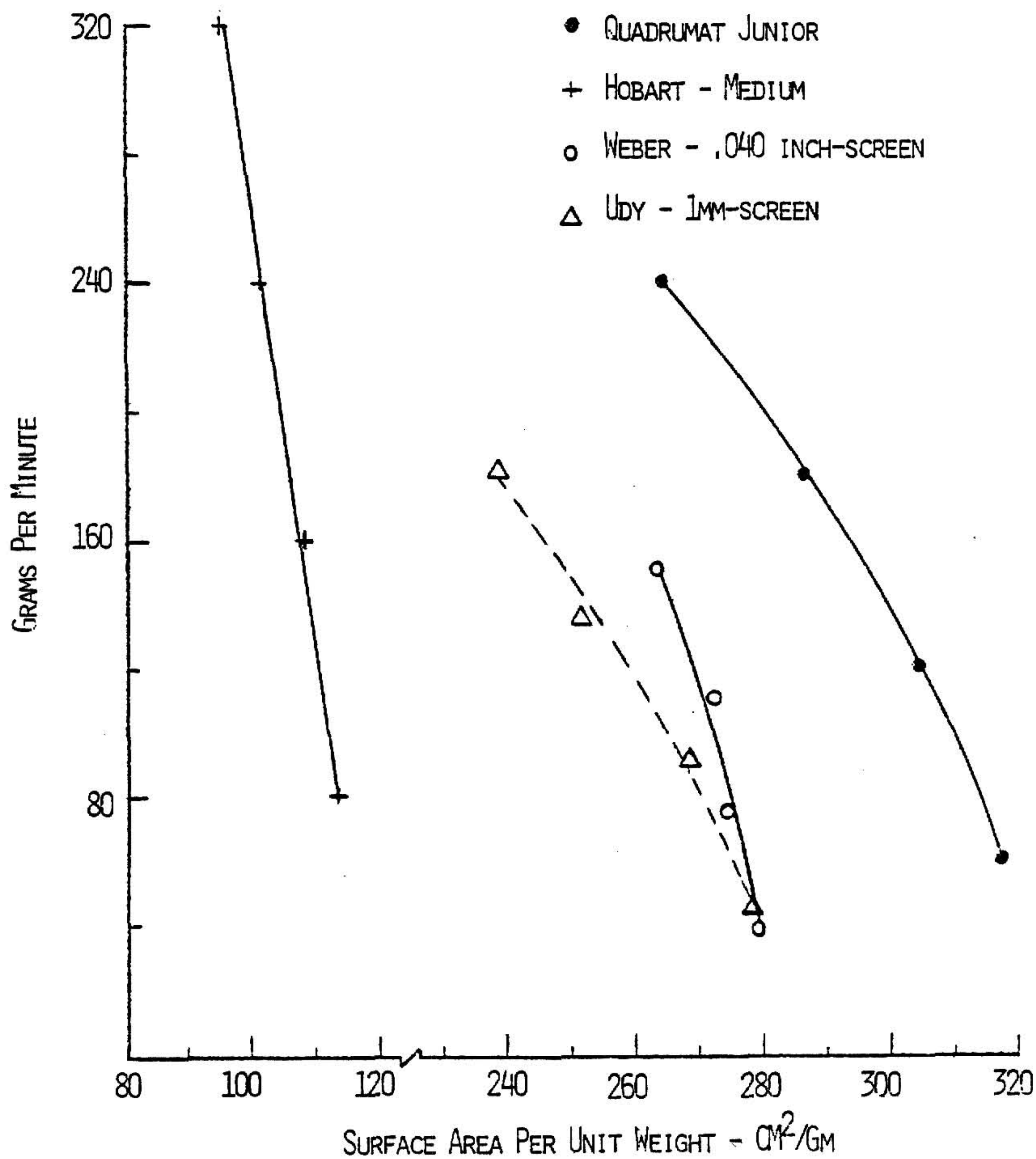


Figure 17-2. Fineness of material ground with the Quadrumat Junior, the Weber equipped with a .040 inch-screen, the Udy equipped with a 1mm-screen, and the Hobart with burr-clearance set at medium.

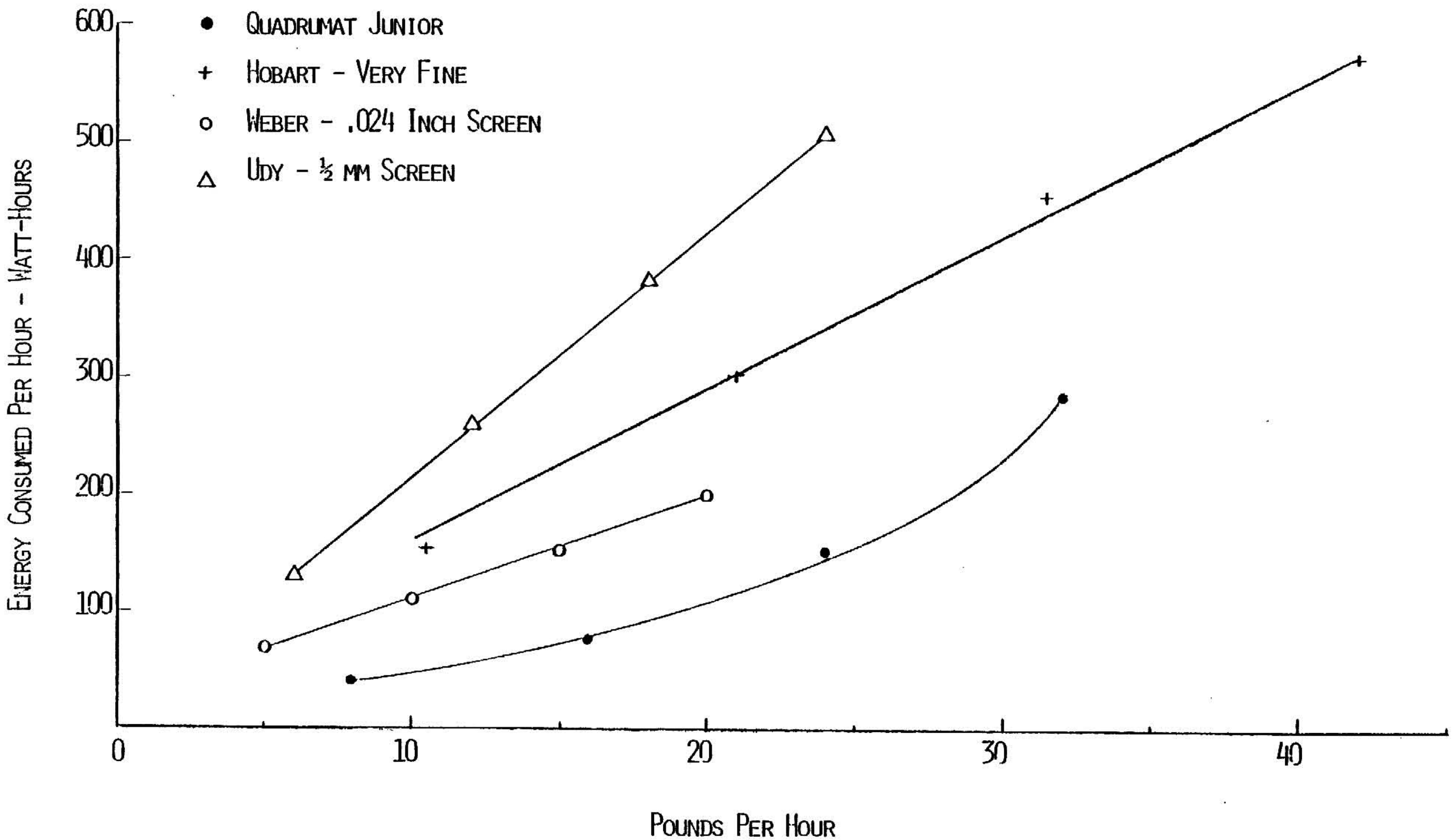


Figure 18-1. Energy consumption of the Quadrumat Junior, Hobart, Weber and Udy with specifications as shown above.

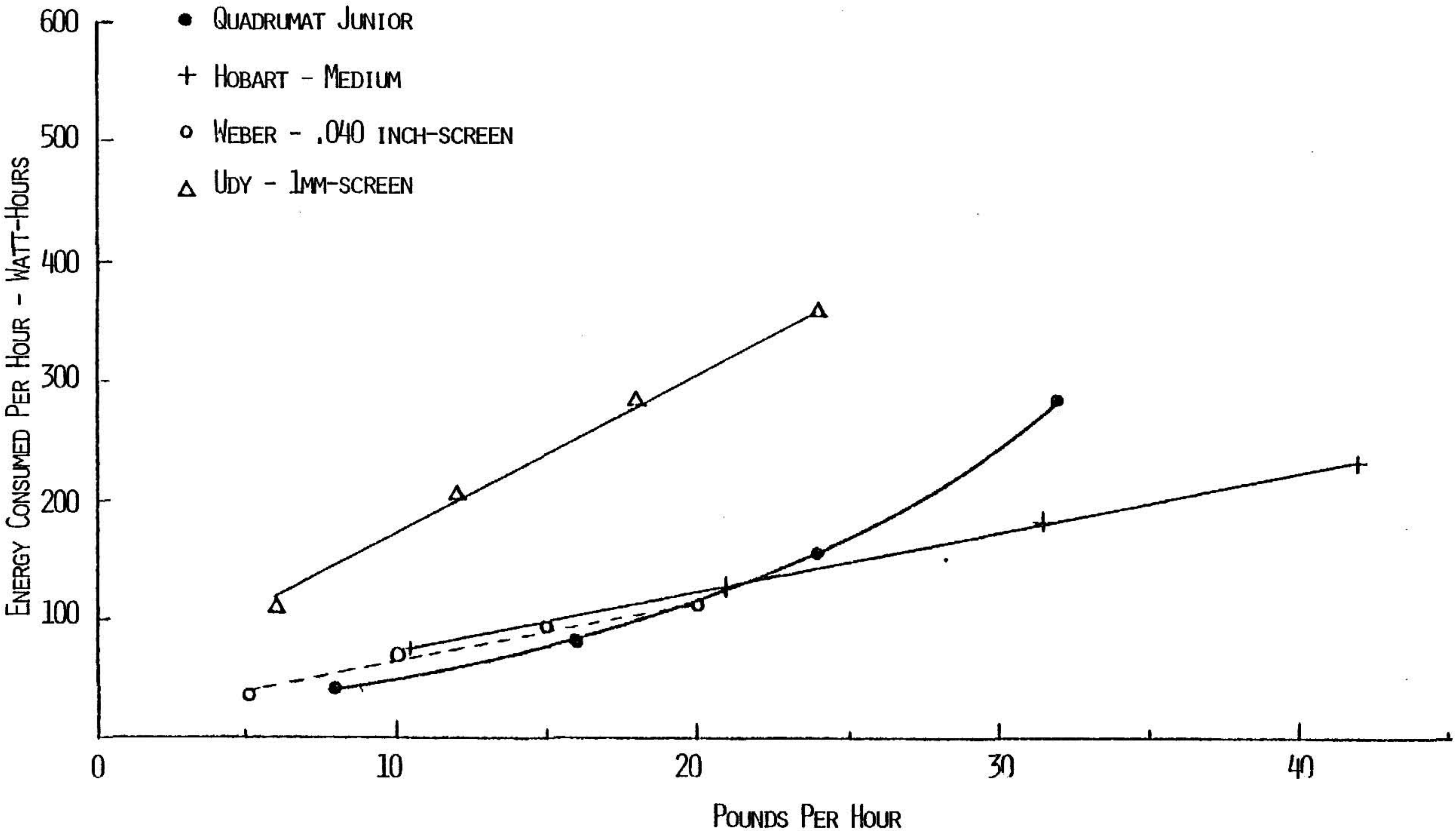


Figure 18-2. Energy consumption of the Quadrumat Junior, Hobart, Weber and Udy with specifications as shown above.

the Weber, and the Udy grinders, this relationship was exactly the same, regarding the lower the feed rate, the finer the product, and the larger the amount of energy to grind one pound of grain. For the Quadrumat Junior, the statement that the lower the feed rate, the finer the product, was also verified, but the energy required per pound of grain started first to decrease, then increased, even though the product became coarser. This could only mean that it is not economical to grind above a certain feed rate, because the additional amount of energy would be totally wasted. This probably is a good illustration of a well-known fact which is that size reduction is a very inefficient process, and only a small amount of the energy absorbed is used to create a new surface, that is, to increase the fineness of the ground product.

When the Wiley mill was considered, it was noted that the larger batch size gave the coarser product and required a larger amount of energy per pound. This was predictable, because after a certain amount of material has passed through the screen, the mill ran almost empty and most of the energy was, therefore, wasted. In addition, the amount of energy wasted was more important for a 200-gram batch than for a 100-gram batch, because, for the former, the length of time during which the mill ran almost empty was longer.

Temperature Rise

This energy waste, associated with the process of size reduction, was confirmed by the tests run to determine the temperature rise of each grinder. The temperature of the ground material was taken every four minutes with the

Table 7. Temperature Rise.

Grinder	Temperature After Grinding (^oF)	Time for Temperature to level off (mn)
Quadrumat Junior	102.2	56
Hobart	112.1	36
Weber	89.6	48
Udy	111.2	20
Wiley	95.0	100

mill running at full capacity. The data are shown in Table 7. The initial temperature of the wheat was 71.6°F.

The Hobart and the Udy were the grinders that heated up the most and almost to the same degree. However, the time for the temperature to level off in the case of the Hobart was almost twice the time recorded for the Udy.

This heat generation was also noticeable in the case of the Quadrumat Junior but to a lesser degree.

The Wiley mill is a slow grinder, and, therefore, it is not surprising that the temperature rise was much lower than that observed with the previous mills. Furthermore, this rise in temperature was reached only after 100 minutes.

The Weber mill registered the least temperature rise, due to the cooling effect of the vacuum source.

CONCLUSIONS

The results of the grinding tests run on the various grinders led to the distinction between the two methods of expressing particle size, the method based on the use of the modified moduli, and the method based on the use of the surface area of the ground product. The study showed that the modified modulus of fineness can be used to express the particle size of a ground sample within certain limits, but when used extensively, it can be misleading. On the contrary, the method of surface area takes into consideration both the average size of the particles and the uniformity of the product and, thus, gives more accurate results.

The results also showed that the size reduction operation was very effective when performed by the Quadrumat Junior and the Weber mill.

However, when the Quadrumat Junior is used, the feed rate should be kept to a level not to exceed 120 grams per minute, otherwise there will be a loss in both product quality and energy. For the Weber, since the heating-up of the grinder is taken care of by the vacuum source which provides a very effective cooling, the only objection remaining to its use is the tremendous noise generated during the grinding operation. Provision should be made to locate the grinder in an insulated room, and the user should have his ears protected.

This study also showed that the Udy mill is a very fine grinder. The fineness of grind reached was very close to that obtained with the Weber hammermill. However, this mill consumes an excessive amount of energy which is mostly wasted. When operating the grinder over a long period of time, the heat generated could lead to the clogging of the mill. It was also noticed, during this study, that feed rates of 135 grams per minute or higher were very damaging to the screen under sustained use.

The grinding tests also revealed that as far as product fineness was concerned, the Hobart grinder was not able to compete with the other grinders even when the burr-clearance was at its finest setting. Furthermore, the grinder consumed a tremendous amount of energy and generated a lot of heat. The positive aspect about this mill is probably its high throughput. This mill would probably fit in a feed production research laboratory where fine grinding would not be a requirement and the energy consumption of the grinder would then be reduced to reasonable levels by proper adjustment of the burrs.

The Wiley mill, for its part, is a rather coarse grinder. The fineness of the grind could be increased by using a .5-mm screen, but, because of the slow grinding action of this mill, the operation would be very uneconomical. In favor of this mill, it should be mentioned that the grinding operation requires little attention from the part of the user.

Our prime concern throughout this study was to compare the pros and cons of the different grinders tested with particular reference to the particle size of the ground material and the grinders' energy consumption. As to which grinder to select, this depends mainly on the grain to be ground, the intended use of the end product, and the frequency of use of the grinder, which is closely related to the amount of energy the user is willing to pay.

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APPENDIX

Modified Modulus of Fineness

The screen analysis obtained for the Wiley mill when 100-gram batch was tested with 1-mm screen was used as an example to show how the modified modulus of fineness was defined.

Tyler Mesh Number	Percent of Material on each screen	x	factor		
14	0	x	6	=	0
24	2	x	5	=	10
35	52	x	4	=	208
60	28	x	3	=	84
100	12	x	2	=	24
170	5	x	1	=	5
PAN	1	x	0	=	0
TOTALS	100				331

$$\text{Modified Modulus of Fineness} = \frac{331}{100} = 3.31$$

Modified Modulus of Uniformity

The same screen analysis was used as an example to show how modified modulus of uniformity was defined for all the grinds.

(A) Tyler Mesh Number		(B) Percent of Material On each Screen	(C) Total				(D)
14		0					
	Coarse		2	÷	10	=	.2
24		2					
35		52					
	Medium		80	÷	10	=	8.0
60		28					
100		12					
170	Fine	5	18	÷	10	=	1.8
PAN		1					

Figures in column (D) are converted to nearest whole number and their sum must equal 10. Thus:

The modified modulus of uniformity is: C:M:F
0:8:2

Because of the considerable difference of opinion relative to what constitutes coarse, medium, or fine grinding, the modified modulus of uniformity can be defined differently.

For example, the same screen analysis will give:

(A) Tyler Mesh Number		(B) Percent of Material On each Screen	(C) Total				
14		0					
24	Coarse	2	54	÷	10	=	5.4
35		52					
60	Medium	28	40	÷	10	=	4.0
100		12					
170	Fine	5	6	÷	10	=	.6
PAN		1					

Modified modulus of uniformity: C:M:F
5:4:1

Shape Factor of Particles

Volume and surface of a particle of any shape can respectively be written as:

$$V_p = {}_pD_p{}^3$$

$$S_p = 6qD_p{}^2$$

Where p and q are geometric constants which depend only on the shape of the particle and D_p the typical dimension or diameter of the particle.

The ratio of surface to volume,

$$\frac{S_p}{V_p} = \frac{6q}{pD_p} = \frac{6\lambda}{D_p} ,$$

defines the shape factor of the particle: $\lambda = \frac{q}{p}$

- For a cube $V_p = D_p{}^3$ and $S_p = 6D_p{}^2$, thus: $\frac{S_p}{V_p} = \frac{6}{D_p}$

- For a sphere $V_p = \frac{\pi}{6} D_p{}^3$ and $S_p = \pi D_p{}^2$, thus: $\frac{S_p}{V_p} = \frac{6}{D_p}$

It can be seen that in both cases $\lambda = 1$

The two constants p and q, respectively, refer to β_V shape factor for calculating volume of particles, and β_S shape factor for calculating surface area of particles, introduced by Pfost and Headley in the equation for total surface area (28),

$$\beta_V = p$$

$$\beta_S = 6q$$

Therefore $\lambda = \frac{\beta_S}{6\beta_V}$, or $6\lambda = \frac{\beta_S}{\beta_V}$

Equation for Total Surface Area of a Ground Product

The equation for total surface area given by Pfost and Headley (28) is:

$$A_{st} = \frac{\beta s \; Wt}{\beta v \; p} \exp\left(.5 \, Ln^2 \sigma_w - Ln \, \mu_w\right)$$

By replacing $\frac{\beta s}{\beta v}$ by 6λ, the equation can be written

$$A_{st} = \frac{6\lambda \; Wt}{p} \exp\left(.5 \, Ln^2 \sigma_w - Ln \, \mu w\right)$$

with:

A_{st} in cm^2/gm, is total surface area

W_t in gm, is total sample weight

p in gm/cm^3, is specific weight of ground sample

μ_w in cm, is diameter by weight distribution of parent population

σ_w geometric log-normal standard deviation by weight distribution of parent population

Quadrumat Junior - 60 gm/mn

TYLER MESH NUMBER	d_i (microns)	W_i (grams)	$\log d_i$	$W_i \log d_i$	$\log d_i - \log d_w$	$W_i (\log d_i - \log d_w)^2$
14	1190	3	3.076	9.228	.839	2.112
28	595	16	2.775	44.4	.538	4.631
48	297	9	2.473	22.257	.236	.501
100	149	32	2.173	69.536	-.064	.131
150	105	25	2.021	50.525	-.216	1.166
200	74	11	1.869	20.559	-.368	1.490
PAN		4	1.799	7.196	-.438	.767
TOTALS		100		223.701		10.798

$d_w = 173\ \mu$

$S_w = 2.13$

Quadrumat Junior - 120 gm/mn

TYLER MESH NUMBER	d_i (microns)	W_i (grams)	log d_i	W_i log d_i	log d_i - log d_w	W_i (log di - log $d_w)^2$
14	1190	3	3.076	9.228	.817	2.002
28	595	17	2.775	47.175	.516	4.526
48	297	11	2.473	27.203	.214	.504
100	149	30	2.173	65.190	-.086	.222
150	105	24	2.021	48.504	-.238	1.359
200	74	10	1.869	18.69	-.390	1.521
PAN		3	1.799	5.397	-.460	.635
TOTALS		98		221.387		10.769

d_w = 182 μ

S_w = 2.15

Quadrumat Junior - 180 gm/mn

TYLER MESH NUMBER	d_i (microns)	W_i (grams)	log d_i	W_i log d_i	log d_i - log d_w	W_i (log di - log $d_w)^2$
14	1190	3	3.076	9.228	.796	1.901
28	595	18	2.775	49.950	.495	4.410
48	297	12	2.473	29.676	.193	.447
100	149	32	2.173	69.536	-.107	.366
150	105	23	2.021	46.483	-.259	1.543
200	74	8	1.869	14.952	-.411	1.351
PAN		2	1.799	3.598	-.481	.463
TOTALS		98		223.423		10.481

d_w = 191 μ

S_w = 2.12

Quadrumat Junior - 240 gm/mn

TYLER MESH NUMBER	d_i (microns)	W_i (grams)	$\log d_i$	$W_i \log d_i$	$\log d_i - \log d_w$	$W_i (\log d_i - \log d_w)^2$
14	1190	4	3.076	12.304	.747	2.232
28	595	22	2.775	61.050	.446	4.376
48	297	15	2.473	37.095	.144	.311
100	149	29	2.173	63.017	-.156	.706
150	105	20	2.021	40.420	-.308	1.897
200	74	7	1.869	13.083	-.460	1.481
PAN		2	1.799	3.598	-.530	.562
TOTALS		99		230.567		11.565

$d_w = 213\ \mu$

$S_w = 2.20$

Hobart - burr-clearance set at very fine - 80 gm/mn

TYLER MESH NUMBER	d_i (microns)	W_i (grams)	log d_i	W_i log d_i	log d_i - log d_w	W_i (log di - log $d_w)^2$
14	1190	2	3.076	6.152	.745	1.110
28	595	20	2.775	55.5	.444	3.943
48	297	25	2.473	61.825	.142	.504
100	149	25	2.173	54.325	-.158	.624
150	105	18	2.021	36.378	-.310	1.730
200	74	6	1.869	11.214	-.462	1.281
PAN		3	1.799	5.397	-.532	.849
TOTALS		99		230.791		10.041

$d_w = 214\ \mu$

$S_w = 2.08$

Hobart - burr-clearance set at very fine - 160 gm/mn

TYLER MESH NUMBER	d_i (microns)	W_i (grams)	log d_i	W_i log d_i	log d_i - log d_w	W_i (log di - log d_w)^2
14	1190	2	3.076	6.152	.733	1.075
28	595	21	2.775	58.275	.432	3.919
48	297	26	2.473	64.298	.130	.439
100	149	25	2.173	54.325	-.170	.723
150	105	16	2.021	32.336	-.322	1.659
200	74	6	1.869	11.214	-.474	1.348
PAN		3	1.799	5.397	-.544	.888
TOTALS		99		231.997		10.051

d_w = 220 μ

S_w = 2.08

Hobart - burr-clearance set at very fine - 240 gm/mn

TYLER MESH NUMBER	d_i (microns)	W_i (grams)	log d_i	W_i log d_i	log d_i - log d_w	W_i (log di - log $d_w)^2$
14	1190	2	3.076	6.152	.712	1.014
28	595	22	2.775	61.050	.411	3.716
48	297	28	2.473	69.244	.109	.333
100	149	25	2.173	54.325	-.191	.912
150	105	15	2.021	30.315	-.343	1.765
200	74	5	1.869	9.345	-.495	1.225
PAN		2	1.799	3.598	-.565	.639
TOTALS		99		234.029		9.604

$d_w = 231\ \mu$

$S_w = 2.05$

Hobart - burr-clearance set at very fine - 320 gm/mn

TYLER MESH NUMBER	d_i (microns)	W_i (grams)	log d_i	W_i log d_i	log d_i - log d_w	W_i (log di - log $d_w)^2$
14	1190	2	3.076	6.152	.706	.997
28	595	23	2.775	63.825	.405	3.773
48	297	28	2.473	69.244	.103	.297
100	149	24	2.173	52.152	-.197	.931
150	105	15	2.021	30.315	-.349	1.827
200	74	5	1.869	9.345	-.501	1.255
PAN		2	1.799	3.598	-.571	.652
TOTALS		99		234.631		9.732

$d_w = 234\ \mu$

$S_w = 2.06$

Hobart - burr-clearance set at medium - 80 gm/mn

TYLER MESH NUMBER	d_i (microns)	W_i (grams)	log d_i	W_i log d_i	log d_i - log d_w	W_i (log di - log $d_w)^2$
14	1190	24	3.076	73.824	.388	3.613
28	595	43	2.775	119.325	.087	.326
48	297	16	2.473	39.568	-.215	.740
100	149	8	2.173	17.384	-.515	2.122
150	105	4.5	2.021	9.095	-.667	2.002
200	74	2	1.869	3.738	-.819	1.341
PAN		1	1.799	1.799	-.889	.790
TOTALS		98.5		264.733		10.934

d_w = 488 μ

S_w = 2.15

Hobart - burr-clearance set at medium - 160 gm/mn

TYLER MESH NUMBER	d_i (microns)	W_i (grams)	log d_i	W_i log d_i	log d_i - log d_w	W_i (log di - log $d_w)^2$
14	1190	24	3.076	73.824	.376	3.393
28	595	46	2.775	127.650	.075	.259
48	297	16	2.473	39.568	-.227	.824
100	149	7	2.173	15.211	-.527	1.944
150	105	4	2.021	8.084	-.679	1.844
200	74	2	1.869	3.738	-.831	1.381
PAN		1	1.799	1.799	-.901	.812
TOTALS		100		269.874		10.457

d_w = 501 μ

S_w = 2.11

Hobart - burr-clearance set at medium - 240 gm/mn

TYLER MESH NUMBER	d_i (microns)	W_i (grams)	log d_i	W_i log d_i	log d_i - log d_w	W_i (log di - log $d_w)^2$
14	1190	25	3.076	76.9	.358	3.204
28	595	47	2.775	130.425	.057	.153
48	297	16	2.473	39.568	-.245	.960
100	149	6	2.173	13.038	-.545	1.782
150	105	4	2.021	8.084	-.697	1.943
200	74	2	1.869	3.738	-.849	1.442
PAN		0	1.799	0	-.919	0
TOTALS		100		271.753		9.484

d_w = 522 μ

S_w = 2.03

Hobart - burr-clearance set at medium - 320 gm/mn

TYLER MESH NUMBER	d_i (microns)	W_i (grams)	$\log d_i$	$W_i \log d_i$	$\log d_i - \log d_w$	$W_i (\log di - \log d_w)^2$
14	1190	25	3.076	76.9	.347	3.010
28	595	47	2.775	130.425	.046	.099
48	297	17	2.473	42.041	-.256	1.114
100	149	5	2.173	10.865	-.556	1.546
150	105	4	2.021	8.084	-.708	2.005
200	74	1	1.869	1.869	-.860	.740
PAN		0	1.799	0	-.930	0
TOTALS		99		270.184		8.514

$d_w = 536\ \mu$

$S_w = 1.96$

Weber - .024 inch-screen - 38 gm/mn

TYLER MESH NUMBER	d_i (microns)	W_i (grams)	log d_i	W_i log d_i	log d_i - log d_w	W_i (log di - log $d_w)^2$
14	1190	0	3.076	0	.886	0
28	595	0	2.775	0	.585	0
48	297	22	2.473	54.406	.283	1.762
100	149	47	2.173	102.131	-.017	.014
150	105	24	2.021	48.504	-.169	.686
200	74	3	1.869	5.607	-.321	.309
PAN		1	1.799	1.799	-.391	.153
TOTALS		97		212.447		2.924

$d_w = 155\mu$

$S_w = 1.49$

Weber - .024 inch-screen - 75 gm/mn

TYLER MESH NUMBER	d_i (microns)	W_i (grams)	$\log d_i$	$W_i \log d_i$	$\log d_i - \log d_w$	$W_i (\log d_i - \log d_w)^2$
14	1190	0	3.076	0	.872	0
28	595	0	2.775	0	.571	0
48	297	26	2.473	64.298	.269	1.881
100	149	45	2.173	97.785	-.031	.043
150	105	23	2.021	46.483	-.183	.770
200	74	3	1.869	5.607	-.335	.337
PAN		1	1.799	1.799	-.405	.164
TOTALS		98		215.972		3.195

$d_w = 160\ \mu$

$S_w = 1.52$

Weber - .024 inch-screen - 110 gm/mn

TYLER MESH NUMBER	d_i (microns)	W_i (grams)	log d_i	W_i log d_i	log d_i - log d_w	W_i (log di - log $d_w)^2$
14	1190	0	3.076	0	.872	0
28	595	0	2.775	0	.571	0
48	297	26	2.473	64.298	.269	1.881
100	149	46	2.173	99.958	-.031	.044
150	105	23	2.021	46.483	-.183	.770
200	74	3	1.869	5.607	-.335	.337
PAN		1	1.799	1.799	-.405	.164
TOTALS		99		218.145		3.196

d_w = 160 μ

S_w = 1.51

Weber - .024 inch-screen - 150 gm/mn

TYLER MESH NUMBER	d_i (microns)	W_i (grams)	log d_i	W_i log d_i	log d_i - log d_w	W_i (log di - log $d_w)^2$
14	1190	0	3.076	0	.857	0
28	595	0	2.775	0	.556	0
48	297	29	2.473	71.717	.254	1.871
100	149	46	2.173	99.958	-.046	.097
150	105	22	2.021	44.462	-.198	.862
200	74	2	1.869	3.738	-.350	.245
PAN		.5	1.799	.900	-.420	.088
TOTALS		99.5		220.775		3.163

d_w = 166 μ

S_w = 1.51

Weber - .040 inch-screen - 38 gm/mn

TYLER MESH NUMBER	d_i (microns)	W_i (grams)	$\log d_i$	$W_i \log d_i$	$\log d_i - \log d_w$	$W_i (\log d_i - \log d_w)^2$
14	1190	0	3.076	0	.851	0
28	595	6	2.775	16.65	.550	1.815
48	297	21	2.473	51.933	.248	1.292
100	149	45	2.173	97.785	-.052	.122
150	105	23	2.021	46.483	-.204	.957
200	74	3	1.869	5.607	-.356	.380
PAN		1	1.799	1.799	-.426	.182
TOTALS		99		220.257		4.748

$d_w = 168\ \mu$

$S_w = 1.66$

Weber - .040 inch-screen - 75 gm/mn

TYLER MESH NUMBER	d_i (microns)	W_i (grams)	log d_i	W_i log d_i	log d_i - log d_w	W_i (log di - log $d_w)^2$
14	1190	0	3.076	0	.834	0
28	595	7	2.775	19.425	.533	1.989
48	297	26	2.473	64.298	.231	1.387
100	149	36	2.173	78.228	-.069	.171
150	105	24	2.021	48.504	-.221	1.172
200	74	4	1.869	7.476	-.373	.557
PAN		1	1.799	1.799	-.443	.196
TOTALS		98		219.730		5.472

d_w = 175 μ

S_w = 1.73

Weber - .040 inch-screen - 110 gm/mn

TYLER MESH NUMBER	d_i (microns)	W_i (grams)	log d_i	W_i log d_i	log d_i - log d_w	W_i (log di - log d_w)^2
14	1190	0	3.076	0	.834	0
28	595	7	2.775	19.425	.533	1.989
48	297	25	2.473	61.825	.231	1.334
100	149	39	2.173	84.747	-.069	.186
150	105	24	2.021	48.504	-.221	1.172
200	74	3	1.869	5.607	-.373	.417
PAN		1	1.799	1.799	-.443	.196
TOTALS		99		221.907		5.294

$d_w = 175\mu$

$S_w = 1.71$

Weber - .040 inch-screen - 150 gm/mn

TYLER MESH NUMBER	d_i (microns)	W_i (grams)	log d_i	W_i log d_i	log d_i - log d_w	W_i (log di - log $d_w)^2$
14	1190	0	3.076	0	.816	0
28	595	8	2.775	22.2	.515	2.122
48	297	28	2.473	69.244	.213	1.270
100	149	34	2.173	73.882	-.087	.257
150	105	24	2.021	48.504	-.239	1.371
200	74	3	1.869	5.607	-.391	.459
PAN		.5	1.799	.900	-.461	.106
TOTALS		97.5		220.337		5.585

$d_w = 182\ \mu$

$S_w = 1.73$

Udy - ½mm-screen - 45 gm/mn

TYLER MESH NUMBER	d_i (microns)	W_i (grams)	$\log d_i$	$W_i \log d_i$	$\log d_i - \log d_w$	$W_i (\log d_i - \log d_w)^2$
14	1190	0	3.076	0	.876	0
28	595	0	2.775	0	.575	0
48	297	23	2.473	56.879	.273	1.714
100	149	48	2.173	104.304	-.027	.035
150	105	24	2.021	48.504	-.179	.769
200	74	2	1.869	3.738	-.331	.219
PAN		0	1.799	0	-.401	0
TOTALS		97		213.425		2.737

$d_w = 159\ \mu$

$S_w = 1.47$

Udy - ½mm-screen - 90 gm/mn

TYLER MESH NUMBER	d_i (microns)	W_i (grams)	$\log d_i$	$W_i \log d_i$	$\log d_i - \log d_w$	$W_i (\log di - \log d_w)^2$
14	1190	0	3.076	0	.866	0
28	595	0	2.775	0	.565	0
48	297	26	2.473	64.298	.263	1.798
100	149	48	2.173	104.304	-.037	.066
150	105	23	2.021	46.483	-.189	.822
200	74	2	1.869	3.738	-.341	.233
PAN		0	1.799	0	-.411	0
TOTALS		99		218.823		2.919

$d_w = 162\ \mu$

$S_w = 1.48$

Udy - ½mm-screen - 135 gm/mn

TYLER MESH NUMBER	d_i (microns)	W_i (grams)	log d_i	W_i log d_i	log d_i - log d_w	W_i (log di - log $d_w)^2$
14	1190	0	3.076	0	.839	0
28	595	0	2.775	0	.538	0
48	297	30	2.473	74.19	.236	1.671
100	149	51	2.173	110.823	-.064	.209
150	105	16	2.021	32.336	-.216	.747
200	74	1	1.869	1.869	-.368	.135
PAN		0	1.799	0	-.438	0
TOTALS		98		219.218		2.762

d_w = 173 μ

S_w = 1.47

Udy - ½mm-screen - 180 gm/mn

TYLER MESH NUMBER	d_i (microns)	W_i (grams)	log d_i	W_i log d_i	log d_i - log d_w	W_i (log di - log $d_w)^2$
14	1190	0	3.076	0	.802	0
28	595	0	2.775	0	.501	0
48	297	39	2.473	96.447	.199	1.544
100	149	48	2.173	104.304	-.101	.490
150	105	10	2.021	20.21	-.253	.640
200	74	1	1.869	1.869	-.405	.164
PAN		0	1.799	0	-.475	0
TOTALS		98		222.83		2.838

d_w = 186 μ

S_w = 1.48

Udy - 1mm-screen - 45 gm/mn

TYLER MESH NUMBER	d_i (microns)	W_i (grams)	$\log d_i$	$W_i \log d_i$	$\log d_i - \log d_w$	$W_i (\log d_i - \log d_w)^2$
14	1190	0	3.076	0	.866	0
28	595	2	2.775	5.55	.565	.638
48	297	22	2.473	54.406	.263	1.522
100	149	50	2.173	108.650	-.037	.069
150	105	23	2.021	46.483	-.189	.822
200	74	2	1.869	3.738	-.341	.233
PAN		0	1.799	0	-.411	0
TOTALS		99		218.827		3.284

$d_w = 162\ \mu$

$S_w = 1.52$

Udy - 1mm-screen - 90 gm/mn

TYLER MESH NUMBER	d_i (microns)	W_i (grams)	log d_i	W_i log d_i	log d_i - log d_w	W_i (log di - log $d_w)^2$
14	1190	0	3.076	0	.850	0
28	595	2	2.775	5.55	.549	.603
48	297	25	2.473	61.825	.247	1.525
100	149	49	2.173	106.477	-.053	.138
150	105	21	2.021	42.441	-.205	.883
200	74	1	1.869	1.869	-.357	.127
PAN		0	1.799	0	-.427	0
TOTALS		98		218.162		3.276

$d_w = 168\ \mu$

$S_w = 1.52$

Udy - 1mm-screen - 135 gm/mn

TYLER MESH NUMBER	d_i (microns)	W_i (grams)	$\log d_i$	$W_i \log d_i$	$\log d_i - \log d_w$	$W_i (\log di - \log d_w)^2$
14	1190	0	3.076	0	.821	0
28	595	2	2.775	5.55	.520	.541
48	297	32	2.473	79.136	.218	1.521
100	149	47	2.173	102.131	-.082	.316
150	105	16	2.021	32.336	-.234	.876
200	74	1	1.869	1.869	-.386	.149
PAN		0	1.799	0	-.456	0
TOTALS		98		221.022		3.403

$d_w = 180\ \mu$

$S_w = 1.54$

Udy - 1mm-screen - 180 gm/mn

TYLER MESH NUMBER	d_i (microns)	W_i (grams)	log d_i	W_i log d_i	log d_i - log d_w	W_i (log di - log $d_w)^2$
14	1190	0	3.076	0	.797	0
28	595	2	2.775	5.55	.496	.492
48	297	37	2.473	91.501	.194	1.393
100	149	44	2.173	95.612	-.106	.494
150	105	12	2.021	24.252	-.258	.799
200	74	1	1.869	1.869	-.410	.168
PAN		0	1.799	0	-.480	0
TOTALS		96		218.784		3.346

d_w = 190 μ

S_w = 1.54

Wiley - 1mm-screen - 100 gm-batch

TYLER MESH NUMBER	d_i (microns)	W_i (grams)	log d_i	W_i log d_i	log d_i - log d_w	W_i (log di - log $d_w)^2$
14	1190	0	3.076	0	.610	0
28	595	17	2.775	47.175	.309	1.623
48	297	66	2.473	163.218	.007	.003
100	149	13	2.173	28.249	-.293	1.116
150	105	3	2.021	6.063	-.445	.594
200	74	1	1.869	1.869	-.597	.356
PAN		0	1.799	0	-.667	0
TOTALS		100		246.574		3.692

d_w = 292 μ

S_w = 1.56

Wiley - 1mm-screen - 200 gm - batch

TYLER MESH NUMBER	d_i (microns)	W_i (grams)	log d_i	W_i log d_i	log d_i - log d_w	W_i (log di - log $d_w)^2$
14	1190	0	3.076	0	.592	0
28	595	22	2.775	61.05	.291	1.863
48	297	62	2.473	153.326	-.011	.008
100	149	12	2.173	26.076	-.311	1.161
150	105	3	2.021	6.063	-.463	.643
200	74	1	1.869	1.869	-.615	.378
PAN		0	1.799	0	-.685	0
TOTALS		100		248.384		4.053

$d_w = 305\ \mu$

$S_w = 1.59$

Wiley - 2mm-screen - 100 gm-batch

TYLER MESH NUMBER	d_i (microns)	W_i (grams)	log d_i	W_i log d_i	log d_i - log d_w	W_i (log di - log $d_w)^2$
14	1190	2	3.076	6.152	.445	.396
28	595	66	2.775	183.150	.144	1.369
48	297	19	2.473	46.987	-.158	.474
100	149	7	2.173	15.211	-.458	1.468
150	105	3	2.021	6.063	-.610	1.116
200	74	2	1.869	3.738	-.762	1.161
PAN		1	1.799	1.799	-.832	.692
TOTALS		100		263.100		6.676

$d_w = 428\ \mu$

$S_w = 1.82$

Wiley - 2mm-screen - 200 gm-batch

TYLER MESH NUMBER	d_i (microns)	W_i (grams)	log d_i	W_i log d_i	log d_i - log d_w	W_i (log di - log $d_w)^2$
14	1190	5	3.076	15.38	.417	.870
28	595	66	2.775	183.15	.116	.888
48	297	16	2.473	39.568	-.186	.554
100	149	7	2.173	15.211	-.486	1.653
150	105	4	2.021	8.084	-.638	1.628
200	74	1	1.869	1.869	-.790	.624
PAN		0	1.799	0	-.860	0
TOTALS		99		263.262		6.217

$d_w = 456\ \mu$

$S_w = 1.78$

Determination of the Total Number of Particles

The equation for the total number of particles given by Pfost and Headley (28) is:

$$N_t = \frac{Wt}{\rho \beta v} \exp\left(4.5 \, Ln^2 \sigma w - 3 \, Ln \, \mu_w\right)$$

In this equation βv represents the shape factor for calculating volume of particles.

If cubical particles are assumed then $\beta v = 1$

If spherical particles are assumed then $\beta v = \frac{\pi}{6}$ (28)

Throughout the experiment, grinding was achieved by different grinding principles. The determination of which of the two values of βv fit which grind was not made because of the difficulty to determine which of these principles yielded either cubical or spherical particles. For this reason, the total number of particles was not calculated.

Wiley Energy Measurements

1mm screen

Batch Size	Watt Hours	Time Required For Grinding
(gm)		
100	6.3	8mn - 30 sec
200	13.32	12mn

2mm screen

Batch Size	Watt Hours	Time Required For Grinding
(gm)		
100	1.38	1mn - 20 sec.
200	3.3	1mn - 55 sec.

EVALUATION OF FIVE LABORATORY GRINDERS ON THE BASIS OF THE PARTICLE SIZE OF THE GROUND MATERIAL AND THE ENERGY CONSUMPTION

by

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B. S., Institut National Agronomique, El Harrach, 1974

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The purpose of this study was to evaluate five laboratory grinders on the basis of the particle size of the ground material and the energy consumption.

Five grinders were chosen on the basis of the grinding principles they used to carry out the experiment. The grinders tested were the Brabender Quadrumat Junior (compression), the Hobart Coffee grinder Model 275 (attrition), the Weber laboratory pulverizing mill Model 22 (dynamic impact), the Udy Cyclotec grinder (gravity impact), and the Wiley mill Model 4 (cutting action).

The grain used for all the grinding tests was dry Hard Red Winter Wheat with 11.3% moisture content.

For the Quadrumat Junior, the Hobart, the Weber, and the Udy grinders, four feed rates were tested: full capacity, three-quarter, one-half, and one-quarter of full capacity. The Wiley mill was fed batchwise; two batch-sizes were tested: 100-gram batch and 200-gram batch.

For the Weber hammermill, the Udy Cyclotec grinder, and the Wiley mill, which are equipped with interchangeable screens, two screen sizes were tested. For the Hobart grinder, clearance between the burrs was adjusted at two different settings: "very fine" and "medium".

To express the particle size of the ground product two methods were used. The first was based on the use of a modified modulus of uniformity and a modified modulus of fineness and was derived from the method of modulus of uniformity and modulus of fineness as approved by the American Society of Agricultural Engineers (Recommendation: ASAE R 246.1) for ground feed. The second method is based on the particle size distribution and the determination of the total surface area of the ground material as described by Pfost and Headley.

To measure the energy consumed by the grinder three watthour-meters were used; the same meter was used with the Weber hammermill, the Udy Cyclotec grinder, and the Wiley mill. Furthermore, to determine which grinders heated up the most, temperature measurements were effected on each grind.

The study found that the method based on particle size distribution and total surface area of the ground material was more suitable than the method of the modified moduli for determining the fineness of a ground product. The results showed that the method on the modified moduli can be used but only within certain limits. When it is used extensively, it can be misleading.

The results also indicated that the Quadrumat Junior, the Weber, and the Udy grinders gave a fine product, whereas the Hobart, even at the finest setting of the burrs clearance, yielded a medium grind, and the Wiley mill yielded a coarse material. The response of the fineness of the ground material to a variation in the feed rate was more noticeable with the Quadrumat Junior than with the other grinders. For the mills equipped with a screen, the fineness of grind was more affected by the screen size in the case of the Wiley mill than in the case of the Weber or the Udy grinders.

The study also showed that the Udy and the Hobart grinders consumed large amounts of energy. The measurement of temperature rise of the product confirmed that most of the energy consumed by these two grinders was wasted. The Weber was the grinder which heated up the least because of the cooling effect of the vacuum source.