

Short Title . . .

COMMINUTION IN AN ELECTRIC FIELD

ELECTRICAL, MECHANICAL AND
RESIDUAL STRESS INTERACTIONS
IN MINERALS COMMINUTION

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ELECTRICAL, MECHANICAL AND RESIDUAL STRESS

INTERACTIONS IN MINERALS COMMINUTION

ABSTRACT

A review of the fracture process and of piezoelectric phenomena leads to the suggestion that stresses generated in piezoelectric minerals when subjected to an electric field might improve comminution efficiency and effectiveness.

The construction and use of an apparatus to test this hypothesis is described. Quartzite, monocrystalline quartz, mono- and polycrystalline sphalerite, iron ore and polycrystalline hematite were crushed in fields of up to 10^7 V/m using a modified Carey-Stairmand procedure. The energy consumed in fracture and size and shape factors of the product size distribution were determined and the effects of the applied field shown by comparison.

Contrary to expectations, comminution efficiency generally decreased and, with four of the materials, passed through a minimum at an intermediate field strength. No change in liberation of form of particle size distribution was detected.

The initial hypothesis is re-examined and alternative mechanisms discussed.

INTERACTION DES CONTRAINTES ELECTRIQUES,
MECANIQUES ET RESIDUELLES DANS LE BROYAGE DES MINERALS

Anthony C. Partridge

L'étude des mécanismes de fracture et des phénomènes piézoélectriques suggère qu'il pourrait être possible d'améliorer l'efficacité et le rendement du broyage des matériaux piézoélectriques par l'application de champs électriques.

Afin de vérifier cette hypothèse, on a construit un appareil qui utilise la méthode de Carey et Stairmand et qui permet l'application de champs électriques pouvant atteindre 10^7 V/m. On a utilisé comme matériaux d'essai de la quartzite, du quartz monocristallin, de la sphalerite mono- et polycristalline, du minerai de fer et de l'hématite polycristalline.

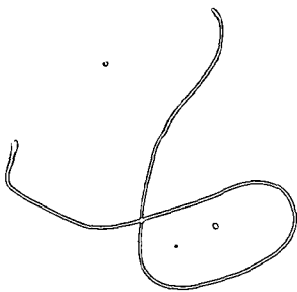
On a déterminé pour ces matériaux l'énergie nécessaire au broyage, ainsi que la taille des fragments et la forme de la courbe de distribution de taille des produits de broyage. Les résultats permettent d'évaluer les effets des champs électriques.

Contrairement à toute attente, l'efficacité du broyage décroît en général lorsque le champ électrique augmente. Pour quatre des matériaux étudiés l'efficacité

est minimale pour des valeurs intermédiaires du champ.

L'application du champ ne semble pas favoriser la fracture intercristalline et n'affecte pas la forme de la courbe de distribution de taille des fragments.

L'hypothèse de base est ré-examinée et l'on discute l'action des champs par d'autres mécanismes.



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and most of all to

ISABEL

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I INTRODUCTION

I.1. Comminution

Comminution, the reduction in size of rock particles by fracture, is usually the first stage of a milling process, carried out with the chief aim of liberating the valuable minerals before concentration. An ideal comminution process can therefore be envisaged in which preferential grain boundary fracture is achieved with minimum expenditure of energy. Unfortunately, conventional methods fall far short of this goal. Trans-granular fracture is common, necessitating grinding to a size considerably smaller than the natural grain size of the valuable component in order to achieve acceptable liberation, and efficiencies are very low.

The research to be described in this thesis was carried out in an attempt to improve both liberation effectiveness and the efficiency of the comminution process. As an introduction to the author's work some aspects of conventional processes will first be considered, followed, in Chapter II, by a survey of some of the novel approaches made by other workers which have some bearing on the present study.

I.2. The Fracture Process

Most minerals exhibit effectively brittle characteristics when subjected to uniaxial stress at room temperature. That is, the stress-strain curve is near-linear up to the point of rupture and shows no plastic deformation if the stress is removed before fracture occurs. Stress-strain graphs or tabulated values of Young's modulus, Y , and the ultimate strengths of some common rocks and minerals are given by Birch et al. (1942), Judd and Huber (1962), Obert and Duvall (1967), Bieniawski (1967), Jaeger and Cook (1969) and many others. Values vary considerably but for rocks (e.g. marble, sandstone, granite, quartzite, limestone) are commonly in the range $7 - 40 \text{ MN/m}^2$ ($10 - 60 \text{ k.p.s.i.}$) in compression and $0.5 - 7 \text{ MN/m}^2$ in tension.

It is important to note that the ultimate compressive strength is always considerably greater than the tensile strength. Judd and Huber indicate an average ratio of approximately eight to one, a factor which can be derived theoretically (Jaeger, 1963). Sosman (1927a) found a factor in excess of twenty for quartz single crystals and Obert (1966) gives nominal general values for fracture strain, $S_{ult.}$, of

3×10^{-3} in compression and 3×10^{-4} in tension. As a result of this large difference in strengths fracture is usually attributable to tensile failure, even though the principal comminution methods involve crushing or impact, i.e. compressive loading. The photo-elastic studies of Gallagher (1971) and Oka and Majima (1970) support this conclusion.

Many fracture criteria have been suggested, the best known being the early, largely empirical, approaches of Coulomb (1773) and Mohr (1900), the critical stress theory of Griffith (1921) developed by Orowan (1949), modifications in the Griffith theory to include compressive loading (Brace, 1960; McClintock and Walsh, 1963), Weibull's (1939) statistical theory, and the 'average stress' theory recently introduced by Chen and Marovelli (1966). An analysis of these theories would be inappropriate here but a general picture of the fracture process can be derived from them as follows.

Strain is induced by the comminution operation, work done on the particles being stored as elastic (stress) energy. As a result of the strain, dislocations are formed in the crystal lattices and migrate until they encounter an obstruction such as a grain boundary. Further dislocations

pile up as the strain is increased, giving rise to the formation of cracks (Kingery, 1960a). Evidence that such 'microfracturing' occurs at less than half the ultimate fracture stress has been given by Scholz (1968a,b). As a result of the lattice distortion which occurs in the immediate vicinity of such cracks, elastic energy flows to the crack tips and the crack extends at a rate dependent on the applied stress. Ultimately, with continued loading, a state is reached in which the rate at which strain energy can be dissipated in the form of free surface energy by the formation and extension of micro-cracks is exceeded by the rate of transfer of strain energy into the particle. The particle then fails catastrophically, most of the strain energy being converted into free surface energy of freshly exposed surfaces or into kinetic energy of the fragments.

Two basically different approaches have been made to predict conditions which lead to ultimate failure. The most widely known is that of Griffith (1921) who assumed that crack extension ensued when the stress at a crack tip reached some critical value characteristic of the material. His solution depends on the value assumed for the radius of the crack tip which Orowan (1949) pointed out to be approximated by the inter-atomic spacing in the material. The resultant

equation, formulated for a plate of unit thickness, may be expressed:

$$T_{crit} = \sqrt{2\gamma E/\pi c} \quad \dots (1)$$

where T_{crit} is the applied uniaxial tensile stress required to cause crack extension, γ is the specific surface energy of the fresh surface, E is Young's modulus, and $2c$ is the crack length.

Irwin (1960), considering brittle fracture in metals, proposed an alternative criterion, suggesting the rate of crack propagation to be a function of the energy released per unit new surface. His result may be expressed:

$$T = \sqrt{GE/\pi c} \quad \dots (2)$$

where G is the amount of energy released per unit new surface in a crack of length $2c$ when subjected to a uniaxial tensile stress T .

The similarity between equations (1) and (2) is obvious but the parameter G in the second equation is a function of T and c , the equation describing a range of conditions.

Bieniawski (1967), who appears to be the first author to apply Irwin's concept to rocks, points out that the Griffith criterion is not strictly applicable to the ultimate failure event, but rather describes the required conditions for stable propagation of micro-cracks, a stage in the fracture process

which can be of extended duration. Irwin's equation, on the other hand, can be re-expressed:

$$T = T_{ult} = \sqrt{G_{ult} E / \pi c} \quad \dots (2a)$$

where G_{ult} is a critical value for the energy released per unit new surface, reached under a tensile stress, T_{ult} .

Values of G_{ult} have been determined for a wide range of materials and a standard has been suggested for test specimens (A.S.T.M., 1960).

In practice both concepts are applicable to rock fracture as, once crack propagation is initiated, failure occurs very rapidly.

I.3. Energy Consumption and its Measurement

The well known equations of Rittinger (1867), Kick (1885) and Bond (1952), relating energy consumed by a grinding device and the resultant changes in particle size, have been shown by Charles (1957) to be special cases of the general differential equation:

$$dE = - C dx / x^n \quad \dots (3)$$

In this equation, first proposed by Walker et al. in 1937, dE is the amount of energy required to effect a change, dx , in the particle size x . C and n are constants, C being related

to material grindability and the method of grinding and the exponent n taking values of 1, 1.5 and 2 respectively in the Kick, Bond and Rittinger equations. Holmes (1957), assuming a relationship between particle size and fracture strength, and Arbiter and Bhargava (1960), using a kinetic model, derived alternative expressions for the energy - particle size relationship which Agar and Somasundaran (1973) have shown to be closely related to the Charles equation. Oka and Majima (1970) have presented a further equation incorporating Weibull's (1939) homogeneity factor and have shown that the three basic 'laws' can be derived as special cases.

Although theoretical justifications have been suggested for all three expressions it is better to regard them as empirical guides which are principally of value in equipment scale up and comparison uses. The Rittinger theory has been substantiated in a number of laboratory tests (e.g. Gross and Zimmerley, 1930; Prentice, 1946; Piret et al., 1949) while Bond's 'Third Law' has been shown to give excellent fit to much industrial data (Bond, 1961) and is widely used in plant design. Kick's law seems valid only in unusual circumstances; for instance Walker and Shaw (1954) suggest its applicability in very fine (submicron) grinding.

Equation (3) has two drawbacks. Firstly, as the comminution operation is not continuous in that fracture results in a finite (and considerable) step change in particle size, integration to derive practical laws is not strictly acceptable. Schuhmann (1960) points out that a simple summation notation can remove this problem. Secondly, and more important in terms of practical usage, neither feed nor product size can be defined fully by a single parameter, x , without making assumptions about the nature of the size distribution. Fortunately such assumptions can be made in many cases, as is shown in Appendix I, and the procedure is followed extensively in this thesis.

An alternative approach is suggested by Rittinger's 'law'. Rittinger (1867) postulated that the energy consumed in comminution would be proportional to the new surface area created, a relationship which can be expressed mathematically as:

$$E = C (\sigma_P - \sigma_F) \dots (4)$$

where E is the energy required to reduce a unit volume of feed of specific surface (area/unit volume) σ_F to a product with specific surface σ_P .
 C is a constant.

Assuming a constant shape factor, equation (4) may be

expressed:

$$E = C' \left(\frac{1}{x_P} - \frac{1}{x_F} \right) \quad \dots (5)$$

where x_P and x_F are some characteristic linear dimension of product and feed particles respectively and C' is a new constant.

As stated above, equation (5) can also be obtained by integration of Charles' general expression (equation (3)) with n taking the value 2.

The constant, C , in equation (4) is clearly dependent in part on the free surface energy of the solid being crushed. Indeed a perfect comminution operation might be considered to be one in which all the energy consumed is converted into surface energy of freshly exposed surfaces. Thus the ratio of energy input to free energy of fresh surfaces can be used as a measure of the efficiency of a practical fracture process. This has been done, for instance, by Dean (1939) using the linear relationship between specific surface and magnetic coercivity of magnetite for surface measurement, by Gross and Zimmerley (1930) using the dissolution rate of quartz in HF acid to indicate specific surface area, and by Axelson and Piret (1950) who determined the specific surface by a gas adsorption technique. Low

efficiencies were found in all cases, Gross and Zimmerley, for instance, finding the efficiency of their drop-weight crushing apparatus to be approximately 3%.

An alternative approach to the determination of milling efficiency is to calculate the energy consumed in the fracture event by a difference method, i.e. after accounting for other energy losses. Examples of this approach are provided by Carey and Halton (1946), who showed that 99% of the energy used in various kinds of ball mills was dissipated as heat, and by Prentice (1946) who accounted for over 90% of the supplied energy by mechanical and heat losses to the mill.

In view of the very low theoretical efficiencies of conventional milling methods, and the great difficulty of the measurements on which such theoretical determinations are based, it was suggested by Carey and Stairmand (1952) that a standard laboratory test be adopted as a basis for estimating the efficiency of industrial operations. They recommended a procedure in which closely sized feed particles were slowly crushed between hardened steel platens. Only small reduction ratios were permitted in any one stage to prevent the formation of packed beds and the resultant inefficiencies arising from particle interactions. Axelson

and Piret (1950) had previously shown that this mode of comminution was one of the most efficient, provided free fracture conditions were maintained. On the basis of the surface energy criterion described above they found efficiencies averaging about 9% for single particle fracture by slow compression, falling to 1.4% for many-particle beds. Schoenert, (1972) has recently compared his own slow crushing results and those of Axelson and Piret with published energy - surface relationships for impact crushing and ball milling and has shown Carey and Stairmand's method to be between one and two orders of magnitude more efficient. That is, the conventional processes were between 1 and 10% efficient on a scale with slow free crushing = 100%. Jowett (1971) strongly advocates the general adoption of the method, in part because the product size distribution tends to conform to Andreasen's (1928) 'natural' form, a straight line of unit gradient on a log-log cumulative size plot - the Schuhmann plot described in Appendix I and used in the first part of this study. Among recent users of the method, or modifications of it, have been Steier and Schoenert (1971), Everell et al. (1971) and Bradley et al. (1972). Bradley found the efficiency of the comminution process to be about 80% compared with the Carey and Stairmand standard. Unspecified 'corrections were made

to account for bearing and resistance losses', however, so the result is somewhat inconclusive.

I.4. Liberation

Run-of-mine ore consists of rock particles, of various sizes, each in general composed of a number of different mineral phases dispersed throughout the particle, either as individual grains or as a continuous matrix. (A grain, in the sense used throughout this thesis, is a single crystal or portion of a single crystal defined by clear boundaries - free surfaces or interfaces with either similar or disparate grains.) In order that the valuable components of the ore may be concentrated it is necessary that they be liberated, i.e. physically freed from gangue material. This is usually achieved by comminution.

Gaudin (1939) used the schematic model shown in Figure I.1. to demonstrate that the extent of liberation of a minor component in an ore depends on both the volumetric abundance of that component and the ratio of the product particle size to the natural grain size.

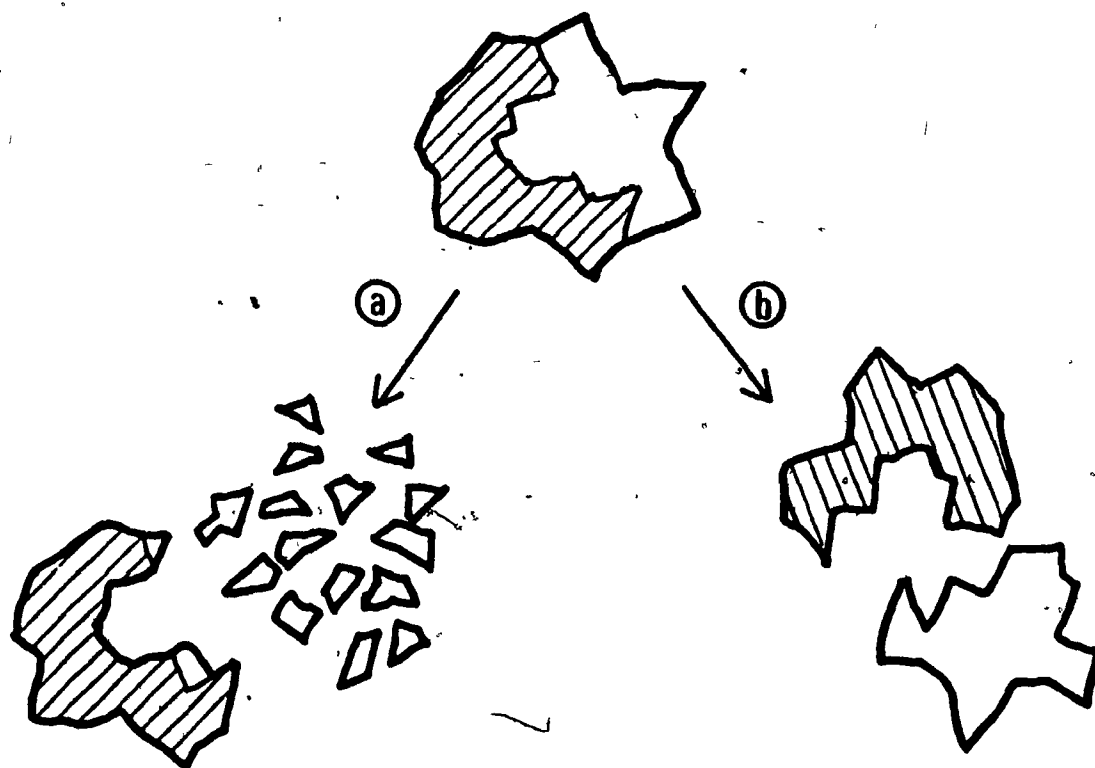
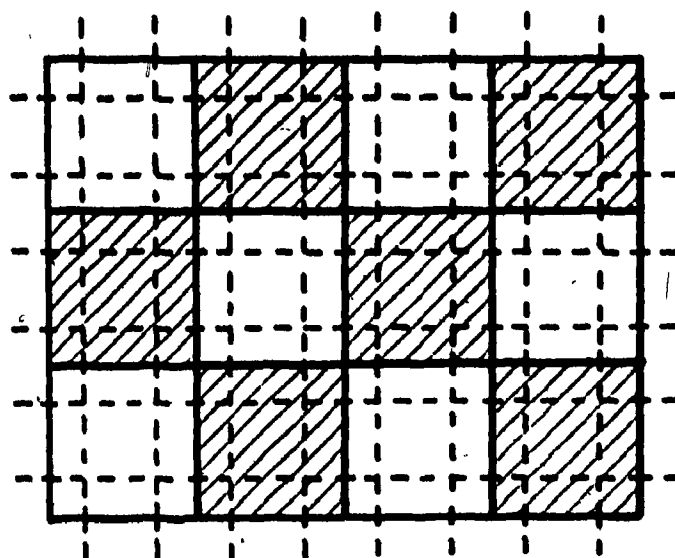
The model has been improved (Wiegel, 1964; Wiegel and Li, 1967) by considering a random distribution of mineral

FIGURE I.1.

Gaudin's (1939) Liberation Model

FIGURE I.2.

- (a) Liberation by Selective Breakage**
- (b) Liberation by Detachment**



grains (and, hence, of grain sizes) in the ore particles. Gaudin's assumption of a fracture grid superimposed without reference to the grain structure was retained. On this basis it was shown, for instance, that liberation of a minor component occupying one tenth of the total volume will reach 90% only on crushing to a particle size range of approximately one thirtieth of the natural grain size.

Fortunately total liberation is rarely essential, nor are practical results as poor as the theory indicates, liberation by selective breakage (Figure I.2(a)) and detachment (I.2(b)) tending to occur, rather than the totally random fracture envisaged in the theory. Liberation by selective breakage may not confer significant advantages, however, as it is frequently the valuable minerals (e.g. the sulphides) which fracture preferentially, but detachment is clearly a desirable goal. Existence of liberation by detachment is shown by a size analysis of the crushed product as there will exist a preponderance of particles of grain size, revealed by the development of a mode in the frequency distribution at that size. Such modes, which are usually masked in a conventional cumulative size distribution plot, are especially obvious in some weathered and sedimentary rocks.

Although, as described, adequate liberation is frequently achieved without the excessive comminution theoretically predicted, any method which gives rise to stress concentration at the grain boundaries should show superior liberation characteristics. The complexity of the micro-distribution of stresses in a granular rock precludes theoretical analysis and measurement techniques such as the use of strain gauges, X-ray line broadening (Gross, 1965; Gross and Paterson, 1965), calorimetric stress relief (Faulkener, 1960) and even the sophisticated X-ray technique of Friedman (1967,68) are only capable of indicating some mean strain value, averaged over a number of grains. Gallagher (1971) noted this lack of knowledge and used photo-mechanical models to reveal the stress patterns in two-dimensional arrangements of discs, both loose and embedded in cement, and of irregular slabs. He clearly showed that little stress concentration occurs in an externally loaded cemented aggregate unless the cement and grain materials have markedly different elastic properties. This is only rarely so in economic ore deposits. It would appear, therefore, that in order to enhance liberation it is necessary in some way to develop stresses within the material at the level of the grain structure.

II NOVEL APPROACHES TO COMMINUTION

II.1. Introduction

As shown in the previous section, conventional comminution processes are largely unsatisfactory in terms both of efficiency (energy consumption) and effectiveness (product characteristics). Consequently crushing and grinding is receiving increasing research attention. Extensive reviews of recent progress have been given by Farmer (1965), Kochanovsky and Singhal (1966), Geller (1967), Hiorns (1970), Karpinski (1972), Snow (1973) and Mitchell (1973).

Two distinct approaches can be identified; mathematical modelling of conventional grinding processes and circuits, and investigations of new or modified techniques. Austin (1971/2) and Agar and Somasundaran (1973) have presented useful summaries of the modelling approach and the topic will not be considered further here. The research which is the subject of this thesis falls into the second category and, as it can be related to a number of previous studies, these will now be described.

II.2. Chemical Environment

That some physical properties of crystals, such as hardness, can be modified by altering the chemical environment was first noted by Rehbinder (1928), after whom the effect has been named. Rehbinder and his associates have subsequently shown the industrial significance of the effect in improved rock drilling rates (1944,47), have demonstrated the effect in metals (1949), and have extended their studies to fracture (1957). Numerous other workers have found confirmation of the existence of the Rehbinder effect in comminution operations (Somasundaran and Lin, 1972, give extensive references) and have usually adopted the following explanation, first given by Rehbinder and specifically applied to grinding by Rose and Sullivan (1958). It is suggested by these workers that, as the grinding process is characterized by the formation of new surfaces and as comminution energy is expended in providing the free surface energy of this new surface, changes in the free surface energy per unit surface effected by surfactant adsorption give rise to corresponding changes in comminution energy requirements. This is a somewhat unsatisfactory explanation as it is difficult to see how the adsorption process, necessarily occurring subsequent

to fracture, can materially affect the fracture process itself. The explanation is still widely held, however (e.g. Vutukuri, 1972; Vutukuri and Heins, 1972) but an alternative explanation more recently suggested by Westwood (1962,67,68) appears preferable. He believes that adsorbed species give rise to localized changes of electronic state in the crystal lattice surface which, in turn, alter the mobility of dislocations originating at the surface.

A similar effect in the bulk phase, dislocation pinning by solute atoms, has been observed in non-metallic crystals by Johnston (1962) and is a well known phenomenon in metals, first described by Cottrell and Bilby in 1949 and recently reviewed by Baird (1971). Westwood has been able to demonstrate changes in dislocation mobility by an etch technique and has recently (1973) achieved drilling rate improvements in excess of one order of magnitude by choice of suitable drilling fluids.

In addition to the Rehbinder effect discussed above, changes in the mechanical properties of minerals as a result of their chemical environment have been attributed to the removal of Griffith cracks from the surface by chemical or dissolution etching, chemical attack - including hydrolysis by atmospheric moisture, and various physical changes in

environment brought about by chemical change. The review by Lin and Somasundaran mentioned earlier considers these aspects in detail.

II.3. Physical Conditions

The author has previously found it convenient to consider the effects of physical conditions on comminution behaviour under the arbitrary sub-headings Pressure, Temperature, and Electrical Effects (Partridge and Smith, 1973). This division will again be followed here.

i) Pressure

It was pointed out in an earlier section that minerals tend to fail under tension at considerably lower stress levels than they do under compressive loading. One way in which tensile stresses can be set up in a mineral particle is to generate an excess pressure, i.e. one greater than the ambient pressure, within the particle. Dean and Gross (1932) appear to have been the earliest to attempt this with the intention of achieving comminution. Their first method, in which an explosive (silver acetylide) was synthesized within the pores of mineral grains by impregnation with silver nitrate and subsequent treatment with acetylene, failed but an alternative approach proved

encouraging. Rock particles (-4 +6 mesh) were water saturated, heated to 180°C in an enclosed space and the container suddenly opened. The resultant expansion of superheated water caused the particles to fracture, a product of more than 50% -6 mesh being obtained with some evidence of enhanced liberation. Technical difficulties apparently prevented use of the method on a large scale until recently when the Snyder process, making use of this principle, was introduced (Cavanaugh, 1972).

ii) Temperature

The fracture effects which result from differential thermal expansion along a thermal gradient were known to Agricola (1556) and, until the discovery of dynamite, fire setting, the alternate heating of rock with fire and then shock cooling by water quench, was the chief means of driving tunnels. Today the phenomenon is regarded almost universally as a nuisance, spalling of furnace linings and the thermal cracking of ceramics being two instances in which it causes problems. The only uses of the effect known to the author are in slag quenching, the experimental quenching of granular ores and in some electrical methods to be covered later.

Less well known are the stresses set up in many

polycrystalline materials in thermal equilibrium at temperatures other than at some unique value, usually the temperature at which the grain structure formed. These stresses, named 'tessellated stresses' by László (1943) and 'textural stresses' by Orowan (1947), arise as a result of unequal responses to temperature changes of the various components of the polycrystalline material. They are characterized by being internally self-compensating, that is they can exist in a body experiencing no external forces. This is vividly expressed by László's term 'tessellated' (chequered), as for each increment of tensile or compressive force acting on any plane in the body there must exist an opposite increment of force of equal magnitude such that the net effect is zero.

Four thermal phenomena can give rise to tessellated stress conditions; namely heterogeneous or homogeneous anisotropic thermal expansion and crystallographic or chemical phase changes.

a) Heterogeneous anisotropy

If two (or more) isotropic solid phases with different coefficients of thermal expansion are bonded together at a temperature, t_0 , and brought to a new

temperature, t_1 , the phases will tend to expand to different degrees. Provided the bond remains intact, however, their natural expansion will be constrained and the composite will take up an intermediate dimension dependent not only upon the thermal expansion coefficients but also on the Young's modulus, Y , of each phase and (in non-linear manner) on their dimensions. This situation is illustrated in Figure II.1. The distribution of stresses in adjacent elements of the composite is indicated by Figure II.2. Stress values are such that the net force across any sectioning plane is zero and it is seen that maximum stress values are encountered at the bonded interface. The results of stresses such as these are seen in everyday life in, for instance, the lifting or crazing of paints and glazes when the resultant stress is compressive or tensile respectively.

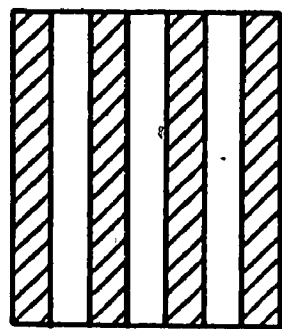
Although a number of studies of the effect of heat treatment on the grindability of rock types have been made, the anisotropic thermal expansion of individual grains of many minerals makes it difficult to distinguish the relative significance of either homogeneous or heterogeneous anisotropic thermal expansion. The evidence for both effects will therefore be reviewed at the end of the next section.

FIGURE II.1.

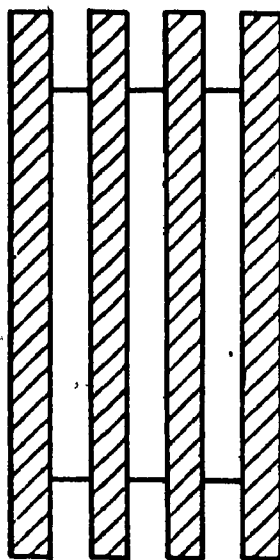
Thermal Expansion of a Composite Body

FIGURE II.2.

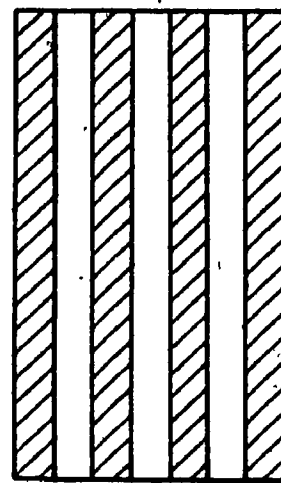
Thermal Stresses set up at Grain Boundaries
in a Composite Body



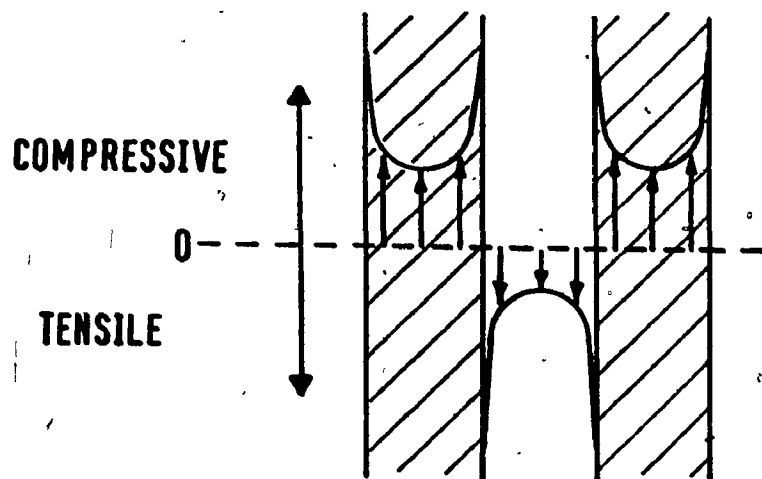
(a)



(b)



(c)



b) Homogeneous anisotropy

Most non-cubic crystals exhibit different coefficients of linear thermal expansion in the various crystallographic directions, differences usually being such that the crystal structure more closely approaches a higher degree of symmetry at elevated temperatures (Kingery, 1960b). The effect is usually insignificant but is appreciable in some materials and leads to the generation of considerable internal stresses with temperature change. Values of the thermal coefficients of expansion for a number of technologically important crystals are given in Table II.1.

Crystal	Coefficient, $^{\circ}\text{C}^{-1} \times 10^6$	
	Normal to C axis	Parallel to C axis
Non-metals:		
Al_2O_3	8.3	9.0
CaCO_3 (calcite)	-6.0	25.
SiO_2 (quartz)	14.	9.
C (graphite)	1.	27.
Metals:		
Sn	30.5	15.45
U	45.5	-13.
Zn	15.	61.5

Table II.1. Thermal Expansion Coefficients
for some Anisotropic Crystals

Although perhaps the earliest reference to the phenomenon was in connection with rock, Howe (1910) listing it as one of the parameters effective in the weathering of building stone, most attention has been given to the effect in metals and, more recently, in ceramics. Boas and Honeycombe (1944,45,47) observed deformation in polished surfaces of pure tin, cadmium, zinc and tellurium and in tin-based bearing alloys when subjected to slow thermal cycling between 30 and 150°C. The deformation increased with the number of cycles but was independent of rate of temperature change provided thermal equilibrium was maintained. No effect was observed with lead or lead-based alloys, in single crystals of any of the metals or in aggregates showing strongly preferred crystal orientation. They concluded that the effect was due to the tendency of grains of the non-cubic metals to change shape (relative axial lengths) when subjected to a temperature change. This is indicated schematically in Figure II.3. The thermal distortion is indicated as a shear strain in the diagram but it is clear that any relative dimensional change will result, in general, in a mis-fit of the grains. Isotropic expansion or contraction, on the other hand, such as that exhibited by the cubic crystals (Pb, Al) and, approximately, by other crystals with axial ratios close

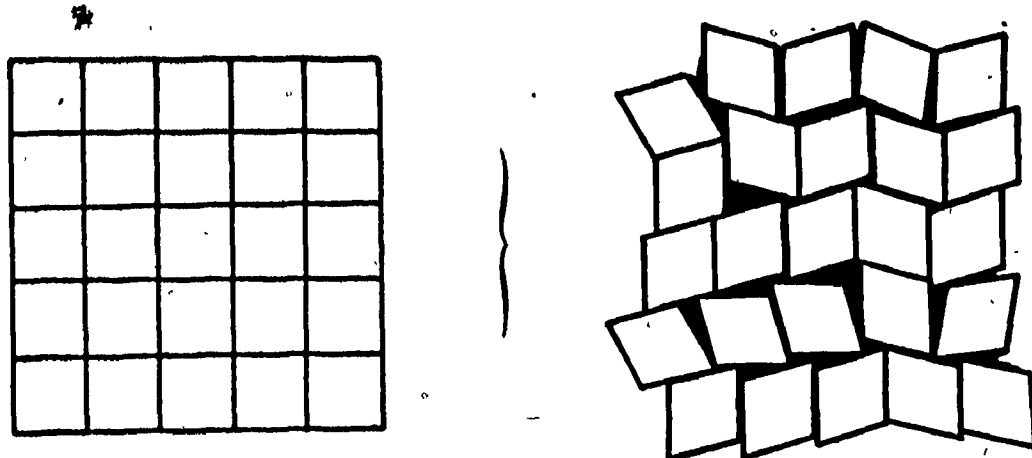


Figure II.3. Mismatch due to Anisotropic Thermal Expansion.

to unity (e.g. magnesium) will not result in mis-fit. Nor will a mis-fit occur in a material in which each component deforms similarly in space, as occurs if the crystals are similarly oriented.

The phenomenon has been observed in metals repeatedly since the work of Boas and Honeycombe. Miller (1965), for instance, working at McGill University, produced excellent photographs of the strain developed in polycrystalline zinc when thermally cycled between room temperature and -190°C (liquid air). He confirmed Boas and Honeycombe's observations that the deformation increased with the number of cycles, grain

boundary separation eventually occurring. The very marked anisotropy of uranium has been studied by, among others, Young et al. (1960), Anderson and Bishop (1962) and Alexander (1964),

The effects of both homogeneous and heterogeneous anisotropy in ceramic materials have been described, in general terms, by Austin (1952), Kingery (1955, 59, 60c) and White (1958a). Coble (1958) showed that thermal stresses in alumina gave rise to intergranular fracture, whereas tensile failure tends to occur transgranularly in this material (White, 1958b). Charvat and Kingery (1957) show similar behaviour in a sintered rutile compact and the phenomenon was noted much earlier in polycrystalline silica by Sosman (1927b).

Silica, as quartz, is also a major rock-forming mineral. However, the effect of its anisotropy on rock properties is usually overshadowed by the α - β phase change at 573°C, discussed later, and by the presence of other minerals with different thermal expansion coefficients. Brown et al. (1958), in a paper which cites a number of references to earlier studies, describe improvements in friability, size distribution and liberation in heat treated granite, syenite and marble. With the last of these

environment control precluded chemical breakdown so that the only effective mechanism was the thermo-mechanical anisotropy of calcite. Tests were also conducted with an almost pure franklinite (ZnFe_2O_4) ore, insignificant changes in comminution characteristics being found with this isotropic mineral.

DeVore (1969) tabulates the compressive stresses theoretically set up in several minerals if totally constrained and heated from 20 to 400°C. Of especial interest is the maximum stress difference $|T_1 - T_3|$ which, for example, is given as 1.01 kilobars ($1.01 \times 10^8 \text{ N/m}^2$) for quartz, 3.29 for hematite and 5.51 for calcite.

c) Crystallographic phase change

Many minerals can exist in more than one crystallographic form, each being stable over a characteristic temperature range. By far the most important of such minerals is silica, especially the enantiomorphs α - and β -quartz. Transition between the low-temperature trigonal form, α -quartz, and the high-temperature hexagonal β form occurs at 573°C and is accompanied by step changes in the linear and volumetric thermal expansion curves as shown in Figure II.4. As a result, a polycrystalline quartz structure stress free at a temperature close to 573°C will become stressed on being heated or cooled through that temperature. In the

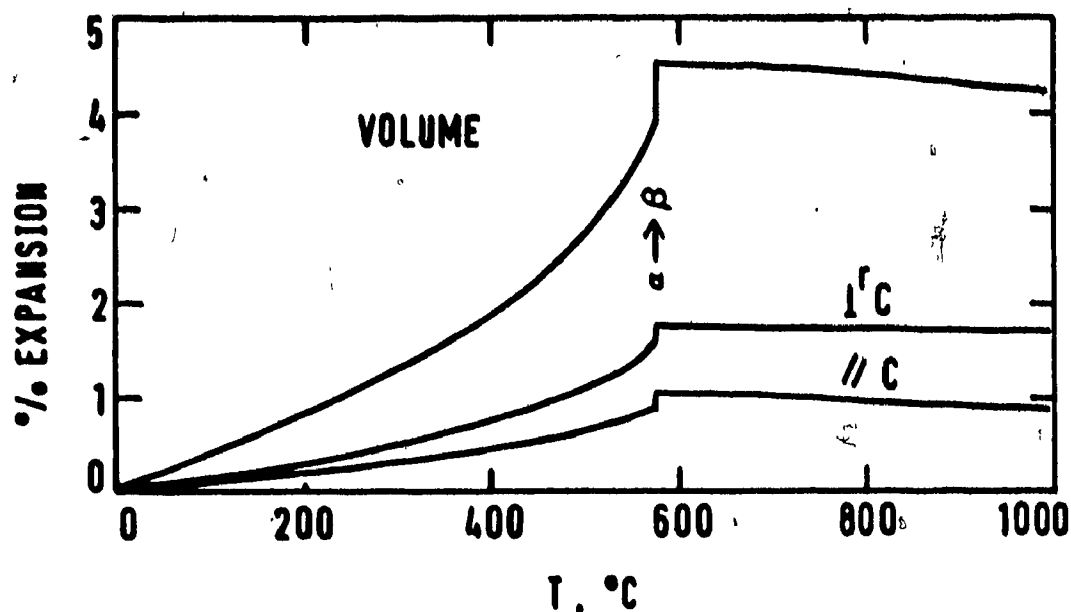


Figure II.4. Thermal Expansion of Quartz.

extreme case of a totally restrained crystal, these stresses would be of the order of 10^9 N/m^2 (DeVore, 1969).

Few practical examples of this phenomenon have been reported, those few again being chiefly in the fields of physical metallurgy (László, 1943) and ceramics (Kingery, 1957; Harris et al., 1965). Kingery (1960d) states, without attribution, that quartzite has been successfully heat treated prior to crushing but the only mineral processing investigations known to the author in which enantiomorphic phase transformations are of clear significance are studies of iron ores which will be described following the next section.

d) Chemical phase change

The fourth mechanism by which dimensional changes may be brought about thermally is that of chemical phase change. Examples include the thermal decomposition of calcite ($\text{CaCO}_3 \rightleftharpoons \text{CaO} + \text{CO}_2$), avoided by Brown et al. (above) by the use of a CO_2 atmosphere, the oxidation of many sulphides by roasting, and the reduction roasting of hexagonal hematite to cubic magnetite ($3\text{Fe}_2\text{O}_3 + \text{H}_2 \rightleftharpoons 2\text{Fe}_3\text{O}_4 + \text{H}_2\text{O}$), used prior to magnetic separation in some installations (Cavanagh and Last, 1961).

The effect of temperature on siliceous iron ores provides an excellent example of all four mechanisms described above. This system has been the subject of investigations by Mitchell et al. (1952), Stephens and Wasner (1959), Lecznar (1962), Lean (1963), Lean and Worner (1963), Daellenbach et al. (1971) and Vik et al. (1971). In general it is found that an increase in strength is obtained by slow heating to the range $400 - 500^\circ\text{C}$, followed by a progressive increase in grindability with higher temperatures, the reduction being particularly evident over the range $550 - 600^\circ\text{C}$ (the $\alpha - \beta$ quartz transform). Further reductions in grindability are effected by shock cooling (thermal gradient), and reducing atmospheres (hematite $\rightarrow$ magnetite). The initial strengthening

is attributed to a relaxation of residual elastic stresses caused by the differential thermal contractions on cooling from the temperature of formation of the ore, estimated to be approximately 600°C (Miles, 1954).

iii) Electrical Methods

Most of the novel methods which utilize electrical energy involve internal heating giving rise to the thermal stresses described above. In another method, electrohydraulic comminution, an underwater spark discharge is used to generate accoustic shock waves which cause fracture. These techniques will be described briefly here before introducing the possibility of the direct conversion of electrical energy into fracture-producing stress.

Thermal stresses may be developed within a rock by resistive, inductive or dielectric heating, depending on the nature of the rock. Epshteyn (1960a) and Kochanovsky and Singhal (1966) review the early work in this field. If the rock as a whole is conductive, the power 'losses' ($I^2 R$, where I is the R.M.S. current flowing and R is the resistance of the rock) on passing an alternating or direct current appear as heat. This technique has been used by Sarapuu (1965) for fracturing taconites. When the rock is not in itself

conductive but contains dispersed conductive or ferromagnetic minerals, high frequency ($10^4 - 10^6$ Hz) electromagnetic fields will give rise to induced eddy currents or electromagnetic hysteresis in the responsive mineral grains leading to localized heating. This method has received most attention in the U.S.S.R. (Epshteyn, 1960a). When the rock components are non-conductors very high frequency electrical fields give rise to dielectric losses and consequent heating. Piekarski (1966), for instance, applied this concept to the fracture of asbestos ore. Dielectric puncturing, the establishment of a narrow conducting path through a rock by pulsed or high frequency voltage applied through pointed electrodes, has been studied recently (Ram, 1969; Ram et al., 1970). The phenomenon is accompanied by melting and/or chemical decomposition along the conducting path. Fracture is enhanced by the passing of a low frequency, high intensity current to give a large heating effect once the conductive path is established (Kravchenko et al., 1961; Young, 1961).

Electrohydraulic comminution was pioneered in Russia (Epshteyn, 1960b) with more recent research being carried out in England and America. In this method a high intensity underwater spark discharge generates a powerful acoustic wave which is used to fracture mineral particles

located near the spark track. Bergstrom (1961) reviewed the Russian studies and reported research carried out earlier in the Allis Chalmers laboratories. He concluded that efficiencies were so low that the method could only be expected to be of value in special circumstances - for instance, if contamination was to be avoided. Since that time Carley-Macaulay (1966,68,71); Maroudas (1967), Maroudas et al. (1967), Yigit (1969) and Hitchon and Carley-Macaulay (1972) have greatly improved the efficiency, which can now be made to approach that of conventional processes, and a continuous laboratory unit has been developed (Hitchon and Carley-Macaulay, 1973). Apart from the absence of contamination the process offers further advantages for some uses as products are found to be more closely sized and less irregular than conventional products (Yigit, 1969). Liberation is also enhanced, possibly due to the reflection of the shock wave at grain boundaries giving rise to tension across the face (Figure II.5.).

The possibility of direct conversion of electrical energy into fracture-producing strain in rock particles does not seem to have been appreciated prior to this study. It will be shown, however, that this effect may be theoretically predicted for rocks containing piezoelectric minerals. Such

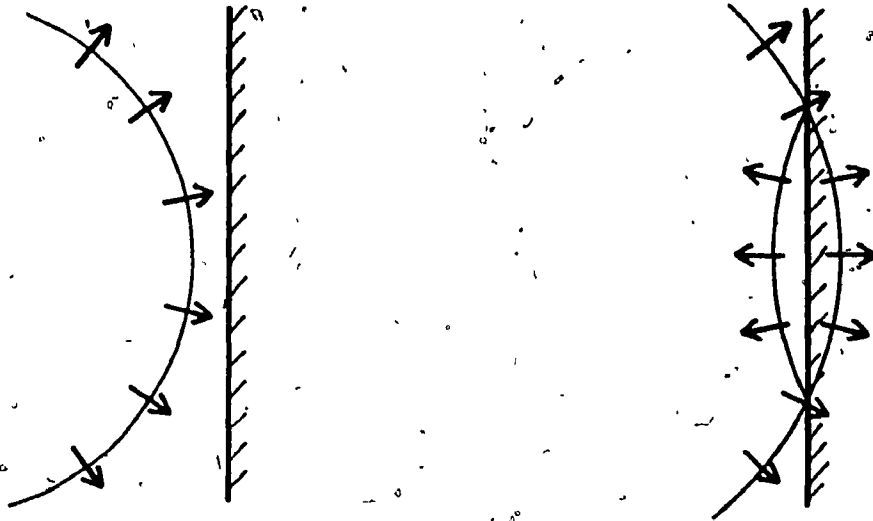


Figure II.5. Grain Boundary Tensile Forces
Resulting from Shock Wave Reflection

minerals tend to deform in an electric field and the deformation may be expected to give rise to stresses analogous to those generated as a result of differential thermal expansion. The piezoelectric effect and its applications in comminution are the subject of the remaining chapters of this thesis.

It has previously been pointed out that considerable losses result from the multiple conversions of energy occurring in conventional comminution procedures (Epshteyn, 1960c; Hiorns, 1970). Many of the novel methods described

in this chapter involve fewer transformations (e.g. heat is generated within the rock) and these are therefore potentially more efficient. In many cases, however, the intensity of energy available is not adequate, in itself, to cause fracture. However, if a portion of the critical stress or energy can be provided by a high efficiency method such as those described above, then the overall efficiency of the process will be improved. (Friedman and Logan (1970) and Friedman (1972a,b) have demonstrated that stress systems can interact to affect fracture characteristics, though efficiency was not considered.) Furthermore, if the supplementary method results in products with more favourable characteristics (size distribution, liberation, etc.), the additional expense incurred may well be justified.

III. PIEZOELECTRICITY

III.1. Introduction

The piezoelectric* effect, in which an electrical polarization is induced in some crystals when subjected to an appropriately directed stress, was anticipated and experimentally demonstrated by the Curie brothers in 1880. The converse effect - a tendency of such crystals to strain spontaneously when polarized by an electric field - was predicted and verified in the following year. Another phenomenon, electrostriction, also links crystal deformation with electrical field conditions but the two phenomena are differentiated in that electrostrictive deformation is proportional to the square of the applied field (and is therefore independent of field direction), whereas piezoelectric deformation is directly proportional to field strength and consequently reverses sign upon reversal of field. Electrostriction is a universal property of dielectric materials but the magnitude of the effect is extremely small and the phenomenon is of no further interest here. Piezoelectricity, on the other hand, is restricted to those crystal

* From the Greek $\piίεζω$, to press.

classes which possess some form of directionality in their structure (Cady, 1946a, refers to this as 'an inherent "one-wayness"'), i.e. it is found only in those crystal classes lacking a centre of symmetry. There are twenty-one such classes (of the total thirty-two) but one, Hermann-Mauguin group symbol 432, has other symmetry elements that combine to exclude the piezoelectric property (Mason, 1950).

Two extensive surveys have been made (W.L. Bond, 1943; Egli, 1948) with the object of finding crystals suitable for industrial use. Bond specifically considered minerals and found that, of some 860 investigated, 8% were potentially piezoelectric, crystallographically, but only seventeen exhibited the property to a significant degree. Quartz, sphalerite and tourmaline were the only members of this group of interest to the minerals scientist.

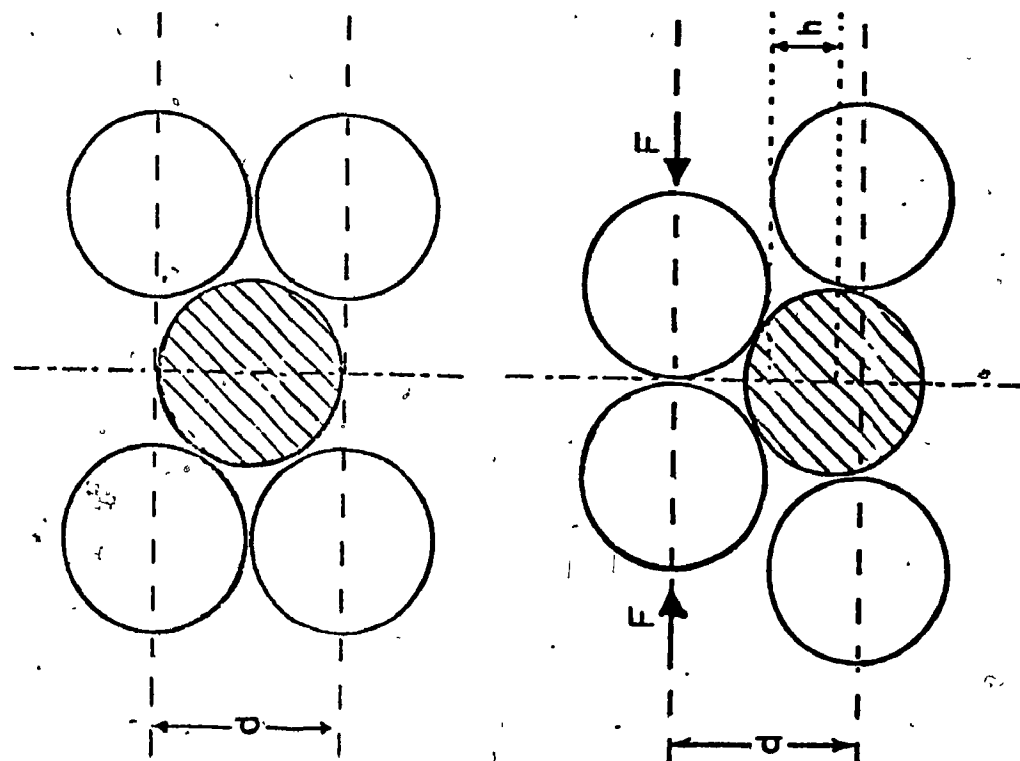
The structural basis for piezoelectric phenomena in sphalerite is shown schematically in Figure III.1. In the symmetrical arrangement illustrated in the upper diagram the centres of negative and positive charges are in coincidence. However, if a lateral strain is imposed on either of the upper or lower pairs of ions the central ion is forced to move vertically, giving rise to a dipole, as indicated in the lower diagram. Such a peculiar strain

FIGURE III.1.

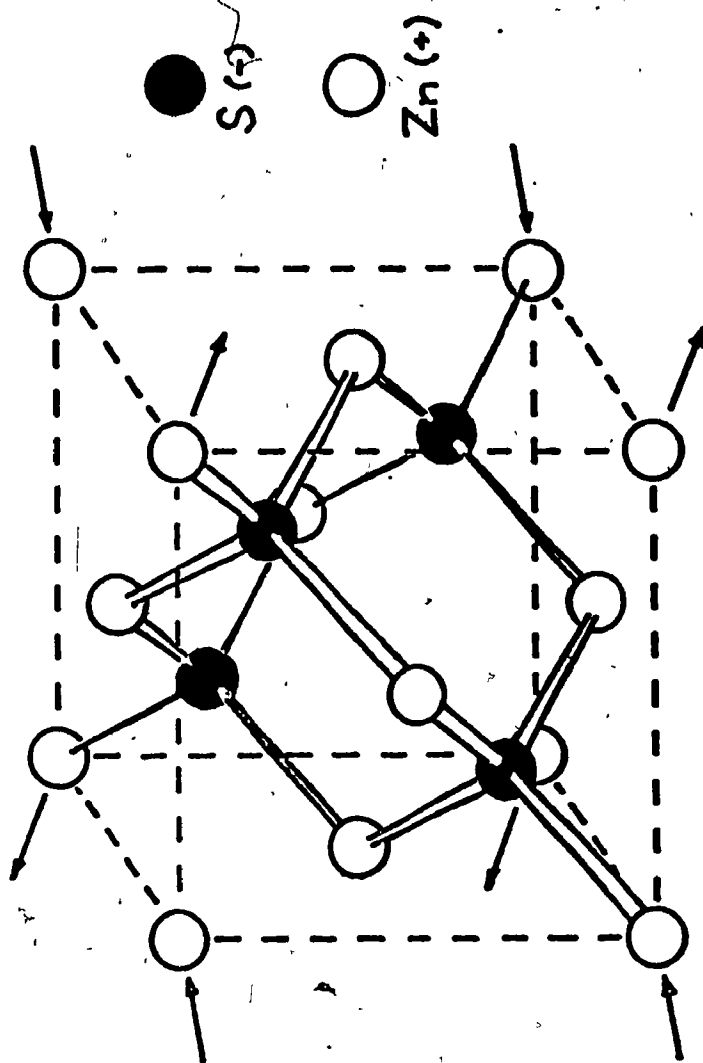
Schematic Representation of the Piezoelectric Effect
in Sphalerite

FIGURE III.2.

The Crystal Structure of Sphalerite



III.1.



III.2.

is hard to imagine in practice, but if either upper or lower pair of ions is rotated through 90° in a plane perpendicular to the page a tetrahedral arrangement is obtained in which a lateral tensile or compressive strain will result in the same dipole moment, the sense depending on that of the applied stress. In the face-centred cubic ($\bar{4}3m$) sphalerite structure (Figure III.2.) four such tetrahedra form a unit cell and, as the four are identically oriented, strain with a component in any of the $[110]$ directions, as indicated, gives rise to polarization of the (001) faces of the unit cell and, hence, of the crystal as a whole. Conversely, subjecting the crystal to an electric field along $[110]$ results in a corresponding strain.

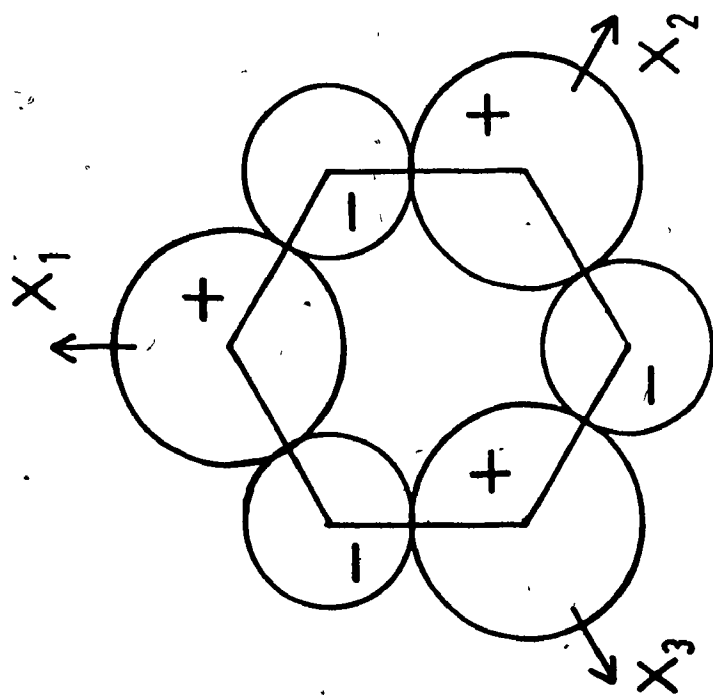
The $\bar{4}3m$ structure is the simplest known to exhibit piezoelectric properties. Structures of lower symmetry have considerably more complex electro-mechanical interactions. α -Quartz, for instance, with its trigonal structure (symbol 32), possesses three polar axes (the X axes) and responds to an electric field or strain with a component along any of them and also to shear in the (0001) (XY) plane. A complete structural analysis of these interactions has not been achieved although the model described below can be used to account qualitatively for the main piezoelectric effects.

The structure, viewed along the Z (optic) axis, is represented schematically by the hexagonal arrangement shown in Figure III.3(a). Each 'oxygen' circle represents two oxygen atoms, respectively above and below the silicon (+4) atom, and hence is attributed with a charge of -4. (The crystal structure differs also in that the silica tetrahedra form a spiral arrangement in the Z direction, i.e. into the page. This is not shown in the diagram, but does not affect the argument.) With the application of a force along an X axis (the electrical or polar axis), the silicon atoms are forced between the oxygen pairs. As a result the centres of positive and negative charges move with respect to one another, as is seen in Figure III.3(b). This phenomenon, in which the dipole moment is aligned parallel with the applied force, is known as the longitudinal piezoelectric effect. A transverse effect is also noted (Figure III.3(c)), in which a force applied perpendicular to both X and Z axes, i.e. in the Y direction, gives rise to polarization parallel with the X axis. In addition to these responses to tensile or compressive strain, shear strain both in a plane parallel with the Z axis and in the XY plane also result in polarization of the X axes, although it will be seen that these effects are of somewhat lower magnitude. As with the sphalerite and all other piezoelectric crystals, each interaction described here has a

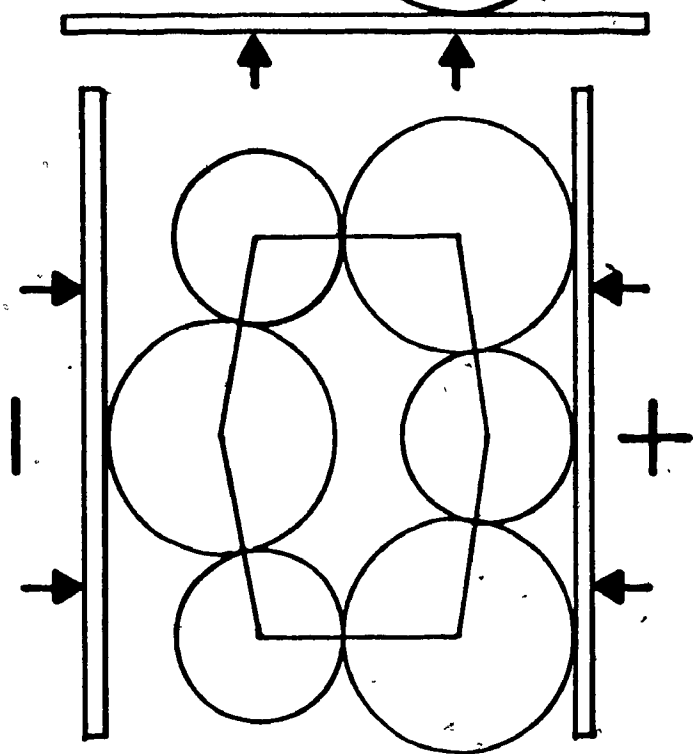
FIGURE III.3.

Schematic Representation of the Piezoelectric Effect
in Quartz

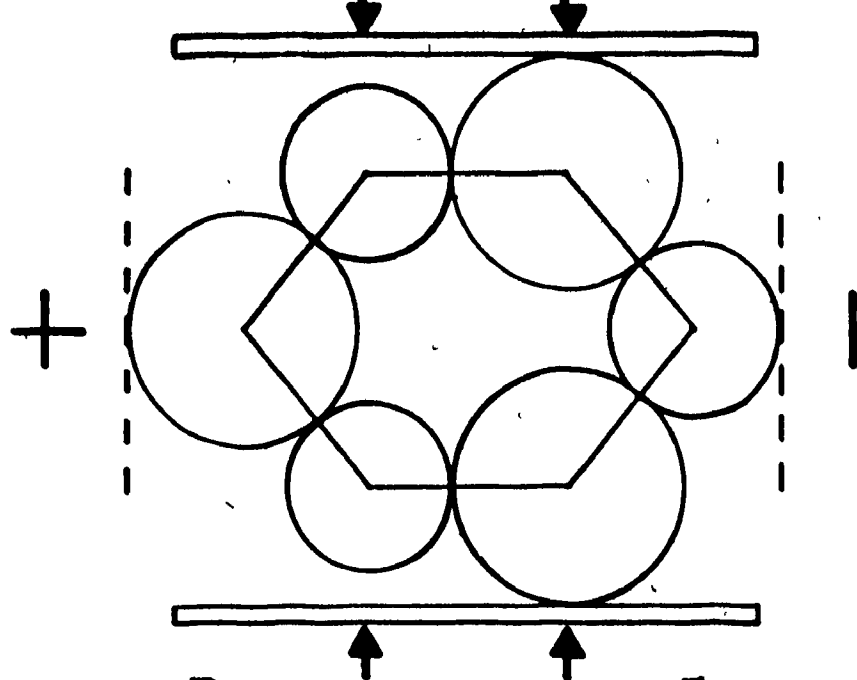
- (a) Schematic Lattice, viewed
along Z Axis
- (b) The Longitudinal Effect
- (c) The Transverse Effect



(a)



(b)



(c)

converse effect, a spontaneous tendency to strain when appropriately polarized.

Attempts to derive quantitative values for the interaction constants theoretically have been made along the lines of the following example for sphalerite (Jaffe, 1969). The amount of displacement of the atoms in the ZnS structure is readily calculated by postulating that the distance between nearest neighbour atoms remains constant. For a shearing strain of $1/1000$ (distortion angle about 0.05°) the displacement of the sulphur atoms against the zinc atoms in the direction perpendicular to the plane of shear is $1/4000$ of the unit cell dimension. The resulting polarization is the product of this displacement with the number of sulphur atoms per unit volume and the electric charge per atom. Agreement with the observed piezoelectric effect is only obtained by assuming a charge of one-fourth of an electron on the sulphur and the same positive charge on the zinc. This is in accord with the partially polar nature of zinc sulphide. The calculation is more complex and includes more assumptions in the case of quartz. An approximate solution proposed by Kelvin (1911), based on the model described earlier, has not been significantly improved.

Very much more accurate values have been obtained

experimentally. The methods will not be described here other than to note that many of the better methods make use of the dynamic response of carefully cut crystal sections to high frequency electric signals. Before giving the values so obtained for the interaction constants of quartz and sphalerite (the minerals examined in this study) it is necessary to describe the system used in defining such constants.

III.2. Stress and Strain

The stress at an arbitrary point, M, in a stressed body is defined as

$$T_M = \lim_{\Delta A \rightarrow 0} \Delta P / \Delta A \quad \dots (6)$$

where ΔP is the force exerted on the small area ΔA as a result of the stress.

This stress may be resolved into two components by projection respectively perpendicular and tangential to the plane of the area. These stresses may be designated T_{ij} where the first subscript defines the plane on which the stress component is acting and the second indicates the axis along which the projection is taken. The plane defined by i is taken normal to the i axis, thus T_{xy} denotes a stress acting on the YZ plane in the Y direction, i.e. a tangential

(shear) stress. The stress at a point may therefore be uniquely defined by considering the components acting on three mutually perpendicular planes, conveniently those defined by the coordinate axes XYZ (Figure III.4.).

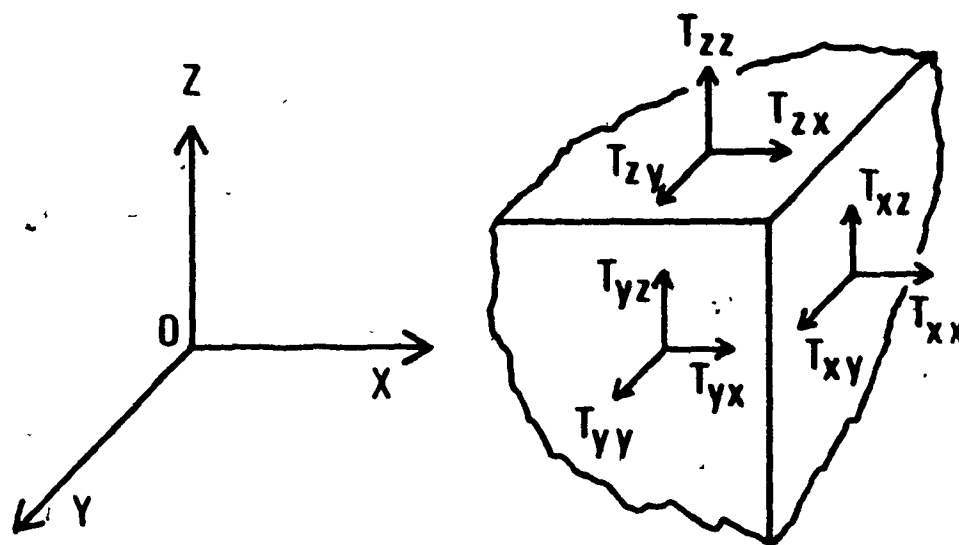


Figure III.4.

Designation of Stresses, T_{xy}

The stress tensor can thus be expressed:

$$\begin{array}{ccc}
 T_{xx} & T_{xy} & T_{xz} \\
 T_{yx} & T_{yy} & T_{yz} \\
 T_{zx} & T_{zy} & T_{zz}
 \end{array} \quad \dots (7)$$

or, more commonly, by the equivalent

$$\begin{array}{ccc}
 T_{11} & T_{12} & T_{13} \\
 T_{21} & T_{22} & T_{23} \\
 T_{31} & T_{32} & T_{33}
 \end{array} \dots (8)$$

As the body is considered in stationary equilibrium it can be seen that the components of tangential stress in mutually perpendicular planes are equal, i.e.

$$T_{12} = T_{21}, \quad T_{13} = T_{31} \quad \text{and} \quad T_{23} = T_{32}$$

The stress tensor is therefore symmetric. By convention, stresses are considered positive if acting in the direction of the positive axes. Consequently tensile stresses are regarded as positive.

Strains resulting from the application of stresses to a body are designated S_{ij} and defined by the expression

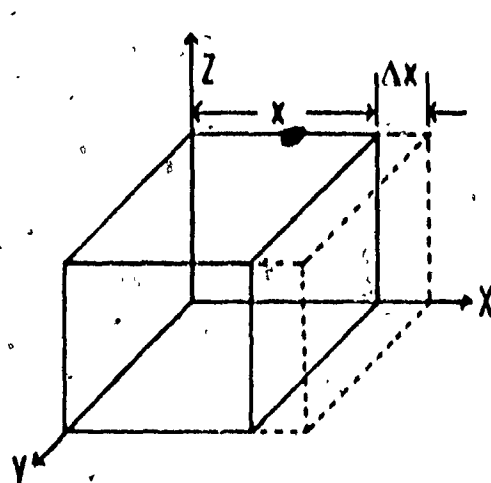
$$S_{ij} = \frac{\Delta i}{J} \dots (9)$$

That is, the strain represents the deformation Δi in axial direction I per unit length in the axial direction J. Thus S_{ij} may indicate linear or shear strain as shown in Figure III.5.

As with the stress tensor, strain in a body may be completely described by the matrix:

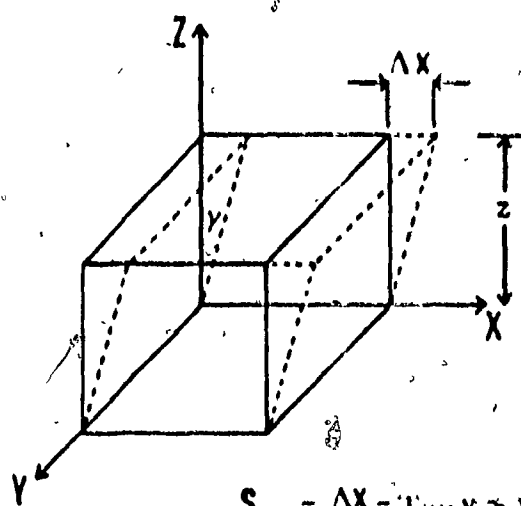
$$\begin{array}{ccc}
 s_{11} & s_{12} & s_{13} \\
 s_{21} & s_{22} & s_{23} \\
 s_{31} & s_{32} & s_{33}
 \end{array} \dots (10)$$

Again it is readily seen that, for a body experiencing no rotation or translation, $s_{ij} = s_{ji}$. Therefore the number of components in the tensor can be reduced to six.



$$S_{xx} = \frac{\Delta x}{x}$$

LINEAR STRAIN



$$S_{xz} = \frac{\Delta x}{z} = \tan \gamma \approx \gamma$$

SHEAR STRAIN

Figure 111.5.

Designation of Strains, S_{xy}

111.3. Piezoelectric Tensors

In the introduction it was stated that the piezoelectric effect is characterized by a linear relationship

between electrical field or polarization and crystal stress or strain. However it is seen above that the mechanical effects must be described in tensor form. Similarly, the electrical parameters, electric field E or polarization P , must be represented by a vector as they possess directionality as well as magnitude. Thus the inter-relationships must be expressed in matrix form such as the following:

$$\begin{array}{cccccccccc}
 & T_{11} & T_{22} & T_{33} & T_{23} & T_{32} & T_{31} & T_{13} & T_{12} & T_{21} \\
 P_1 & d_{111} & d_{122} & d_{133} & d_{123} & d_{132} & d_{131} & d_{113} & d_{112} & d_{121} \\
 P_2 & d_{211} & d_{222} & d_{233} & d_{223} & d_{232} & d_{231} & d_{213} & d_{212} & d_{221} \\
 P_3 & d_{311} & d_{322} & d_{333} & d_{323} & d_{332} & d_{331} & d_{313} & d_{312} & d_{321}
 \end{array} \dots (11)$$

where P_i are the components of the polarization intensity vector, T_{jk} are the components of the stress tensor and d_{ijk} are the coefficients of proportionality, called the piezoelectric moduli.

The same scheme, d_{ijk} , also relates the three components, E_i , of the electric field to the nine components of strain, S_{jk} .

The number of components in the piezoelectric tensor may be reduced from twenty-seven to eighteen on the basis of the equalities $T_{jk} = T_{kj}$ and $S_{jk} = S_{kj}$. Carrying out this operation, reducing the subscripts to two, and incorporating the E-S relationship, equation (11) is

simplified to:

$$\begin{array}{cc}
 \begin{array}{c} \downarrow \\ E_1 \\ E_2 \\ E_3 \end{array} & \begin{array}{c} \rightarrow \\ P_1 \\ P_2 \\ P_3 \end{array} & \begin{array}{|cccccc|} \hline S_1 & S_2 & S_3 & S_4 & S_5 & S_6 \\ \hline T_1 & T_2 & T_3 & T_4 & T_5 & T_6 \\ \hline d_{11} & d_{12} & d_{13} & d_{14} & d_{15} & d_{16} \\ d_{21} & d_{22} & d_{23} & d_{24} & d_{25} & d_{26} \\ d_{31} & d_{32} & d_{33} & d_{34} & d_{35} & d_{36} \\ \hline \end{array} & \dots (12)
 \end{array}$$

Here the first subscript indicates the row and the second the column. Thus the second subscript of 1, 2 or 3 indicates a linear stress or strain in the directions X, Y or Z and subscripts 4, 5 and 6 relate to shear in the planes normal to X, Y and Z respectively. Conversion is made using the relationships:

$$\begin{aligned}
 d_{32} &= d_{322} \quad , \quad \text{etc.} \\
 \text{and } d_{14} &= 2d_{123} = 2d_{132} \\
 d_{15} &= 2d_{131} = 2d_{113} \\
 d_{16} &= 2d_{112} = 2d_{121} \\
 &\quad \text{etc.}
 \end{aligned}$$

The relationships between the intensity of piezoelectric polarization, P_i , and strain, S_{jk} , or between field strength E_i and stress, T_{jk} , are given by:

$$\begin{array}{c}
 \begin{array}{cc}
 \downarrow & \rightarrow \\
 E_1 & P_1 \\
 E_2 & P_2 \\
 E_3 & P_3
 \end{array}
 \begin{array}{cccccc}
 T_1 & T_2 & T_3 & T_4 & T_5 & T_6 \\
 S_1 & S_2 & S_3 & S_4 & S_5 & S_6 \\
 \boxed{
 \begin{array}{cccccc}
 e_{11} & e_{12} & e_{13} & e_{14} & e_{15} & e_{16} \\
 e_{21} & e_{22} & e_{23} & e_{24} & e_{25} & e_{26} \\
 e_{31} & e_{32} & e_{33} & e_{34} & e_{35} & e_{36}
 \end{array}
 }
 \end{array}
 \end{array}
 \quad \dots (13)$$

where e_{jk} are termed the piezoelectric constants.

The piezoelectric moduli, d , and the constants, e , are related by the expressions:

$$\left. \begin{aligned}
 d_{jk} &= \sum e_{ji} S_{ik} \\
 \text{and } e_{jk} &= \sum d_{ji} c_{ik}
 \end{aligned} \right\} \begin{array}{l} j = 1, 2, 3 \\ i, k = 1, 2, \dots, 6 \end{array}$$

where S_{ik} are the elastic compliance constants

and c_{ik} are the elastic moduli.

The direct piezoelectric effect can be determined from (12) and (13) by reading in rows, e.g.

$$P_i = \sum_{j=1}^6 d_{ij} T_j \quad i = 1, 2, 3$$

and the converse effect by reading in columns, e.g.

$$T_i = \sum_{j=1}^3 e_{ij} E_j \quad j = 1, 2, \dots, 6$$

III.4. Piezoelectric properties of Quartz and Sphalerite

The eighteen possible independent piezoelectric moduli are in practice reduced in number by the elements of symmetry in the crystal classes exhibiting piezoelectric effects. (In the extreme case of total symmetry about a point, i.e. isotropism, the number is reduced to zero - no piezoelectric effect can exist.) For quartz the number is reduced to two:

$$\begin{array}{c}
 \begin{array}{cc}
 \downarrow & \rightarrow \\
 \begin{array}{cc}
 E_1 & P_1 \\
 E_2 & P_2 \\
 E_3 & P_3
 \end{array}
 \end{array}
 \begin{array}{cccccc}
 S_1 & S_2 & S_3 & S_4 & S_5 & S_6 \\
 T_1 & T_2 & T_3 & T_4 & T_5 & T_6
 \end{array}
 \end{array}
 \begin{array}{|c|}
 \hline
 \begin{array}{cccccc}
 d_{11} & -d_{11} & 0 & d_{14} & 0 & 0 \\
 0 & 0 & 0 & 0 & -d_{14} & -2d_{11} \\
 0 & 0 & 0 & 0 & 0 & 0
 \end{array}
 \end{array}
 \dots (14)$$

The more symmetrical cubic sphalerite possesses only one:

$$\begin{array}{c}
 \begin{array}{cc}
 \downarrow & \rightarrow \\
 \begin{array}{cc}
 E_1 & P_1 \\
 E_2 & P_2 \\
 E_3 & P_3
 \end{array}
 \end{array}
 \begin{array}{cccccc}
 S_1 & S_2 & S_3 & S_4 & S_5 & S_6 \\
 T_1 & T_2 & T_3 & T_4 & T_5 & T_6
 \end{array}
 \end{array}
 \begin{array}{|c|}
 \hline
 \begin{array}{cccccc}
 0 & 0 & 0 & d_{14} & 0 & 0 \\
 0 & 0 & 0 & 0 & d_{14} & 0 \\
 0 & 0 & 0 & 0 & 0 & d_{14}
 \end{array}
 \end{array}
 \dots (15)$$

These relationships may alternatively be written:

Quartz $P_1 = d_{11}T_1 - d_{11}T_2 + d_{14}T_4 \dots (16)$

$P_2 = -d_{14}T_5 - 2d_{11}T_6 \dots (17)$

$S_1 = d_{11}E_1 \dots (18)$

$S_2 = -d_{11}E_1 \dots (19)$

$S_4 = d_{14}E_1 \dots (20)$

$S_5 = -d_{14}E_2 \dots (21)$

and $S_6 = -2d_{11}E_2 \dots (22)$

Sphalerite $P_1 = d_{14}T_5 \dots (23)$

$P_2 = d_{14}T_5 \dots (24)$

$P_3 = d_{14}T_6 \dots (25)$

$S_4 = d_{14}E_1 \dots (26)$

$S_5 = d_{14}E_2 \dots (27)$

and $S_6 = d_{14}E_3 \dots (28)$

Berlincourt et al. (1964) give the following values for the piezoelectric moduli:

Quartz $d_{11} = 2.31 \text{ pC/N}^*$

$d_{14} = 0.727 \text{ pC/N}$

* $\text{pC/N} = \text{pica Coulombs/Newton}$ ($\text{pica} = 10^{-12}$)
 $1 \text{ Coulomb/Newton} \equiv 1 \text{ metre/volt}$

Sphalerite

$$d_{14} = 3.18 \text{ pC/N}$$

Equivalent expressions for the relationships between T_{ij} and E_i and between S_{ij} and P_i may be written, substituting the piezoelectric constants e_{ij} for d_{ij} in the above equations. Parkhomenko (1971) gives the following values for e_{ij} :

Quartz

$$e_{11} = 0.19 \text{ C/m}^2$$

$$e_{14} = -0.04 \text{ C/m}^2$$

Sphalerite

$$e_{14} = 0.14 \text{ C/m}^2$$

III.5. Estimation of Field Strength required for Fracture

As described earlier, the microdistribution of stresses in a polycrystalline material is exceedingly complex. However, an estimate of the significance of the piezoelectric effect in terms of the fracture process can be made based on Griffith's critical stress theory discussed on page 4. It will be recalled that the Griffith criterion for fracture initiation is that the stress at some point in a body reaches a critical value sufficient to cause unstable crack propagation. Thus it appears that piezoelectric stress or strain would contribute significantly to fracture when the strength

of an applied electric field reaches a value giving rise to stress or strain in an appropriately oriented crystal comparable with those existing in the material at the point of fracture under conventional crushing conditions. Accordingly, the following calculation was made to determine this critical field strength for quartz.

In general, tensile fracture may be expected at a strain of approximately 3×10^{-4} . From equation (18), it may be seen that extension in the X direction is given by an electric field in that direction, the magnitude of the strain depending on the value of d_{11} . By rearranging and substituting the values for d_{11} and fracture strain S_1^* given above, the critical electrical field strength may be estimated as:

$$\begin{aligned} E^* &= S_1^* / d_{11} \\ &= 3 \times 10^{-4} / 2.31 \times 10^{-12} \\ &\approx 10^8 \text{ V/m} \end{aligned}$$

That is, the field strength required to initiate Griffith crack propagation is of the order of 10^8 volts/metre. Stresses resulting from lower field strengths, though inadequate to cause cracking per se, may be expected to contribute to the fracture stresses. Thus a field of

10^7 volts/metre would provide 10% of the stress energy required to achieve fracture in conjunction with a similarly aligned mechanical force.

It should be noted that, in practice, the ideal orientation will only be approached by a small proportion of the total number of grains present in a polycrystalline matrix, assuming random orientation. However, the random boundary angles in such materials will give rise to a greater spread of intergranular forces, the effect of neighbouring crystals being summed to determine the net force.

IV AIMS OF RESEARCH

In Chapter I, it was shown that conventional comminution processes are inefficient and yield products which are unsatisfactory to a minerals engineer in that an excessive proportion of fine material is obtained and liberation is not promoted. These inadequacies have been attributed to the nature of the applied forces. Whereas optimal results would be expected from the direct application of tensile stress across grain boundaries, the particles are in practice subjected to compressive stresses with no regard for the granular structure.

Some of the many novel approaches to this problem made by other workers have been outlined in Chapter II along with relevant material from other fields. It is seen that many of the most promising methods involve the generation of stresses within rock particles by the utilization of crystal properties, notably differential thermal expansion. The suggestion is made that another phenomenon, the converse piezoelectric effect, might be utilized to generate similar stresses in certain materials.

The piezoelectric effect has been reviewed in Chapter III. It is pointed out that the phenomenon is only of significance in three minerals of industrial importance, quartz, sphalerite and tourmaline. The nature of the effect was considered in some detail for the first two of these. An approximate calculation is given which indicates that in order to obtain internal stresses comparable with the material strength fields of the order of 10^8 V/m would be required. Although the generation of such field strengths would present great problems in an industrial context it was thought that the hypothesis was sufficiently interesting to justify laboratory-scale testing. The research described in the remainder of this thesis was therefore carried out to test for and explore the predicted phenomena. Specifically, the research program was designed to detect and measure the effect of constant high intensity electric fields on the mechanical energy required to achieve a given degree of comminution in a variety of rocks and minerals and to detect any changes in liberation or product size distribution effected as a result of the applied fields.

V MATERIALS

The experimental work was carried out in two parts:- a preliminary stage in which the existence of an electric field effect was confirmed and a subsequent, more thorough investigation of the phenomenon. Quartzite and sphalerite were tested in the preliminary work; an iron ore, monocrystalline quartz, hematite and another sphalerite sample being added for the later testing.* It is convenient to describe all the materials in this section. Frequent mention will be made of -8+12 mesh particles as this size fraction was chosen for the crushing tests - see Chapter VI.

a) Quartzite

A polycrystalline quartz rock of medium grain size and high purity was used. Grain-size analysis (Appendix III) indicated a mean true grain size of 0.55 mm expressed in terms of an equivalent passing screen aperture. Apart from some 7% of very fine grained siliceous cement, the size range was not great, the interquartile range being from 410 μ m to 700 μ m (Figure A). The material had a specific gravity of 2.64, determined by pycnometer using the -8+12 mesh fraction, indicating a very low porosity.

*All materials except the iron ore were obtained from Ward's Natural Science Establishment, Rochester, N.Y.

b) Quartz ('mono-quartz')

Large water-clear single crystals of quartz from Arkansas (Figure V.1) were crushed to provide a -8+12 mesh feed material. No impurities were seen and no twinning was observed, either in the parent crystals or in sectioned feed particles.

c) Sphalerite ('mono-sphalerite')

The sphalerite used in the preliminary stages of testing was a blocky high-purity sample from Oklahoma. Microscopic examination of a sectioned portion of the -8+12 mesh fraction showed grain boundaries in very few of the particles although cleavage lines were evident (Figure V.2.). The tested material could therefore be regarded as mono-crystalline and is referred to as mono-sphalerite throughout this thesis to distinguish it from the second sphalerite tested. No twinning was revealed on etching with hydrochloric acid or sodium hypochlorite (Randohr, 1969a). No impurity minerals were observed and the specific gravity of 4.01 was in the range of published values (Randohr, 1969b).

d) Sphalerite ('poly-sphalerite')

A second sphalerite sample, from Timmins, Ontario, was subsequently obtained. This material was moderately fine grained and, although not pure, contained less impurity

FIGURE V.1.

Quartz Crystals

FIGURE V.2.

Monocrystalline Sphalerite (Section)

Magnification X5

FIGURE V.3.

Polycrystalline Sphalerite (Section)

NaOCl/Alcohol Etch

Magnification X36

(Light grains are Pyrite)



minerals than did other samples available at the time.

Pyrite was the only other mineral present in appreciable quantities and, as seen in Figure V.3., most grains exhibited considerable twinning. The specific gravity was found to be only 4.05 despite the higher density of pyrite. It is thought that the low value may be due to isomorphous substitution of iron for zinc in the sphalerite structure which can occur up to a Fe:Zn ratio of 1:1 (Mason and Berry, 1968).

e) Iron Ore

This rock, from the Iron Ore Company of Canada's Carol Lake deposit, remained from a previous study by the author (Partridge, 1970). The sample contained approximately thirty percent iron as hematite and magnetite in a ratio of about two to one. Due to porosity it was necessary to grind the particles finely before determining the specific gravity. A mean value of 3.03 was obtained in this manner.

f) Hematite

A polycrystalline sample of this non-piezoelectric mineral was included as a 'control'. The rock was a fine grained specularite from Michigan and had only minor traces of quartz impurity. The specific gravity was found to be 5.26.

All the materials were crushed in a laboratory jaw

crusher set at about $\frac{1}{4}$ " and dry screened on 8" Tyler screens for twenty minutes on a Ro-Tap machine. Each screen fraction was then washed on the screen and dried at room temperature. During the initial weighing-out of samples for crushing any foreign particles were rejected by hand, together with any particles of anomalous appearance - size, shape, colour, etc.

VI EXPERIMENTAL PROCEDURES - APPARATUS AND

CHOICE OF EXPERIMENTAL CONDITIONS

VI.1. Introduction

The field strength (potential gradient), E , between two electrodes is given by the expression

$$E = V/h \quad \dots (29)$$

where V is the potential difference (volts) between the electrodes and h is the electrode separation (metres).

High intensity fields may therefore be obtained by combining large voltages with small electrode spacing.

The maximum potential which can be sustained by laboratory equipment is generally in the range ten- to one hundred-thousand volts, the source used in this study being capable of maintaining a constant, open-circuit potential of a little over thirty thousand volts with respect to ground.

(As a safety precaution the unit was designed to switch off automatically if current flow, due to shorting, exceeded 5.5 mA.)

It was estimated earlier (page 53) that a field strength of the order of 10^8 V/m would be required to initiate cracking in quartzite. However, structural failure (spontaneous 'falling apart' of the rock particles), by analogy with thermally

generated stress systems, could not be expected without the application of a very much stronger field. As, with the available equipment, a field of 10^8 V/m could only be achieved with an electrode spacing of $(3 \times 10^4 / 10^8) = 3 \times 10^{-4}$ m, 0.3 mm, it was evident that piezoelectric stresses could not be regarded as the sole means of comminution. Consequently, it was decided to adopt a procedure which permitted conventional crushing of closely sized particles whilst subjecting them to an electric field. The chosen technique, based on that advocated by Carey and Stairmand (1952) and discussed earlier, permitted the mechanical energy input to be measured and related to various product parameters in order that changes effected by different field conditions could be determined. It was decided to carry out the preliminary tests in air as subsequent handling and analysis of crushed products would be facilitated. (The choice of product analysis techniques is described in Chapter VIII.) It was felt that these considerations at this stage outweighed the limitation on field strength imposed by the breakdown strength of air, approximately 3×10^6 V/m (Weast, 1972).

VI.2: Apparatus

a) General Assembly

In the Carey and Stairmand procedure particles are crushed between steel plates (platens) and the work done on the particles determined from the area under the recorded load-deflection curve, a correction being applied to allow for elastic deformation of the apparatus. A similar method was adopted in this study, although modifications to both apparatus and procedure were made as necessary.

The essential features of the equipment, shown in Figure VI.1, are a crushing cell (1) mounted in an Instron Universal testing machine (2) and connected to a high voltage source (3). Also seen in the photograph is an automatic integrator (4) which superseded the use of chart recorder load-deflection curves in later stages of this research. To guard against possible violent mechanical failure of the crushing cell the operator was protected by a shaped plexi-glass door which, as a further precaution, tripped a micro-switch. This caused an audible warning to be given if the H.V. unit was switched on while the door was open.

b) The Instron

The Instron machine was capable of delivering loads

FIGURE VI.1.

The Apparatus

1. Crushing Cell
2. Instron Testing Machine
3. High-Voltage Source
4. Instron Integrator



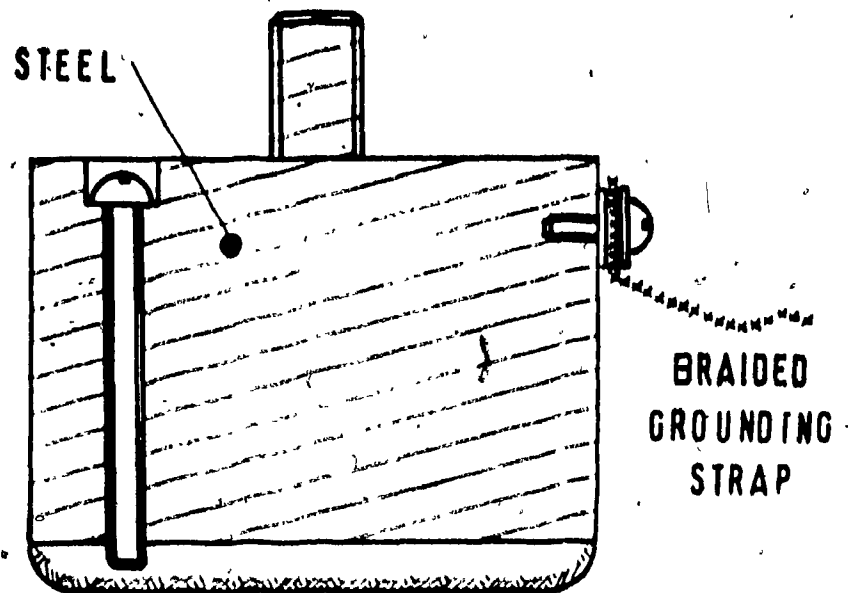
of up to twenty thousand pounds with cross head speeds of 0.02 - 20.0 inch/minute. (As the machine was calibrated in English units these were used in the practical stages of the work and subsequently converted into S.I. units). The chart recorder had the same range of speeds as the cross-head. Using a 'GR' range universal load cell, full scale deflection was adjustable to correspond to an applied load of 0.5, 1.0, 2.0, 5.0, 10.0 or 20.0×10^3 pounds force.

c) The Crushing Cell

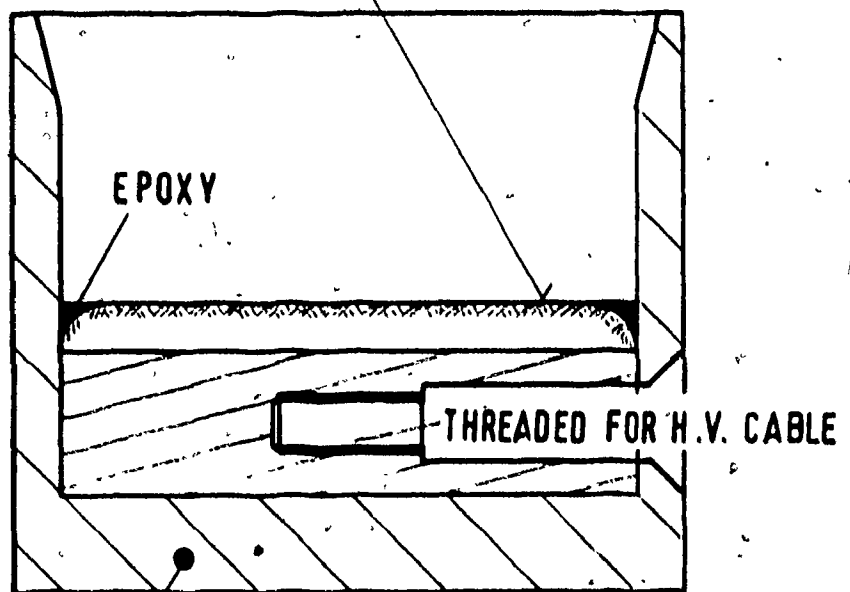
The first cell constructed (Figure VI.2.) consisted of two three inch diameter stainless steel blocks, each faced with hardened steel plates (Rockwell C60) to prevent indentation and the consequent energy losses of plastic deformation (Bradley et al., 1972). The lower block, which was insulated on the bottom and around the sides with plexi-glass, rested on the Instron load cell and was connected, via a screw-in sheathed cable, to the high voltage source. A cylindrical container was provided for crushed products by extending the insulation approximately two inches above the crushing face. The upper block was screwed into the movable cross head of the testing machine and grounded by means of a braided copper strip.

FIGURE VI.2.

The Steel-faced Crushing Cell



FACE HARDENED STEEL
(ROCKWELL C 60)



PLEXIGLASS

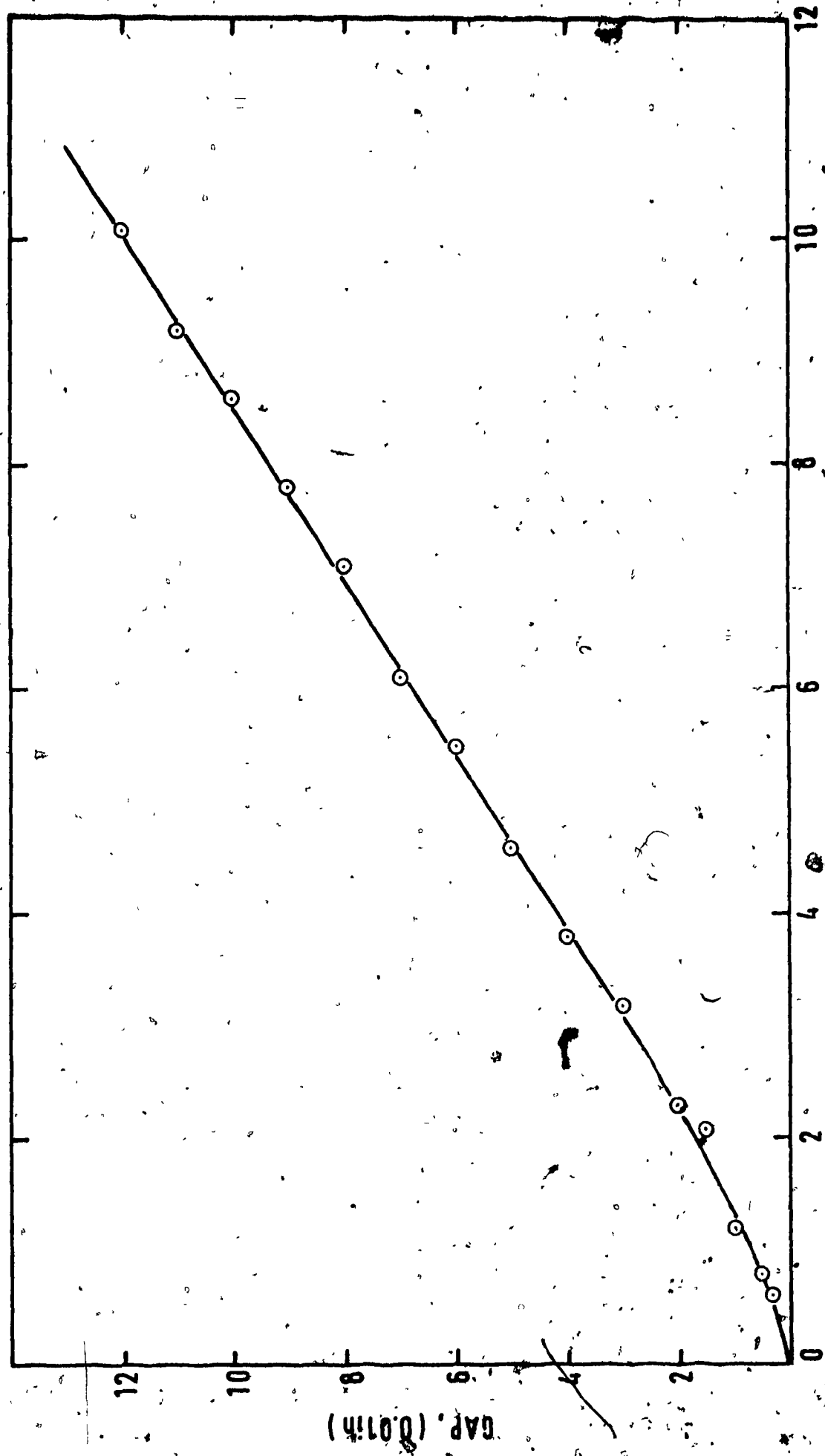
In order to reduce the tendency for arcing from sharp angles, the edges of both crushing faces were rounded as indicated, this shape approximating the ideal form recommended by Stephenson (1933) for the development of a uniform field. A determination of the voltage at breakdown for a range of electrode separations, shown graphically in Figure VI.3., indicated the success of this precaution and served also as a check on the instrumentation. When first tested with quartzite particles, however, it was found that, despite the non-conducting nature of the mineral, arcing occurred at considerably lower applied potentials than had been achieved with the empty cell. This phenomenon, which was attributed to a concentration of charges at projections on the irregularly shaped mineral particles, prevented any meaningful testing with the cell. (Yigit et al., 1969, report an analogous preferential tracking via mineral particles in electrohydraulic crushing.)

d) Alumina-faced Cell

In order to avoid the problem of arcing, two alternative modifications were considered; the use of an insulating medium in place of air, or the addition of adequate insulation in series with the crushing zone to preclude current flow. The use of suitable fluids would give rise to product handling difficulties however, and such an approach would

FIGURE VI.3.

Electrical Breakdown Characteristics of the
Steel Faced Cell



INDICATED BREAKDOWN, KV (EMPTY CELL)

GAP, (0.01 in)

also be unsuitable in planned tests with the conducting or semi-conducting minerals hematite and sphalerite. The second solution was therefore adopted.

With an insulator in series with the crushing zone the potential difference generated by the voltage source is divided between what are effectively two capacitors, C_1 and C_2 , as indicated in Figure VI.4.

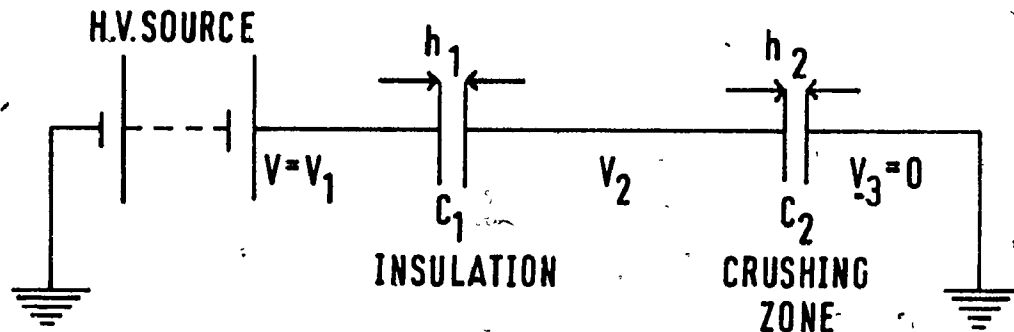


Figure VI.4. Capacitors in Series

The voltage drop across the 'i'th capacitor in a series of n capacitors is given by the equation

$$V_i = (Vh_i) / \left(\epsilon_i \sum_{m=1}^n (h_m / \epsilon_m) \right) \quad \dots (30)$$

where V is the overall applied potential, and h and ϵ are thickness and relative dielectric constant, respectively, of the capacitor indicated by the subscript.

This equation may be rearranged (Cotton and Burt, 1966) and contracted to give the potential gradient in the crushing zone (capacitor C_2) as

$$E_2 = V_2/h_2 = V/(\epsilon_2 (h_1/\epsilon_1 + h_2/\epsilon_2)) \quad \dots (31)$$

Thus to obtain maximal potential drop across the crushing zone it was desirable to use an insulating layer of minimum 'effective thickness', h/ϵ . In order to facilitate calculation of the field in the crushing zone it was also preferable to use an insulator which would not deform significantly under load. Ceramic materials met these requirements best and 99% alumina (Al_2O_3 ; $\epsilon = 9.5$) was chosen. This material has the further advantage of exceptional hardness. Ferreira et al. (1970) give a hardness value for alumina of 1700 - 2000 on the Knoop hardness scale, similar to that of tungsten carbide (1800). Diamond has a value of 6500 - 10,000 on this scale while Rockwell C60 (the hardness of the steel platens first tested) is equivalent to Knoop 732. Quartz, the hardest mineral encountered in this study, has a Knoop hardness of 820. In the initial testing with the quartzite it had been noted that the steel platens became indented, despite being hardened. Although the resultant energy losses were probably insignificant it was evident that an alumina ceramic would be a superior facing material. A

new cell, shown in Figures VI.5 and VI.6, was therefore constructed in which three inch diameter x 1/8 inch thick alumina discs*, attached with an epoxy cement, replaced the hardened steel faces of the earlier unit. In addition the plexiglass insulation was dished, facilitating particle handling, and the screw connection for the high voltage cable was replaced with a banana plug. The H.V. socket was mounted as shown in a locating guide fastened to the load cell platen. To reduce the likelihood of arcing at the edges, the corners of both stainless steel blocks were chamfered and the annular groove filled with epoxy resin.

Despite this last precaution, arcing was found to occur with voltages in excess of about 16 kV when the alumina plates were brought into close proximity. Several attempts to provide complete insulation by renewing the epoxy seal and by replacing it with other sealants proved unsuccessful at the time as cracks which formed when a load was applied were sufficient to provide an electrical path. The limitation on the applied potential was considered acceptable at this stage, however, and the unit was used in the initial tests as described below.

* Coors Porcelain Co., Golden, Colorado. Grade AD99, 99% Al₂O₃.

FIGURE VI.5.

The Alumina-faced Crushing Cell

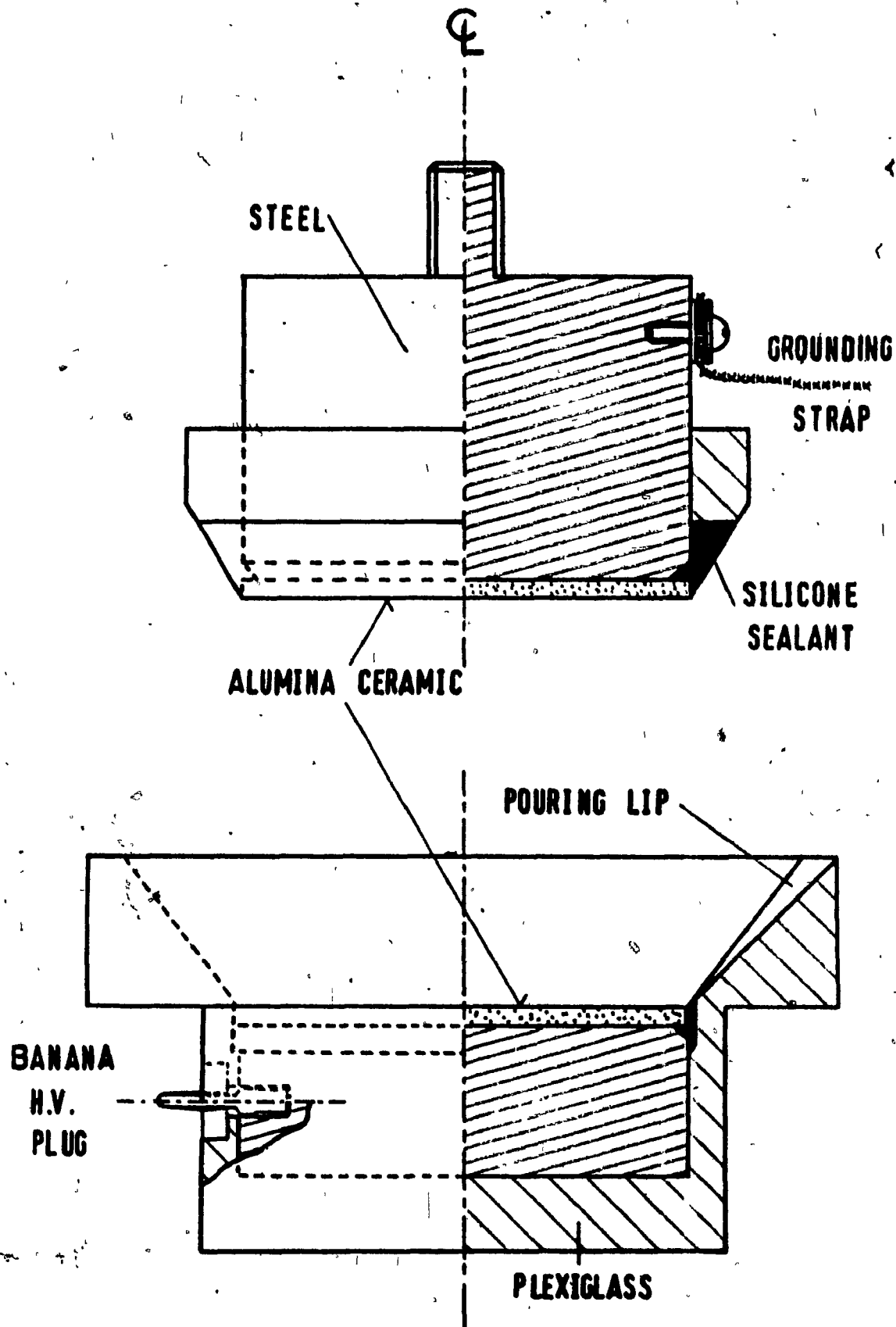


FIGURE VI.6.
The Alumina-faced Crushing Cell
(Photograph)



e) High-voltage source

Full specifications of the high-voltage source are given below, Table VI.1.

Manufacturers:	Kilovolt Corporation 238 High Street Hackensack, N.J., U.S.A.
Model No.	KV30 - 5DMS
Output voltage	0 - 30 kV
Rated current	5 mA
Input voltage	115 V, 60 Hz
Input current	2 A at rated load
Output polarity	Reversible*
Regulation	20% NL/FL
Ripple	2% R.M.S.
Overload relay	5.5 mA, fixed
Meters	0 - 30 kV 0 - 5 mA

* Used positive w.r.t. ground.

Table VI.1. High-Voltage Source Specifications

VI.3. Preliminary testing

Optimal operating parameters were determined in preliminary tests. Variables considered were the weight and particle size of feed material, crushing rate, maximum applied load, and chart speed.

a) Feed size

In order to obtain maximum accuracy in product

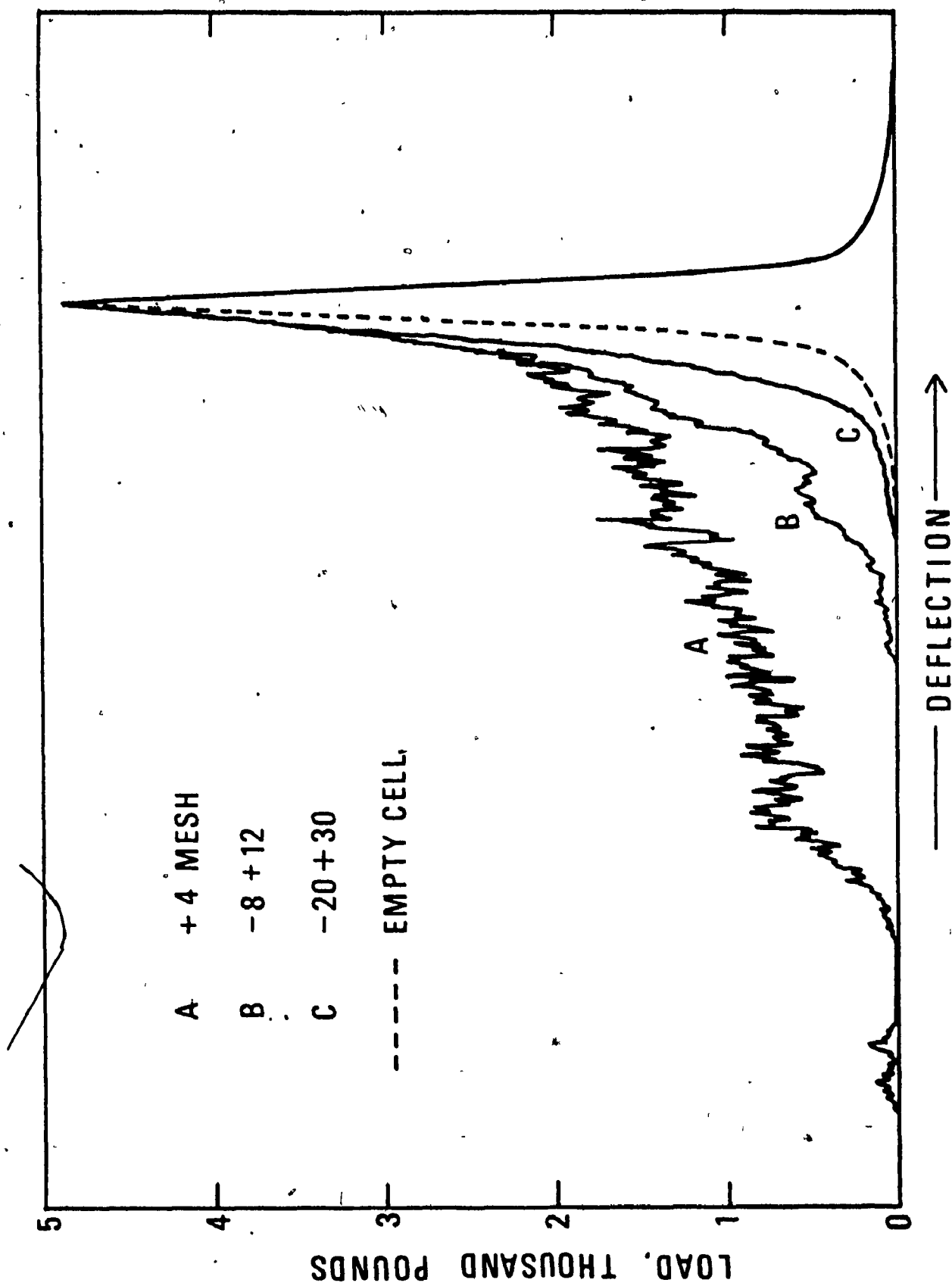
analysis it was desirable to use as large a feed sample as possible, both in terms of particle size and in total weight. To be balanced against this requirement were the considerations that i) large particles would limit the initial field strength due to the greater electrode spacing, ii) large samples would reduce the reduction ratio range before packed bed conditions became objectionable, and iii) large particles would give rise to highly irregular load-deflection curves, reducing the accuracy of integration. Figure VI.7. illustrates the last point for quartz particles. As a compromise, the use of -8 +12 mesh material was adopted. Sample weights (taken proportional to specific gravity to maintain a constant volume for different materials) were based on the amount which gave a well-spaced layer of particles over the crushing face. This was found to correspond to approximately 0.7 ml true volume.

b) Crushing rate

With particles of the chosen size (about 0.1 inch diameter) a cross head speed of 0.1 inch/minute was adopted. Due to the 'softness' (uncompensated elastic deformation) of the Instron the crushing rate experienced by the particles, initially corresponding to the cross head speed, became progressively lower throughout a test. In order to maintain

FIGURE VI.7.

Particle Size Effect on Load-Deflection Curves



a constant relative velocity of the crushing faces consideration was given to the incorporation of a feed-back loop actuated by a velocity transducer or differentiated strain gauge signal to drive the variable-speed motor of the cross head. The Instron is particularly unsuitable for this type of control, however, especially at the low head speeds used in this study, but a comparison of the load-deflection curves for several samples of each material showed that the encountered variation was consistent from sample to sample and was therefore acceptable.* A typical set of results is given in Figure VI.8.

c) Applied load

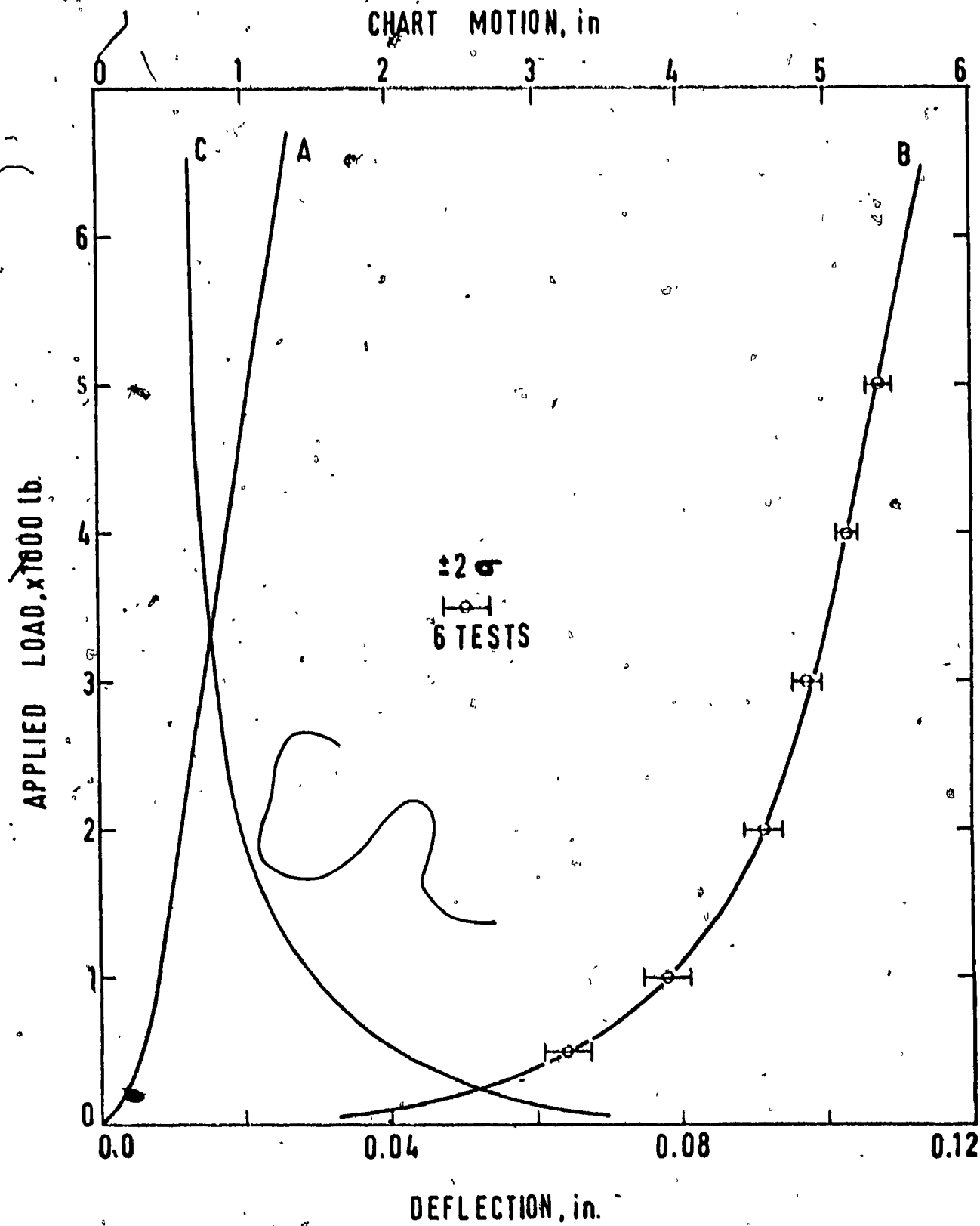
The establishment of packed-bed conditions can also be inferred from Figure VI.8. as the interfacial distance can be seen to approach a minimum asymptotically with increasing load, corresponding to the bedding down of particles into a compact of low porosity. The maximum useful load was dictated by the approach of this limit, being 5-6000 lbs for quartzite (Figure VI.8.).

* A computer-linked M.T.S. universal tester, which exhibits infinitely hard characteristics, is now in use in the department and would provide great advantages in any future study involving rock particles.

FIGURE VI.8.

Typical Load-Deflection Curves

- A) Indicated Load-Deflection Curve,
Empty Cell
- B) Indicated Load-Deflection Curve,
Quartz Particles
- C) Separation of Crushing Faces



d) Chart speed

In order to determine the work done in the preliminary tests the area under the load-deflection curve was determined by counting squares. A chart speed of five inches per minute was chosen as this gave adequate precision without excessive, potentially erroneous counting.

VI.4. Energy losses in elastic deformation of apparatus

Due to the elastic deformation of the apparatus (Instron drive train and crushing cell) some of the work done in the crushing operation was not available for comminution. The load-deformation curve of the apparatus with the cell empty has been given earlier, in Figure VI.8. (curve A). It was found that the unloading curve was the mirror image of curve A (Figure VI.9.). Thus, although Hooke's law was not obeyed, the deformation could be regarded as elastic in that work done by the Instron while loading the empty cell (area A) was totally recovered on unloading (area B). To permit subsequent corrections for the work done in loading the apparatus, a total area (A + B) was determined for a number of cycles to different peak loads and the equivalent work value plotted against peak load (Figure VI.10.). It is seen that this curve did not change

with time, nor was the signal from the load cell affected by the electrical field in the crushing cell.

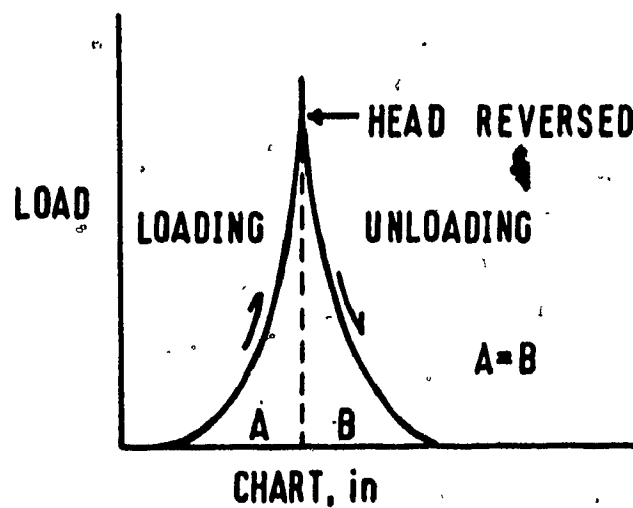
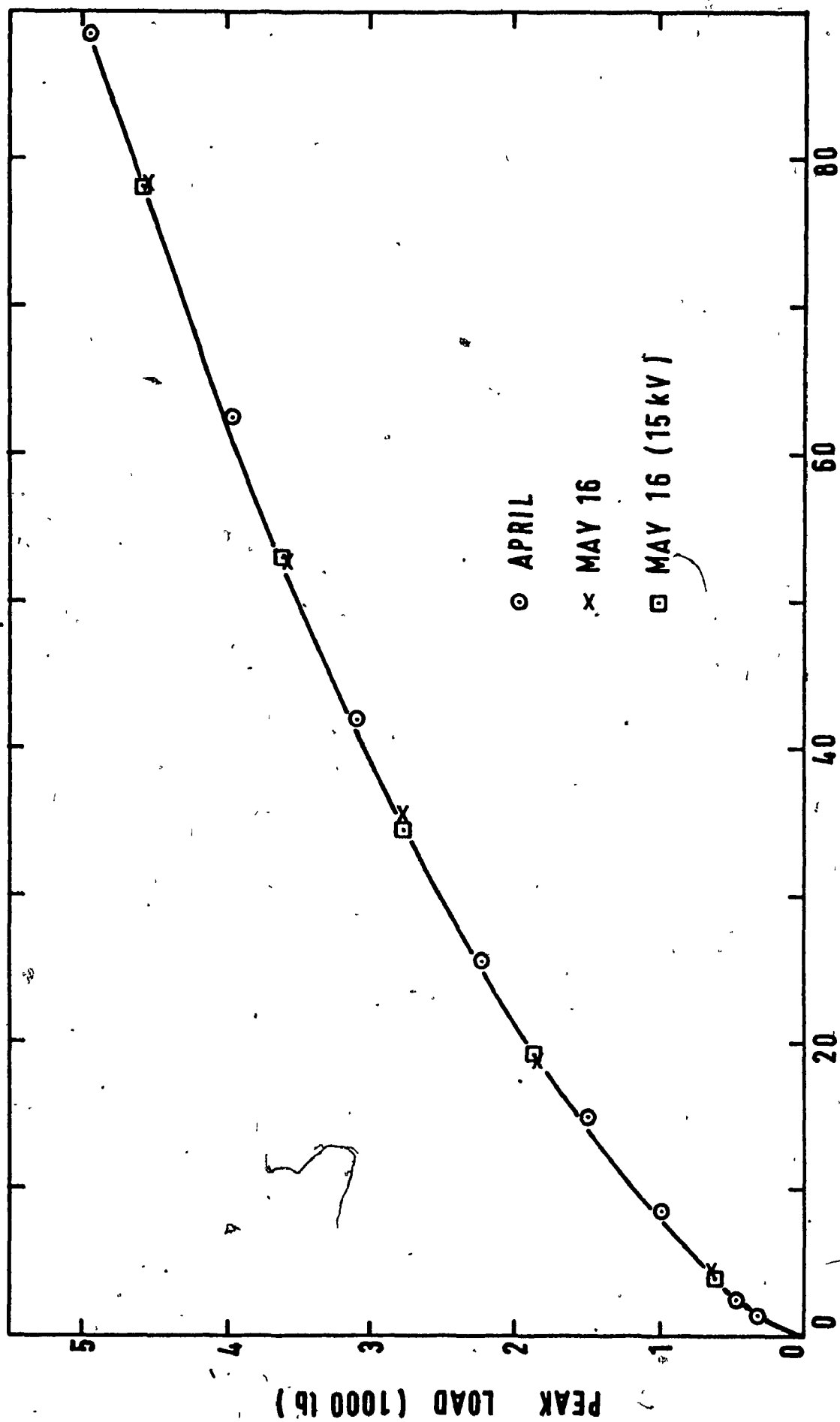


Figure VI.9. General form of the load-deformation curve for the empty apparatus

FIGURE VI.10.**Energy 'Consumed' by Empty Cell**



VII EXPERIMENTAL PROCEDURES - INITIAL TESTS

VII.1. Introduction

The initial crushing experiments were carried out to test the hypothesis that the comminution characteristics of quartz- and sphalerite-bearing rocks would be changed by an electrical field. Only the energy required to achieve a given degree of crushing was considered at this stage and experimentation was limited to two materials, quartzite and sphalerite. It was not feasible to run the tests to a prescribed level of mechanical work input, due to the irregularity of the load-deformation curves and to the uncertainty (during the course of the test) as to the relative amounts of work effective in crushing and in deforming the apparatus. Thus it was not possible to compare directly products of crushing operations differing only in the electrical field conditions. This was not a real disadvantage, however, as the conditions under which a field effect might be most pronounced were not known so that it was preferable to carry out experiments over a wide range of mechanical energy inputs and compare the results for different field conditions graphically.

VII.2. Crushing procedure

The following procedure was used in the crushing experiments. A sample (approximately 1.75 g of quartzite or 2.65 g of sphalerite) was spread evenly on the lower crushing platen and the upper crushing head lowered manually until almost touching the particles. The zero and calibration points of the chart recorder were checked and the load cell range set to the lowest value (highest sensitivity) compatible with the intended maximum load for the particular test. For those tests in which a field was to be applied, the high voltage source, preset to the chosen value, was switched on. Chart-recorder and cross-head drives were started, at 5 and 0.1 inch per minute respectively, and crushing continued until a predetermined load was reached, at which point the head was reversed manually and the voltage source switched off. The chart was allowed to continue running until the indicated load returned to zero. The crushed product was then brushed into a numbered vial and retained for subsequent size analysis. Care was taken to recover particles adhering to the upper platen. A series of tests were carried out to a range of peak loads up to the predetermined limit with both zero and

15 kV applied potential.

VII.3. Determination of Unit Work

The amount of energy effective in causing size reduction was determined from the load deflection chart. Figure VII.1. shows the general form of chart record.

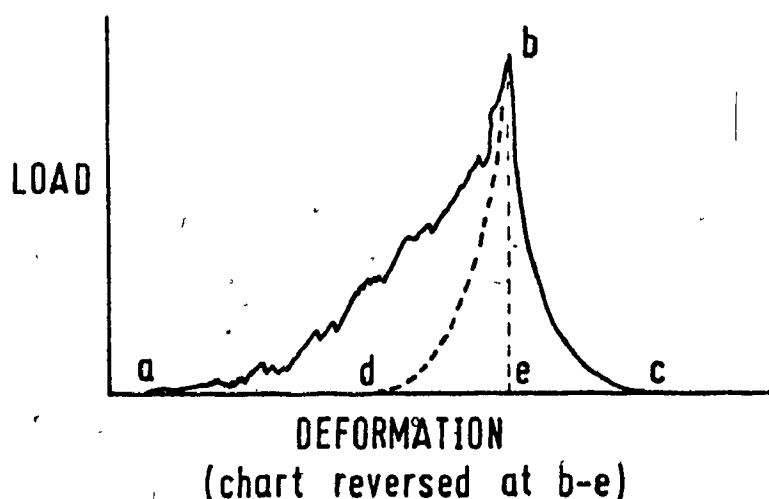


Figure VII.1. General Form of the Load-deformation Curve for a Crushing Operation

The area 'abeda' is a measure of the total work done by the Instron during loading. Area 'bceb' represents recovery of elastic energy of deformation. It has been shown earlier that area 'dbced', symmetrical about b-e, is obtained with an empty cell. A graph of energy values corresponding to this area plotted against peak load was given in Figure VI.10. The energy absorbed by the mineral

particles, proportional to area 'abda', was thus conveniently calculated by counting squares to obtain the entire area 'abceda', converting into an equivalent energy value by use of the appropriate factor* and subtraction of the energy equivalent to area 'dbced', read from graph VI.10.

To provide a uniform basis for comparison a Unit Work value (in.lb/g) was determined by dividing the amount of energy absorbed in crushing by the sample weight.

VII.4. Particle size analysis

The crushed products ranged in size from that of the feed (mean diameter 2 mm) to dust, although the sub-sieve fraction was seen to be very small even with material subjected to the highest unit work. Laws et al. (1963) give an exhaustive classification of particle-sizing methods. Four basic methods were given serious consideration: sedimentation techniques, surface area measurement by adsorption or permeability, microscopic examination utilizing a Quantimet image analyzing computer, and sieving. Sedimentation techniques were ruled out due to the large size

* e.g. For 1000 lb. Full Scale Deflection, 5"/min. chart speed and 0.1"/min. cross-head speed, 1 sq. in. of chart = (0.1/5)in. x (1000/10)lb. = 2.0 in.lb.

range, which effectively precluded single stage treatment, and the possibility of subsequent work with ores containing minerals of differing densities. Similarly, surface area determination was judged unsuitable as adsorption measurements are relatively insensitive to changes of size in the coarser range, and the permeability method is only applicable to the finer sizes. In addition, no information is given about the particle size distribution, only a measure of mean size. Unbiased sample preparation for microscopic examination would be exceptionally difficult with the low weights and wide size distribution of the crushed samples and a series of measurements would again be required to cover the full size range. Consequently, this method was rejected and the fourth procedure, screen analysis, was adopted.

In order to minimize fines losses, which would be especially significant with the small samples available, an Allen-Bradley Sonic Sifter* was used. This precision screening instrument consists of a column of interchangeable standard screens of three-inch diameter mounted in nesting plexiglass frames. Top and bottom of the column are closed with a thin rubber diaphragm, the lower one shaped to act as a fines collector. A 60 Hz acoustic pulse, generated by a

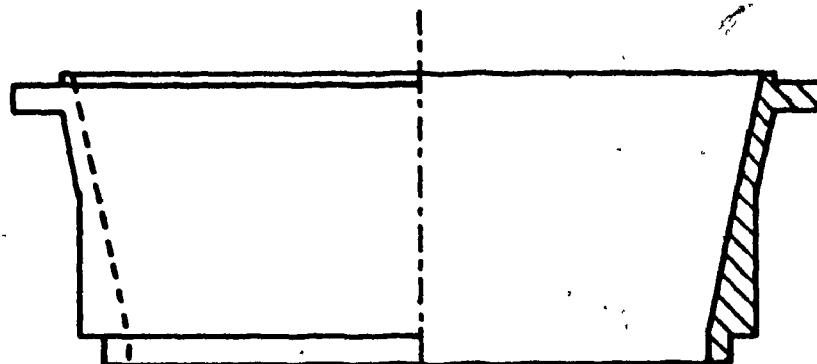
*Allen-Bradley, Milwaukee, Wisconsin, U.S.A.

mains-connected speaker, applied to the upper diaphragm causes the air in the column to oscillate vertically, rapidly carrying undersize particles through the screens. A periodic mechanical shock frees pegged particles. The amplitude of both the mechanical shock and the air pulsation can be controlled. A mid-range setting was found suitable for both controls and was standardized throughout the test work. As supplied, the apparatus is constructed to accept a maximum of six screens. By redesigning an upper connecting ring this number was extended to seven during the first stage of the work and to eight in the subsequent stage. Both these modifications are shown in Figure VII.2. Although the manufacturers claim that screening is complete in less than a minute, the instrument is equipped with a timer extending to sixteen minutes. A standard time of eight minutes was adopted as this fitted conveniently into the routine.

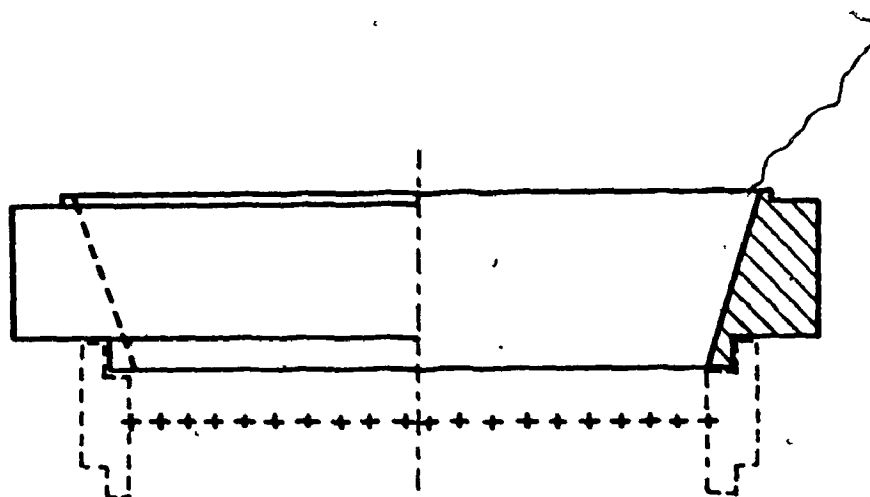
Screens in the $\sqrt{2}$ series were used and an attempt was made to choose an appropriate range for each crushed sample such that the upper screen passed approximately 70% of the material. This was done in order to obtain the maximum number of points on the straight line section of a Schuhmann plot, as described in Appendix I and in Chapter VIII.

FIGURE VII.2.

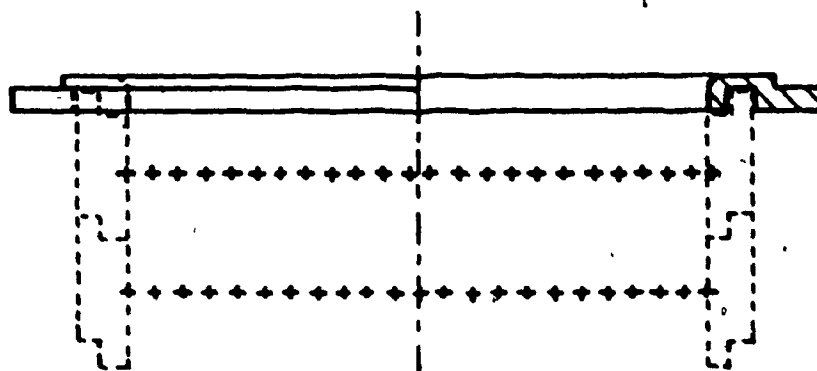
Modifications to the Allen-Bradley Sonic Sifter



TOP CONNECTOR - STANDARD



FIRST MODIFICATION - ONE EXTRA SCREEN



SECOND MODIFICATION - TWO EXTRA SCREENS

VIII. RESULTS AND DISCUSSION OF INITIAL TESTS

VIII.1. Results

Data from the screen analyses are tabulated in Appendix VI.1. Schuhmann curves were prepared from these data by expressing weights as percentages of the total and plotting the cumulative weight per cent passing each screen, Y, against the nominal screen aperture, X, on log-log paper. The results are shown in Figures VIII.1.-4. It can be seen that i) the experimental points are reasonably fitted by straight lines over an extended range, ii) the gradients of these straight lines remain constant for any one material, and iii) no change in gradient resulted from the application of an electrical field during crushing. It follows from this last observation that no appreciable change in the width of product size distribution was effected by the applied field and, specifically, that no reduction in the relative percentage of fines had been achieved. However, the constancy of gradient permitted use of the Schuhmann size modulus, K (i.e. the X value of the extrapolated straight line at Y = 100% passing) as a measure of the degree of comminution. These values have been plotted against unit work in Figures VIII.5. and 6.

FIGURE VIII.1.

• Schuhmann Plot, Quartzite, Zero kV

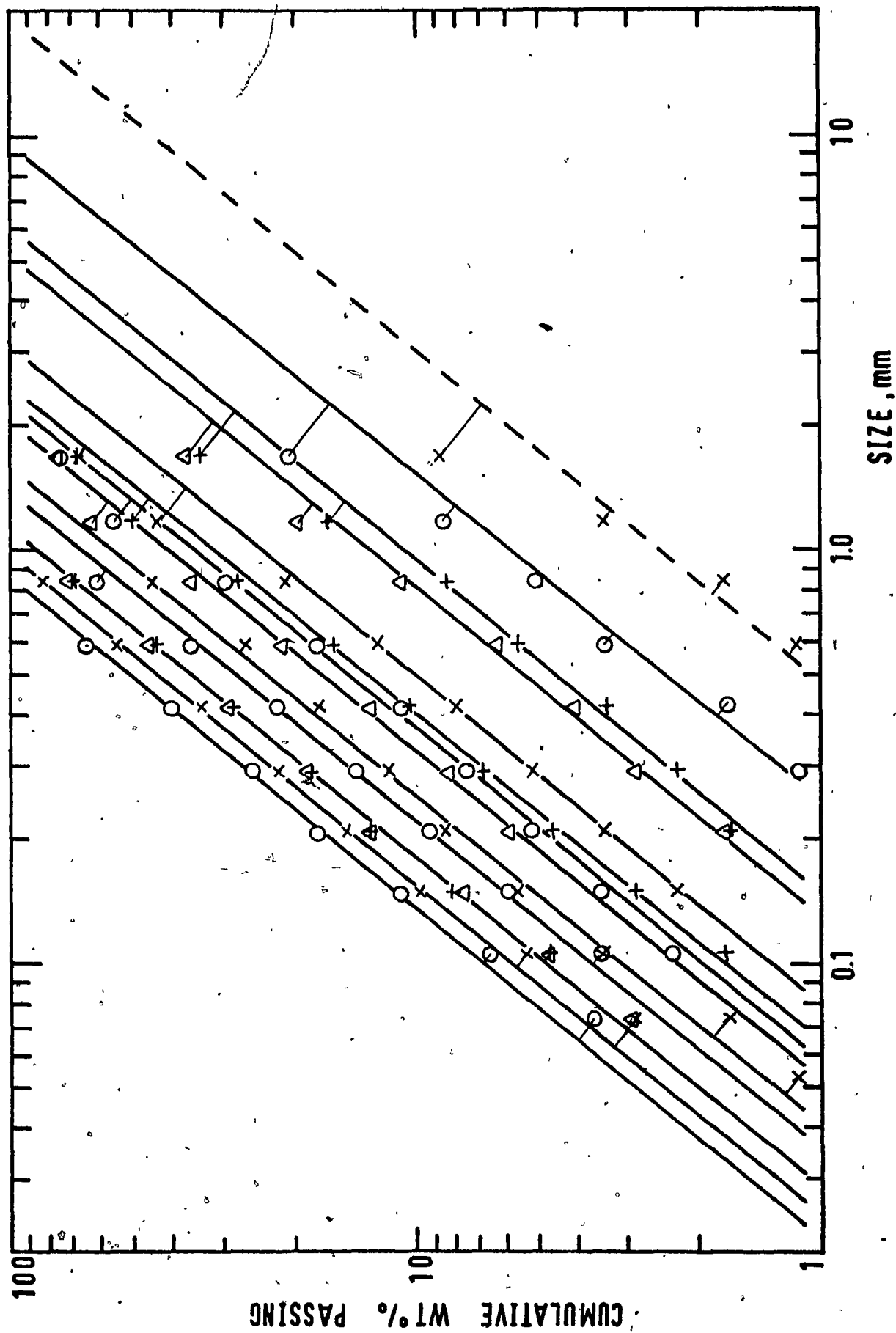


FIGURE VIII.2.

Schuhmann Plot, Quartzite, 15.0 kV

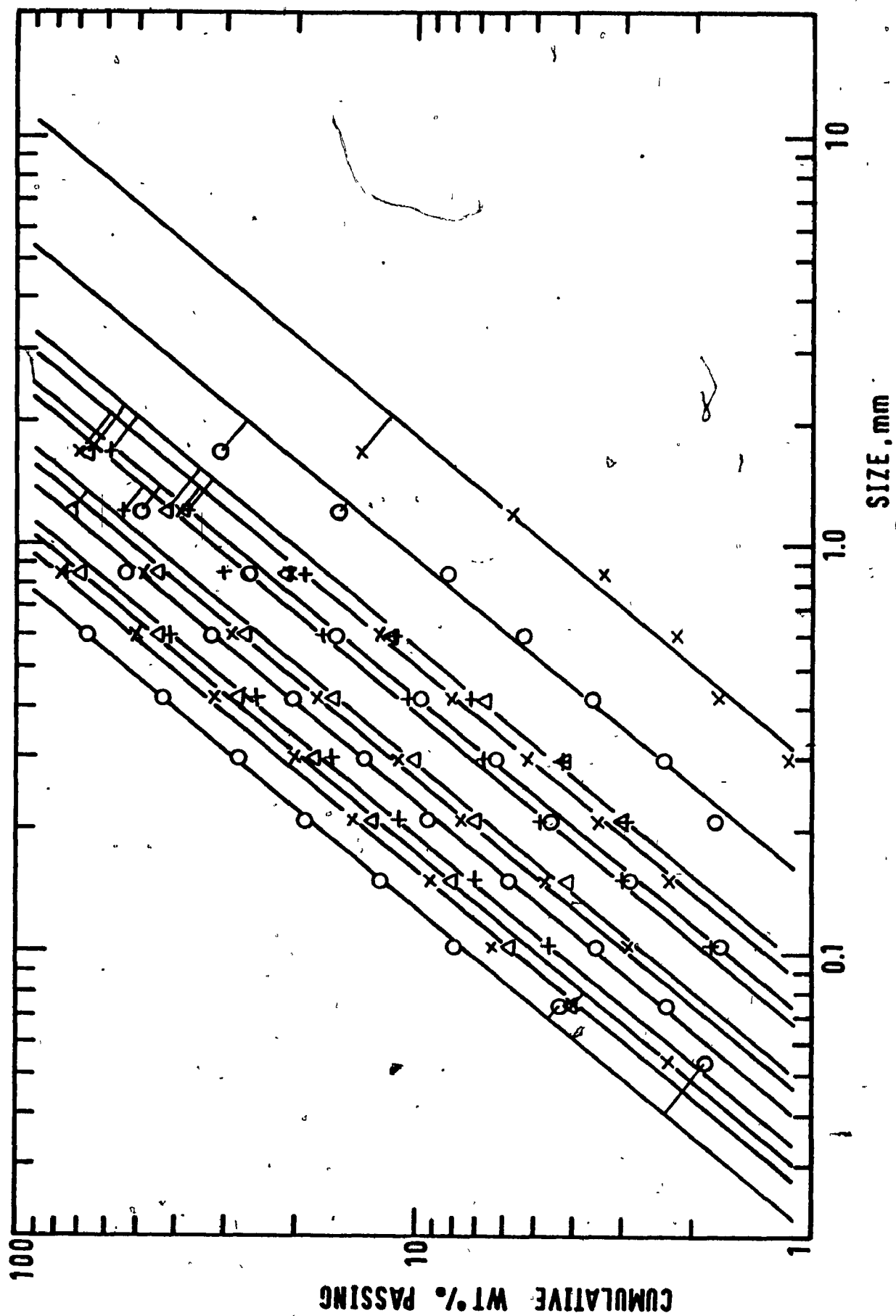


FIGURE VIII.3.

Schuhmann Plot, Sphalerite, Zero kV

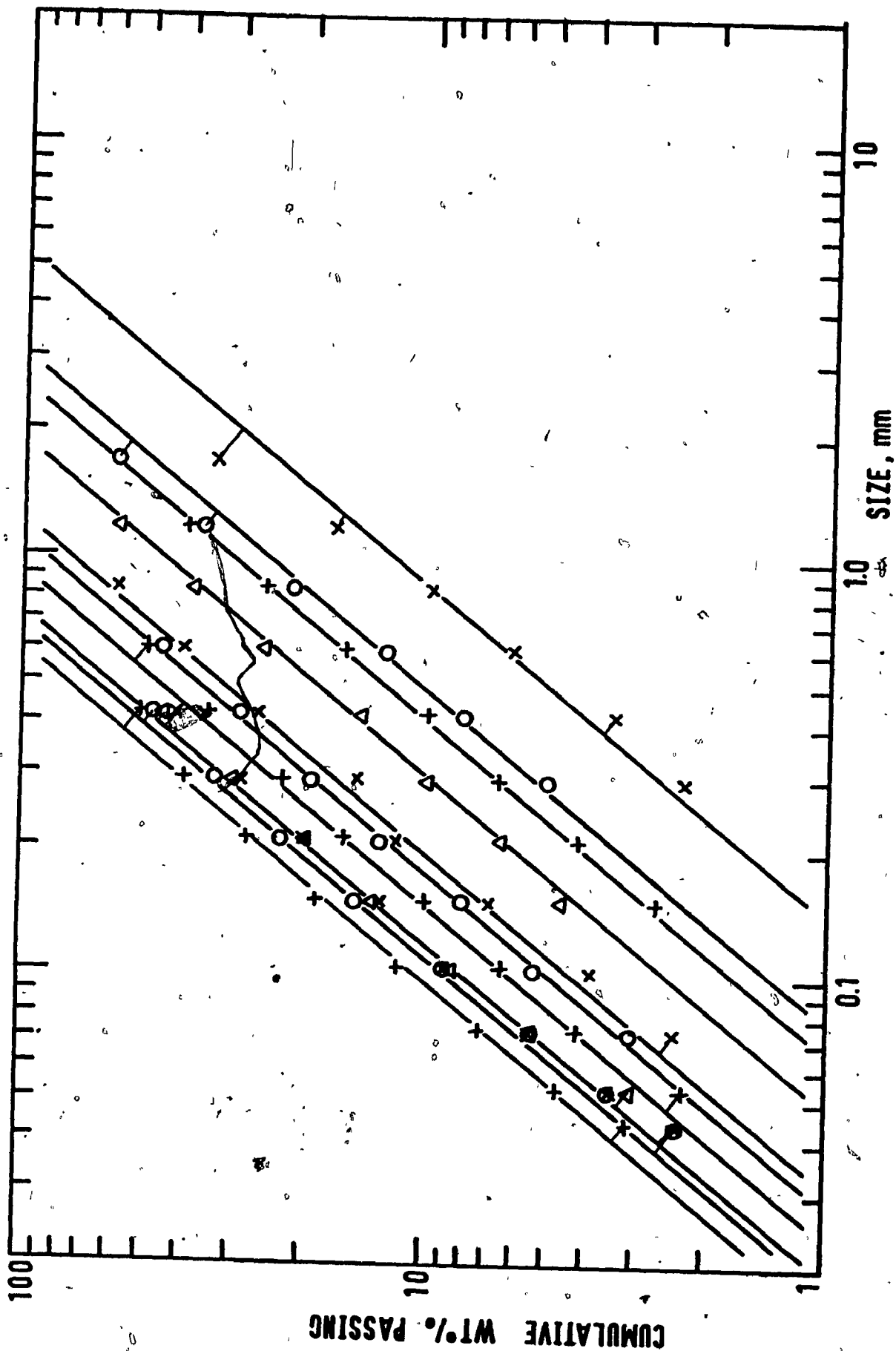


FIGURE VIII.4.

Schuhmann Plot, Sphalerite, 15.0 kV

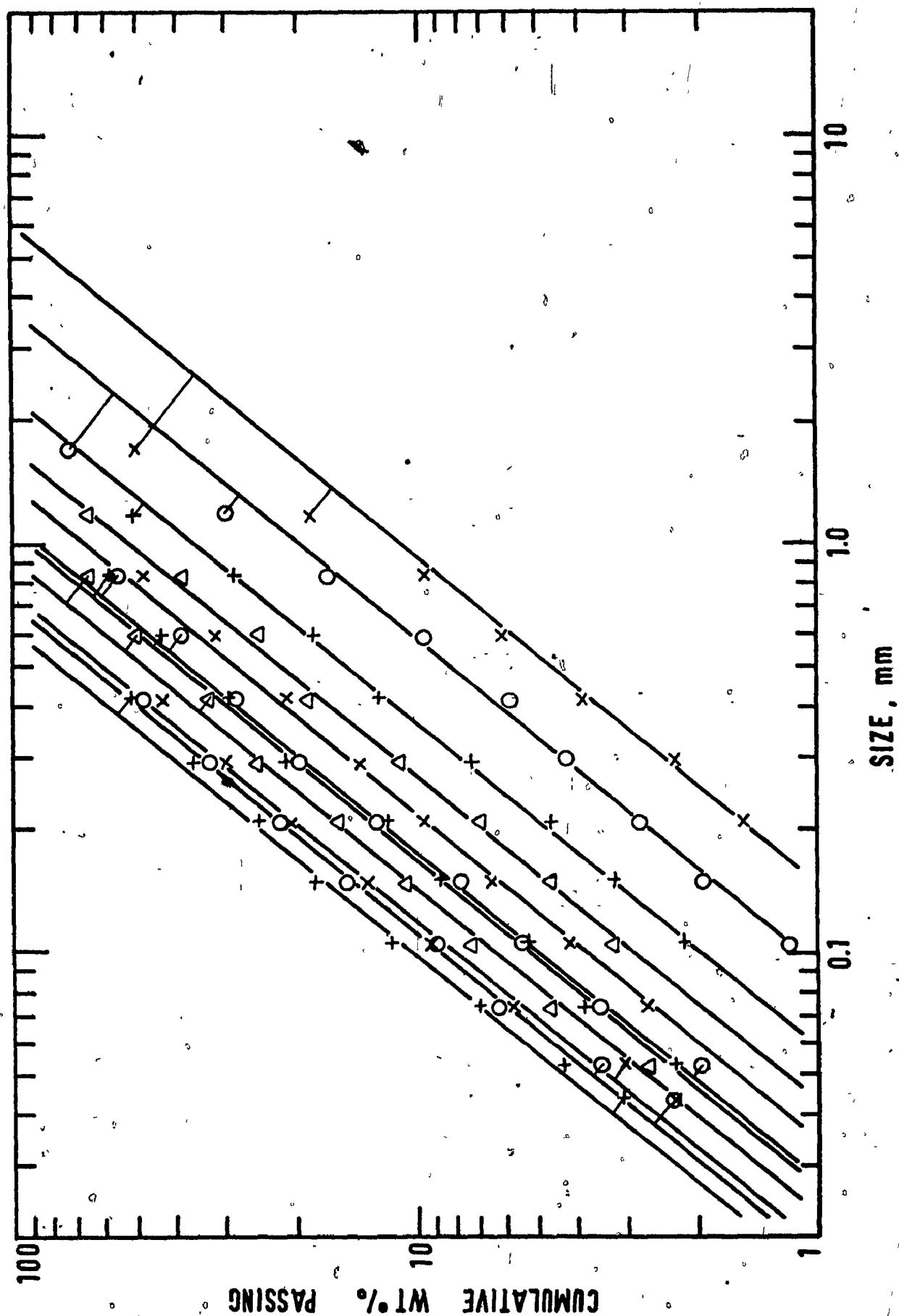


FIGURE VIII.5.

Schuhmann Size Modulus vs. Unit Work:

Quartzite

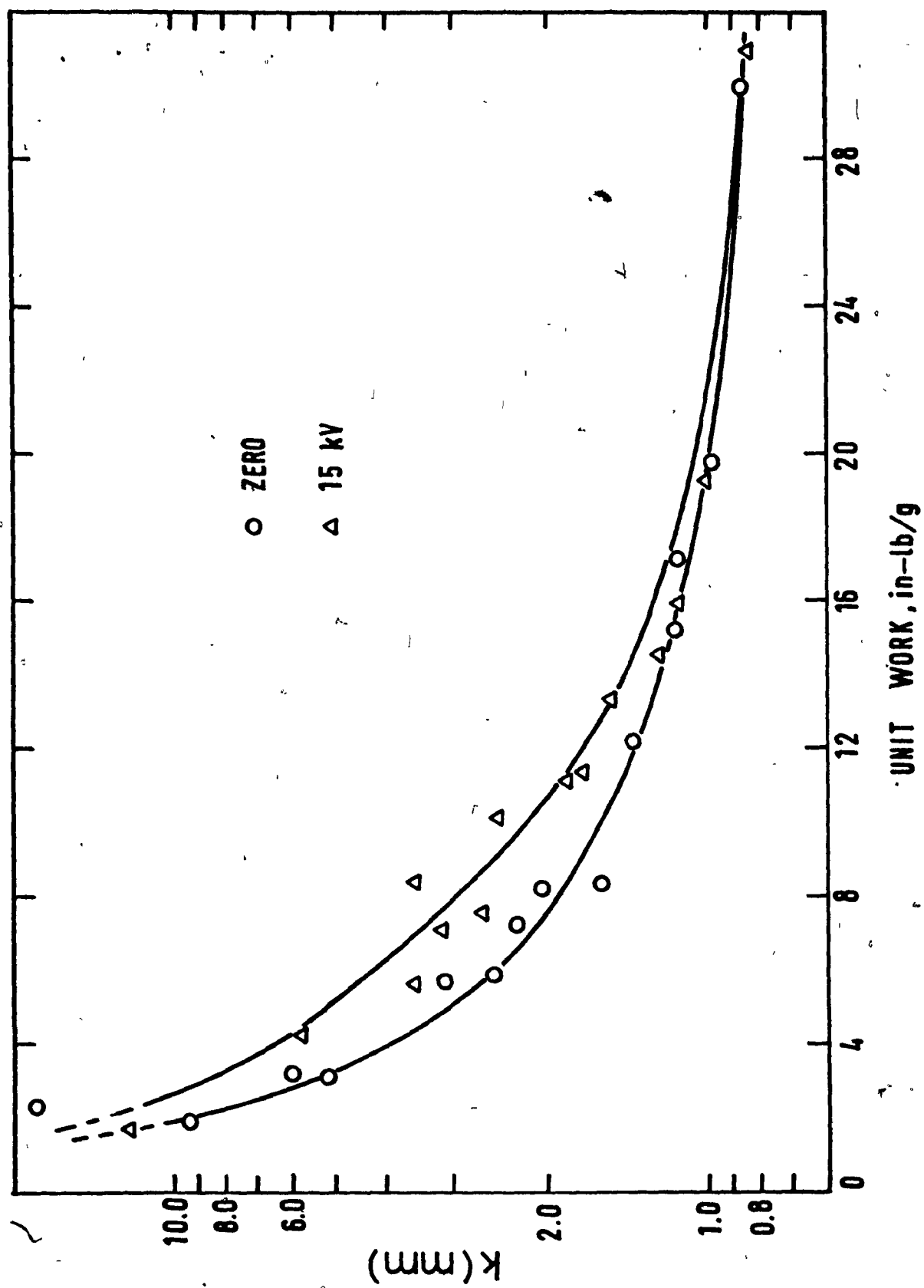
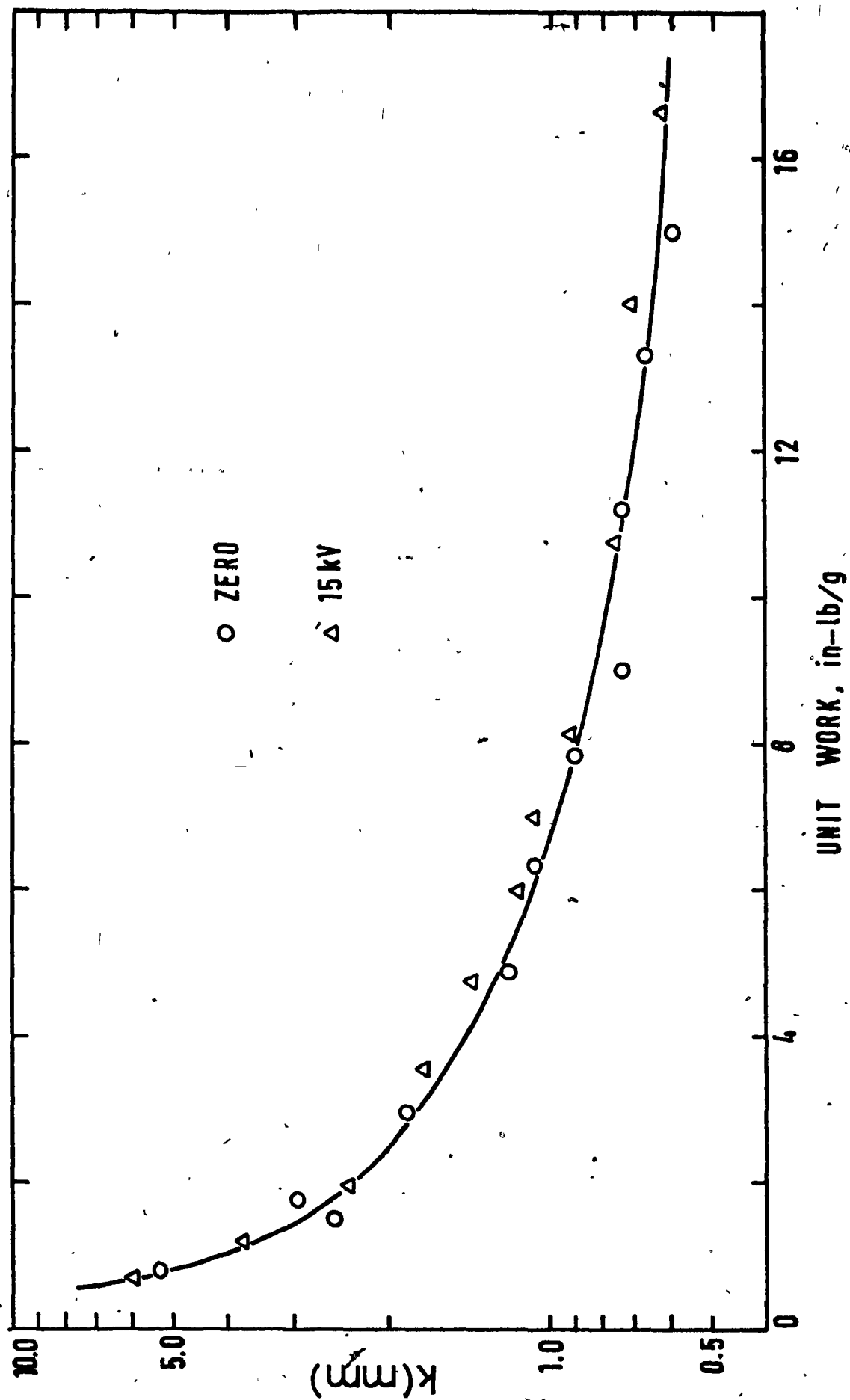


FIGURE VIII.6.

Schuhmann Size Modulus vs. Unit Work

Sphalerite



The difference between the two sets of curves due to the difference in strength of the two materials will not be considered here, only those changes effected by the application of an electric field being of immediate concern. The two graphs are similar in general form, comminution efficiency (indicated by the rate of change of size modulus with respect to unit work) being at a maximum in the early stages of crushing and approaching zero at high values of unit work. No difference between the results obtained in the absence of an electrical field and those obtained with an applied field are discernable in the case of sphalerite but a clear difference is evident with quartzite. Contrary to the predicted results, however, the presence of an electric field gave a decrease in crushing efficiency. This difference is most noticeable in the middle of the experimental range, the mechanical energy required to obtain a product of specified size modulus being up to fifty per cent greater in the field resulting from an applied potential of 15 kV as in zero field. At high values of unit work the two curves converge, becoming indistinguishable at unit work values above about 20 in.lb/g. The curves also appear to be converging in the low unit work region but the determination of size modulus for such samples is unreliable as the Schuhmann plots tend to diverge

considerably from linearity. Furthermore, even though the curves approach in absolute terms, the relative difference may remain high.

VIII.2. Discussion

It is not intended to give an exhaustive discussion at this point but rather to attempt to present the considerations which led to the second stage of the experimental work.

VIII.2.1. Sphalerite

The piezoelectric effect was known to be lower in sphalerite than in quartz and to involve only a shear stress or strain. Nevertheless it had been expected that the effect would be at least as significant with this mineral as with quartz due to the lower intrinsic strength of sphalerite. Microscopic examination of a section through a sample of the feed particles showed that this particular material was essentially monocrystalline however (as described in Section V.c.). Consequently, although piezoelectric strain would occur and might result in a change in mineral strength, the 'misfit' mechanism on which the original hypothesis was based could not be effective. Further tests were therefore planned

using a fine grained polycrystalline sample.

VIII.2.2. Quartzite

The results of the experiments with quartzite were unexpected but, although disappointing in that no practical advantage was indicated, were of considerable interest. It was thought that the apparent strengthening effect of the electric field might be accounted for by a relaxation of stresses locked into the structure. That is, if the quartzite structure were in a state of stress in its natural condition, and the stresses became relaxed by the action of the electric field, an apparent strengthening would be observed. Elastic stresses in quartz grains are indicated in thin section by the presence of undulose extinction, a wave-like dark band which moves across a grain on rotation between polarizing plates (Moorhouse, 1959). Examination of thin sections of the tested material did indeed reveal this phenomenon (Figure VIII.7.) although it was not clear how the stresses had developed. Friedman (1967,68,72a,b) has made a detailed study of residual elastic stresses in rocks which he attributes to the tectonic history of the material, that is, to deformation caused by movement of the earth's crust. He has evolved a sophisticated X-ray technique to determine the

FIGURE VIII.7.
Quartzite Thin Section
Magnification X36
Showing Undulose Extinction on
Rotation between Crossed Polarizers



magnitude of these stresses and their orientation, which tends to be aligned in a particular direction within the rock, and has shown that the breakage pattern may be dictated by this residual stress system (Friedman and Logan, 1970).

However, it would not be possible for such stresses, oriented with respect to the rock as a whole, to be relaxed by a mechanism operating at the level of the individual grains and oriented crystallographically unless the grains were themselves preferentially (and appropriately) oriented. That this was not the case was seen from the random extinction angles of grains in thin sections.

Apart from the highly unlikely possibility that the quartzite was formed in an intense electric field, the only mechanism by which a stress system oriented with respect to the crystallographic axes of each grain might be developed is that of anisotropic thermal expansion. This was the phenomenon assumed both by Lean and by Daellenbach et al. (see page 30) to explain their observations of an increase in strength in iron ores when heated into the range 300 - 500°C. In each case undulose extinction was reported. Except in that they are both directed with respect to the crystallographic axes, however, the strains due to thermal effects and to the converse piezoelectric effect are quite different.

Nevertheless it was thought possible that an interaction might occur in which residual stresses resulting from the thermal history of the quartzite might, in part, be relaxed by piezoelectric stresses of opposite sense. An evaluation of this possibility is given in the main discussion, Chapter XI, but at this stage it is only necessary to present two corollaries of the suggested mechanism. First, if relaxation of pre-existing stresses does occur, a point must be reached (on increasing the field strength) at which such stresses will be completely relaxed. The material will then exhibit maximum strength. Consequently, further increases in field strength would be expected to result in decreasing material strength, as does heating beyond the equilibrium temperature in the analogous thermal system. Secondly, residual stresses can only exist in polycrystalline materials in which individual grains are constrained by their neighbours (Moorhouse, 1959). It follows that the suggested stress relaxation phenomenon, giving rise to an apparent strengthening, cannot be effective in monocrystalline particles. Further testing was therefore planned, a) to higher field strengths and b) with monocrystalline quartz, in an attempt to investigate these aspects more fully.

IX EXPERIMENTAL PROCEDURES - EXTENDED PROGRAM

IX.1. Introduction

The initial testing had shown that the comminution characteristics of quartzite were modified in an electric field, although no effect was detected with monocrystalline sphalerite. The experimentation described in this chapter was carried out i) to test the hypotheses put forward in the discussion of the initial tests, ii) to extend the study to include an industrially important material, iron ore, and iii) to test a non-piezoelectric mineral, polycrystalline hematite, as a control. Apparatus, procedure and treatment of data were all modified to give greater and more precise information about the effect of the imposed field on comminution.

IX.2. Apparatus

i) Crushing cell

Initial testing had been limited to an applied potential of 15 kV due to the arcing at the edges of the alumina plates which occurred at higher voltages. Attempts to prevent this breakdown had failed due to cracking of the

insulation under load but a renewed attempt using a flexible silicone sealant* now proved successful, permitting the use of voltages up to the 30 kV maximum of the source.

ii) Instron integrator.

The method used in the early testing for determining the work concerned in a crushing cycle was unsatisfactory as no reliable indication of the amount of work done was available during the course of the experiment. In addition, the square-counting technique for chart area measurement was extremely tedious and imprecise. Accordingly, an Instron automatic integrator** was obtained which gave an instantaneous digital read-out proportional to the area under the load-displacement curve. Unfortunately no provision was available to permit automatic correction for elastic deformation of the apparatus and no way of incorporating such a correction was found. However, the integrator was provided with two independent read-out meters by means of which it was possible to determine the work utilized in crushing very simply. By connecting the integrator so that one meter registered during loading and the other during unloading, the readings corresponded to areas

* Dow Corning Silicones, Montreal.

** Instron part no. G-90-1.

'abeda' and 'bceb', respectively, of Figure VII.1. (page 85).

A measure of the useful work done was therefore readily obtained by subtracting the second reading from the first.

A small correction (proportional to peak height) was made to correct for lag on reversal of the crushing head.

IX.3. Procedure

The crushing procedure was essentially the same as that employed in the earlier tests with the following exceptions:

i) The weight of sample used in each test was increased to an arbitrary but convenient value numerically equal to the specific gravity of the material. Particle size of feed, -8 + 12 mesh, was not changed. No problems with packed bed formation were encountered and the increased sample size improved the accuracy of subsequent size analyses. One such crushing operation, for iron ore, is illustrated in Figure IX.1.

ii) Three voltage levels, zero, 15 and 30 kV, were generally used, with quartzite also tested at 7.5 and 22.5 kV.

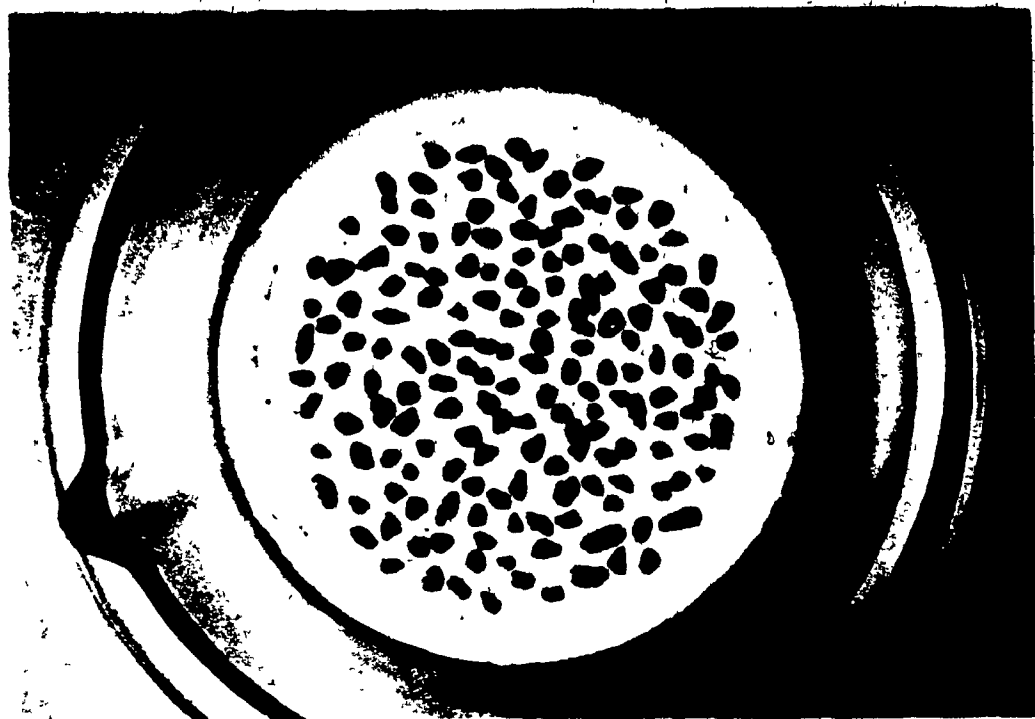
iii) A prescribed load criterion was no longer used for the end point of each test. Instead, the head was reversed when a predetermined integrator reading was reached. This

FIGURE IX.1.

Iron Ore Sample, before and after Crushing.

Unit Work approx. 0.4 J/g.

(Full Size Reproduction)



did not permit duplication of energy input levels, as had at first been hoped, because the read-out was not a direct measure of unit work (as explained above), nor was it feasible to stop a test precisely at the predetermined level due to the rapid rate of change of total work done towards the end of a test. Nevertheless, in addition to greatly facilitating the subsequent determination of unit work, the integrator allowed a more regular spacing of data points than was previously possible. The way in which the integrator was incorporated into the test procedure is evident from the work sheets, reproduced in Appendix VI.2.

IX.4. Product Analysis

i) Size analysis

In order to obtain the fullest data about the size distributions of crushed products, screen analysis using the complete $\sqrt[4]{2}$ series from 10 to 400 mesh was employed, three successive operations (each with eight screens) being required to cover this range. In each case the Sonic Sifter was run for sixteen minutes.

ii) Float and sink analysis

In the case of iron ore an attempt was made to

determine if liberation had in any way been affected by the applied electric field by carrying out float and sink analyses on the crushed products. Similar approaches have been made by Brown et al. (1958) and Elliot (1966). As no suitable liquids are available with densities in the region of 5.2 g/ml, that of the iron oxides, tetrabromoethane (TBE, S.G. = 2.96) was used. In this liquid only pure liberated quartz or quartz with a very small amount of denser mineral attached will float from the crushed iron ore. Consequently the weight fraction of crushed sample floating in such a liquid is a direct measure of the liberation of quartz and, hence, an indirect measure of the liberation of the iron oxide minerals. Tests were carried out on four different size fractions: -50+100, -100+140, -140+200, and -200+400 mesh, the material in these size ranges from all the crushing tests at a given voltage being combined to obtain an adequate sample. The apparatus, shown in Figure IX.2, was extremely simple, consisting of a 25 ml bottle, fitted with a flexible tube which could be pinched off by a screw clip as indicated. The sized sample was placed in a bottle which was then filled with the dense liquid and agitated by hand. As many particles had an effective density very close to that of the TBE, complete separation would have taken a very long time.

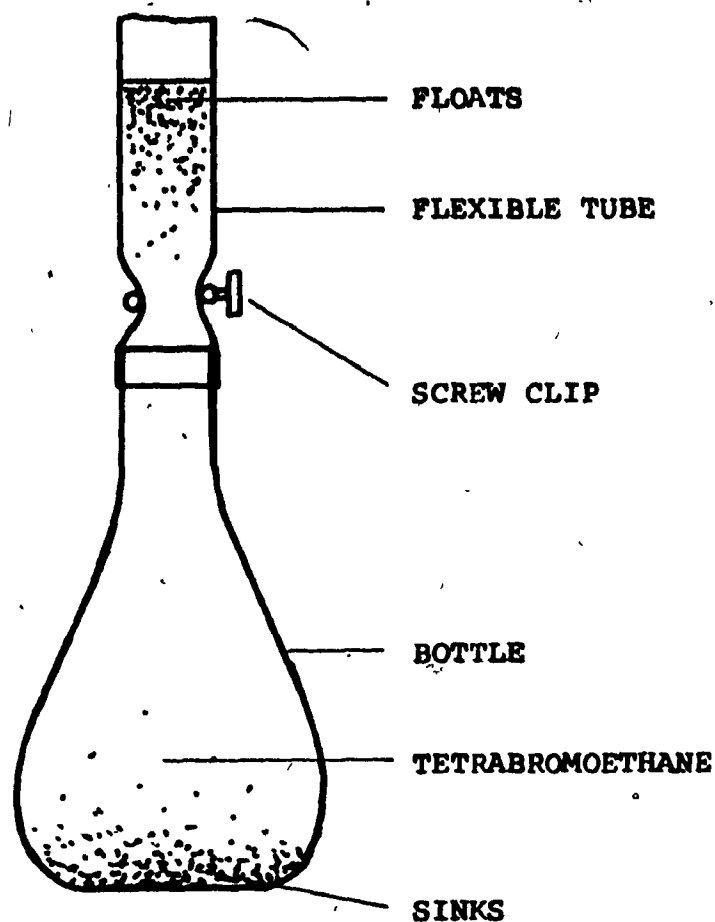


Figure IX.2.

Apparatus for
Float and Sink Tests

Instead, the bottle was allowed to stand for a period of ten minutes before closing the clip and the material above the clip classified as floats. The products were washed out on to separate filter papers, rinsed with carbon tetrachloride to remove the low-volatility TBE, dried and weighed.

IX.5. Treatment of Data

i) Rosin-Rammler plots

Rather than use the Schuhmann-type plots to obtain a parameter characteristic of the product size, as was done in the initial tests, it was decided to present the screen analysis data on Rosin-Rammler graphs. This method of plotting, which is fully described in Appendix I, has the advantages that i) in many cases considerably more of the distribution tends to fall on a straight line, and ii) the conventional size modulus derived from the plot, the X value at $Y = 63.2\%$ passing, involves less extrapolation. A computer program was written (Appendix VII) by means of which the sample weights from the screen analyses were automatically converted to Rosin-Rammler functions and plotted using a Calcomp digital plotter. As will be explained later, the screens were experimentally calibrated and these experimental aperture values used in constructing the Rosin-Rammler graphs.

ii) Frequency plots

Although the Rosin-Rammler plots for four of the six tested materials could be represented over an extended portion by straight lines (see pages 298-317), those for hematite and iron ore were markedly non-linear. Schuhmann

plots offered no advantage as the two functions are very similar below approximately fifty per cent passing, a portion of the plot which was appreciably curved with both materials. Furthermore, cumulative plots only provide information on the overall size of product and the distribution width, masking finer detail such as minor modes, and are dependent on the accuracy of the fitted line which cannot be calculated satisfactorily. Consequently an alternative method was sought which would be sensitive to changes in form of the size distribution and amenable to mathematical treatment in order to preclude human bias or error. The method adopted, an extension of that used previously by Nagahama et al. (1969), was to form a frequency distribution from the screen analysis data by plotting per cent weight retained in each screen interval against the mean size of that interval, interpolating to obtain a smooth curve through all the points, and calculating the mean, standard deviation, skewness and kurtosis for the distribution. Particle sizes were expressed in logarithmic form, $-\log_2(D/D_0)$, where D is the size of the theoretical passing aperture (mm) and D_0 is the mean feed size, equivalent to 10 mesh or 2.0 mm. Hence a size designated '0' indicates feed-size material or zero size reduction, '1' indicates half feed size, and 'n' indicates a particle of $(\frac{1}{2})^n$.

feed size. This scale, which is very similar to the geologists' phi scale ($\phi = -\log_2 d$) (Krumbein, 1934,38), was adopted for computational convenience but also clearly indicates the degree of size reduction.

An estimate of the median was also calculated, all modes (peaks) located and their heights recorded as a possible indication of liberation changes. The calculation and use of statistical parameters to specify a size distribution is described in Appendix I. The interpolation method, which offers a number of advantages over conventional techniques, was developed by the author for this study and is described in Appendix IV. The computer program by which the analysis was carried out is described in Appendix V.2.

X. RESULTS

Experimental data, including all screened sample weights, are recorded in Appendix VI.3. Two main methods were used to evaluate these results, both methods utilizing an intermediate stage, Rosin-Rammler type plots in the first case and frequency distribution analysis in the second.

X.1. Rosin-Rammler Plots

The computer-generated Rosin-Rammler plots are presented in Appendix VII.1. Straight lines used to determine the size modulus are drawn in over the approximate range in which a linear fit is considered appropriate. Fitting was done by eye using a ruled overlay, a constant gradient being used for all samples of a given material. It is seen that the fit is generally good over a large portion of the size distributions of poly- and mono-quartz and sphalerite, thus providing a suitable measure of degree of comminution. In the remaining two materials, iron ore and hematite, the validity of this method to designate product size is less evident due to the extremely limited range over which a

linear fit can be made. Nevertheless it is clear that the family of curves shows a steady progression in form with increasing unit work and that the location of the chosen straight section provides an empirical measure of this progression and, thus, of the extent of comminution.

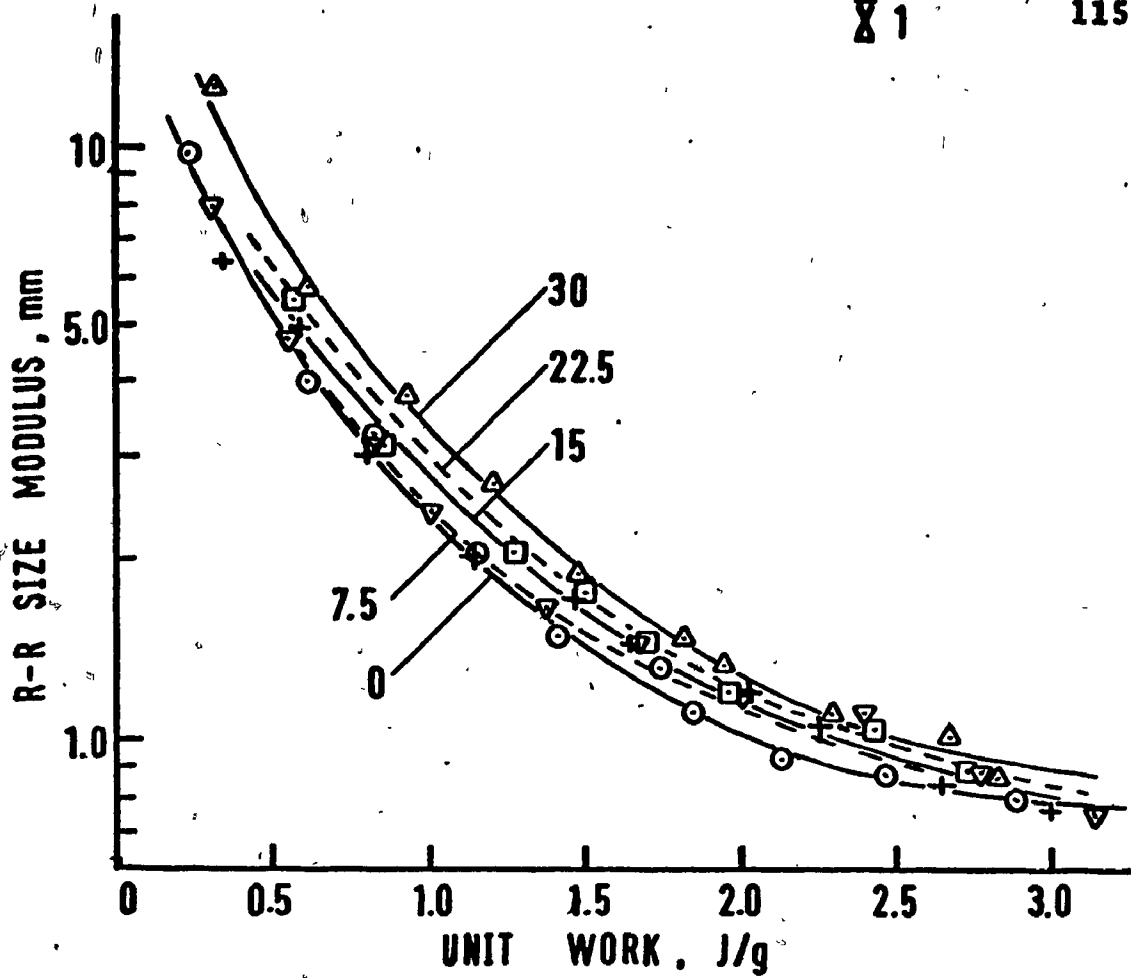
The Rosin-Rammler size modulus for each curve (the theoretical aperture passing 63.2 weight per cent) is plotted against unit work in Figures X.1 to 6. The results for quartzite and mono-sphalerite are comparable with those obtained from Schuhmann plots in the initial tests (Figures VIII.5 and 5). In the case of quartzite, Figure X.1., the shift resulting from the 15 kV applied potential is seen to be increased when using an applied potential of 30 kV although the effect is not as pronounced in the later graphs, based on the Rosin-Rammler modulus, suggesting that the Rosin-Rammler plot is less sensitive to distribution changes, possibly due to the inclusion of coarser particles in its more extended range. Scatter about smooth curves drawn for each applied potential is considerably lower in the later graphs, however, so that the existence of a field effect is clearly established.

Scatter is also reduced in the case of mono-sphalerite, Figure X.4., revealing a slight difference between

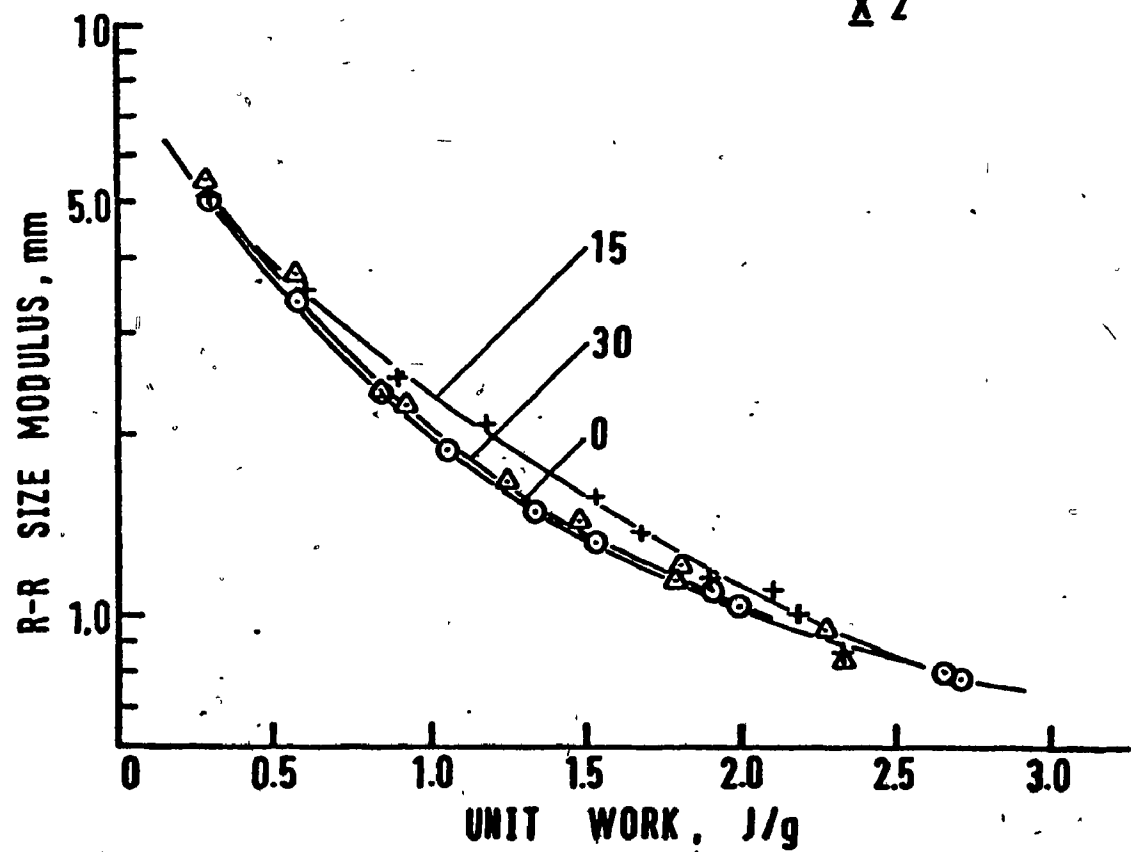
FIGURES X.1. to X.6.

Rosin-Rammler Size Moduli vs. Unit Work

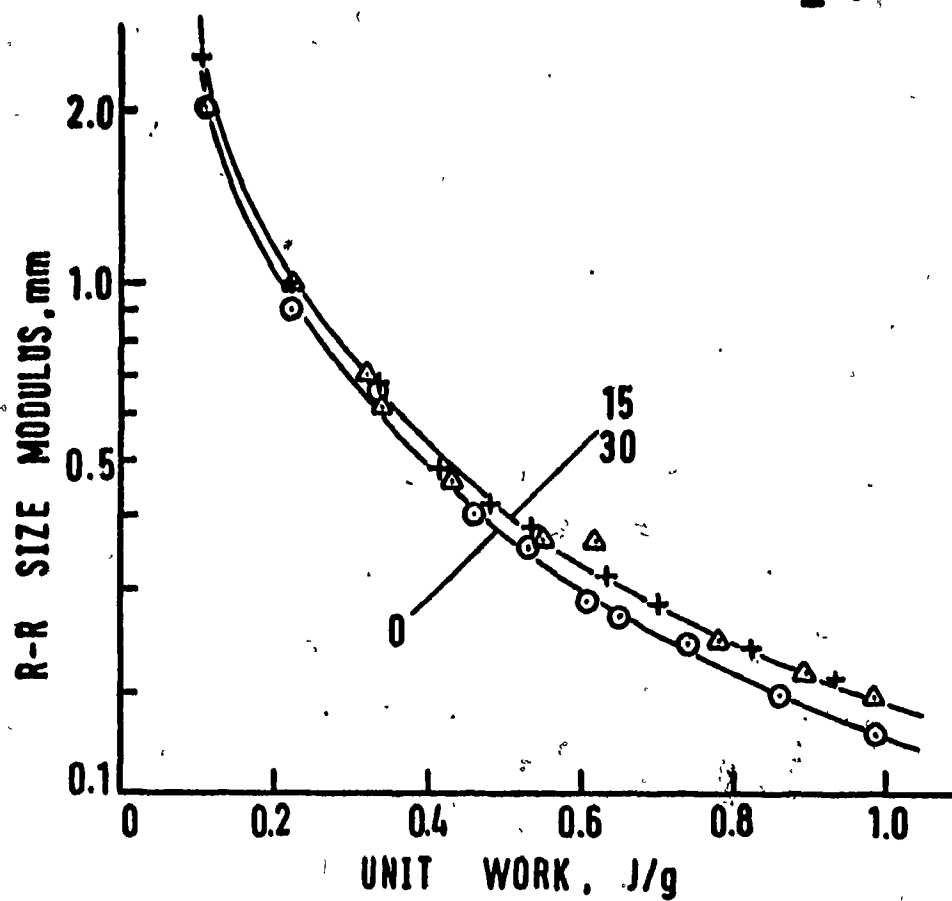
X.1.	Quartzite	page 115 top
X.2.	Mono-Quartz	115 bottom
X.3.	Poly-Sphalerite	116 top
X.4.	Mono-Sphalerite	116 bottom
X.5.	Iron Ore	117 top
X.6.	Poly-Hematite	117 bottom



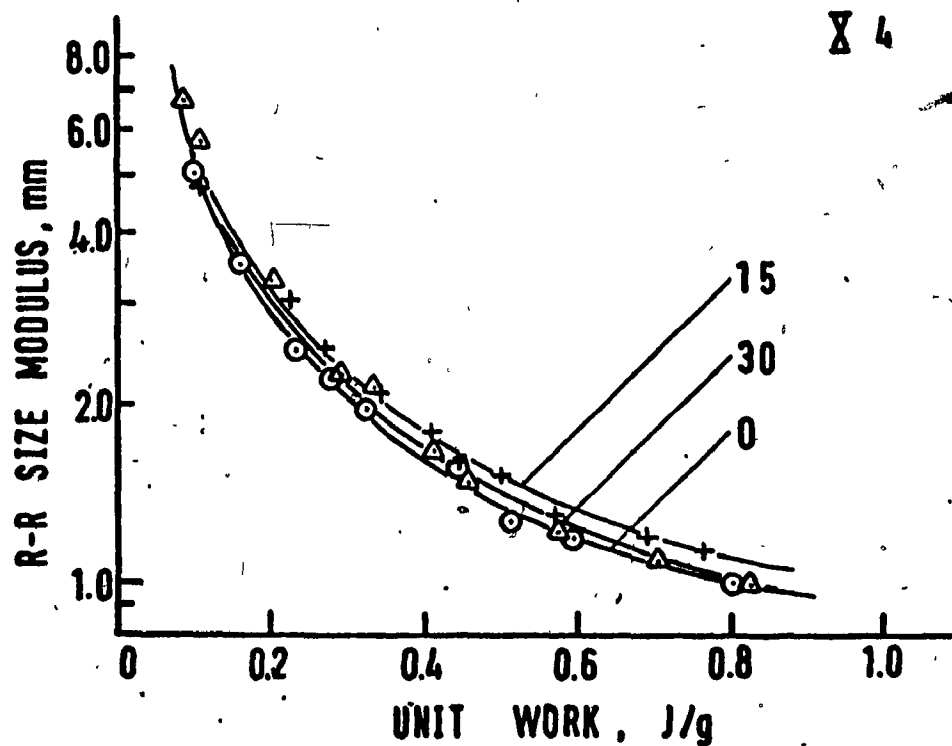
X 2

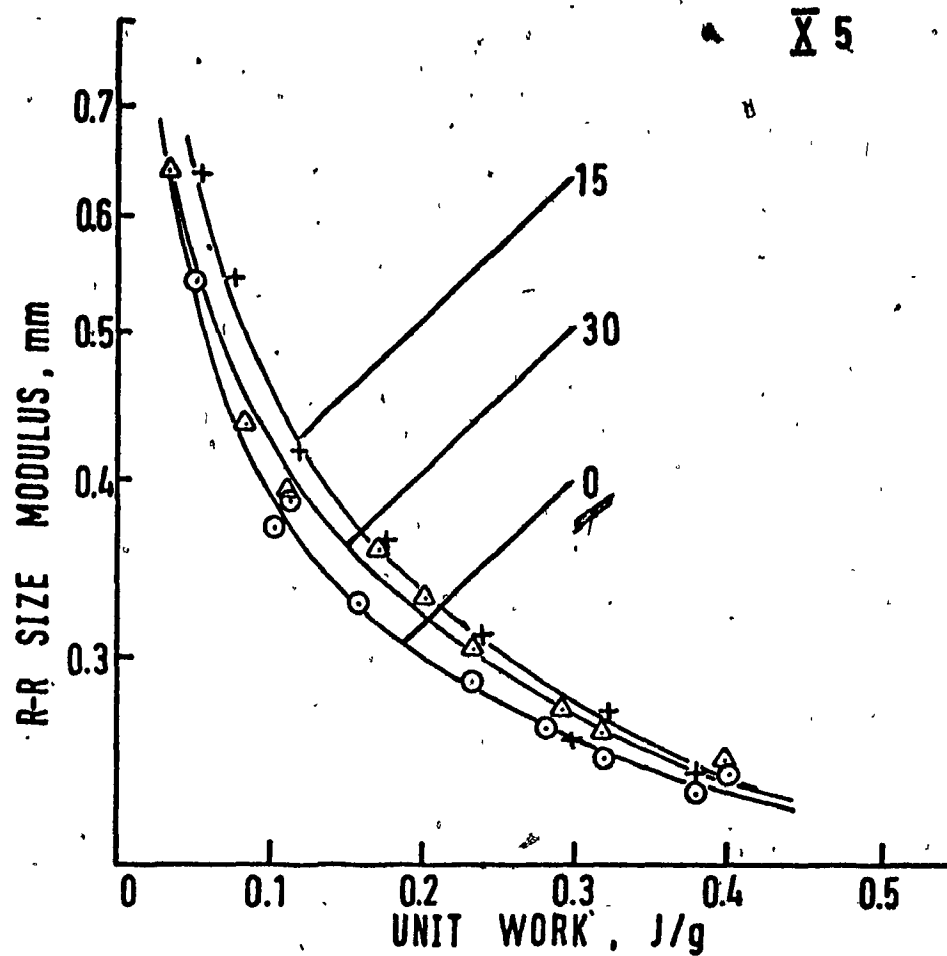
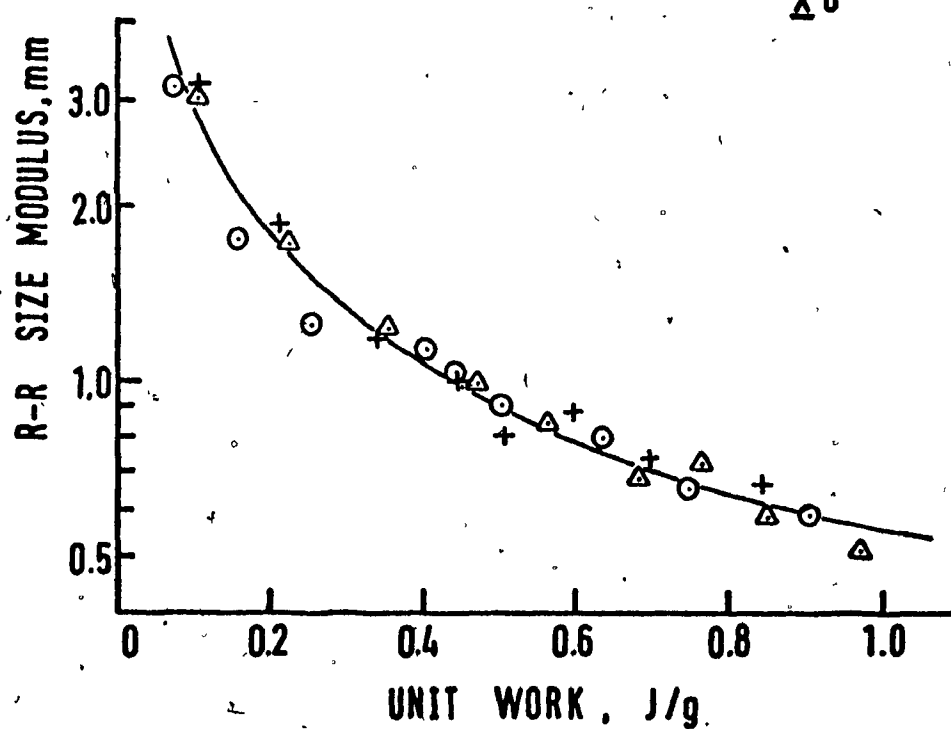


X 3



X 4



$\bar{X} 5$  $\bar{X} 6$ 

the curves which had not been noticed in the previous tests. The indicated change in comminution characteristics is far from proven by these results but efficiency appears to be reduced in the field from 15 kV applied potential and restored in part on increasing the potential to 30 kV.

Of the new materials tested, all except hematite showed small but definite reductions in comminution efficiency as a result of the applied potential. No difference is discernable between the trends described by the hematite data points for the three field conditions (Figure X.6.).

Monocrystalline quartz, Figure X.2., exhibited a reversal at high applied potential similar to that noted with mono-sphalerite. In this case the curves for zero and 30 kV are nearly superimposed. The overall effect was lower with this material than with its polycrystalline counterpart, quartzite.

The curves for polycrystalline sphalerite with 15 and 30 kV applied potential are indistinguishable, Figure X.3., although, by comparison with the other materials, it is probable that a reversal had occurred. That is, a maximum field effect would have been found at some intermediate value

of applied potential.

The comminution efficiency for iron ore also passed through a minimum on increasing the applied potential from zero to 30 kV, Figure X.5., the decrease in efficiency in the field from 15 kV amounting to about fifty per cent in the lower unit work region, becoming less evident at higher degrees of crushing.

X.2. Frequency Distributions

The frequency distribution curves, computer plotted, are given in Appendix VII.2. The origin of each curve is displaced downwards a distance proportional to the unit work done on the sample so that the progression of crushing is clearly seen. A striking aspect of all the curves is their pronounced polymodal nature. That this was a true property of the particle size distribution and not a result of regular deviation in screen apertures from the nominal values is demonstrated in tests described in Appendix II.

Statistical parameters derived from the frequency distributions are given in the lower sections of the tables in Appendix VI.3. and are plotted against unit work in

Figures X.7 to 41. Size values are expressed in the negative logarithmic form, higher numbers thus indicating a greater degree of comminution or smaller size.

An attempt was made to determine the (zero work) origin for each set of curves by a limited size analysis of feed samples from each material. The results are given in Table X.1. Only the first eight screens in the $\sqrt[4]{2}$ series were used, the very small amount passing through 30 mesh (an average of 0.08%) being arbitrarily assumed to be of -80 + 100 mesh size. Both median and mean values are seen to be very close to 'zero' (the nominal feed size, D_0 , 2.0 mm) and will be taken equal to zero. The standard deviation is also fairly constant for the six samples, averaging 0.177 with a mean deviation of 14.2%, but the skewness and, even more notably, the kurtosis are so sensitive to the small weight outlier that their values are meaningless.

The various parameters derived from the frequency distributions of the crushed products are described below in order of increasing complexity.

i) Medians

Median values were estimated by calculating cumulative weight per cent and interpolating linearly in the

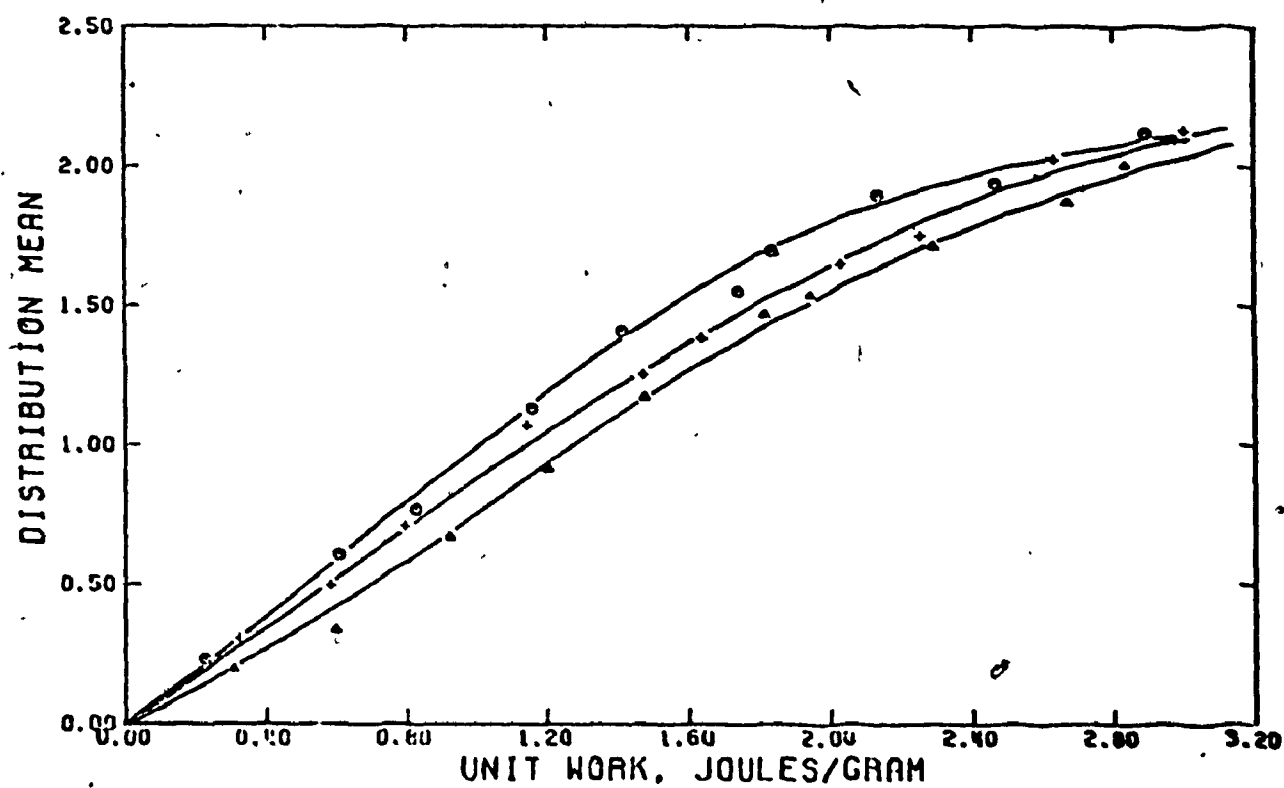
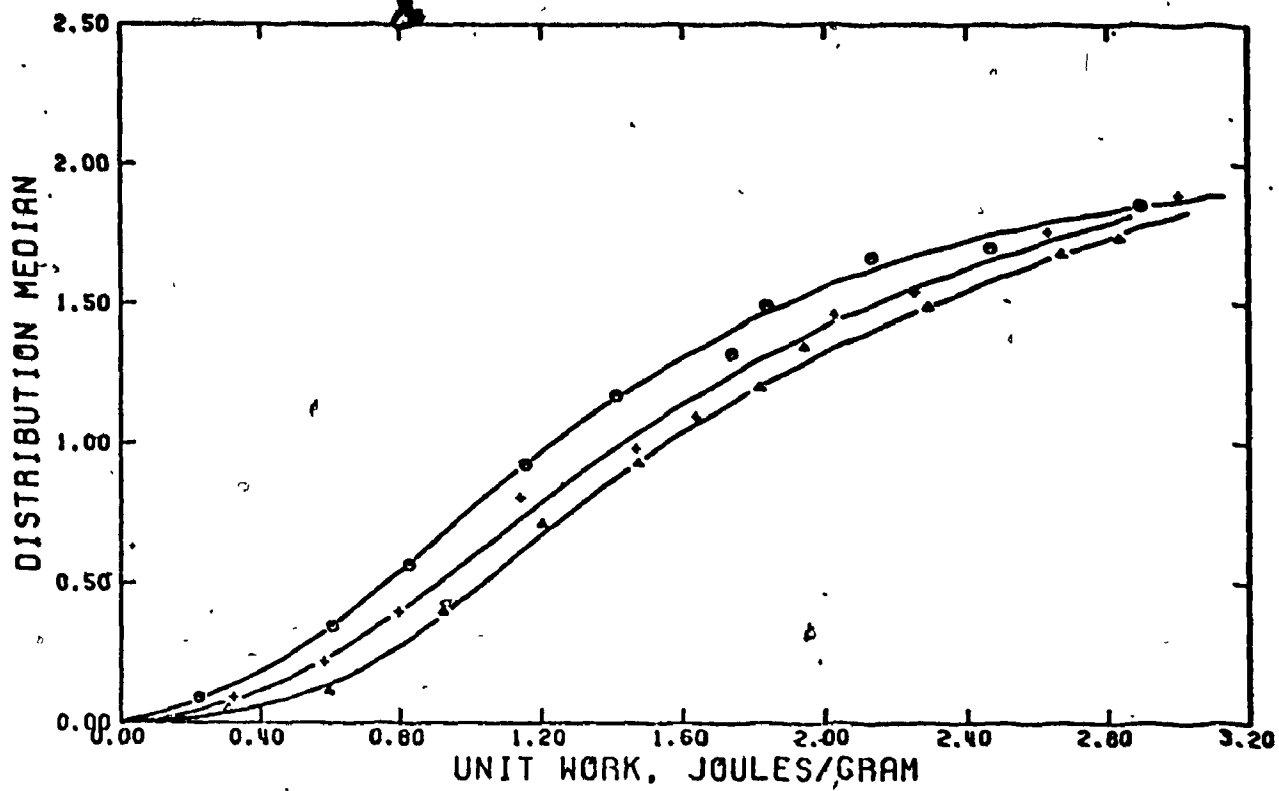
Material	QUARTZITE	MONO- QUARTZ	POLY- SPHALERITE	MONO- SPHALERITE	POLY- HEMATITE	IRON ORE
Mesh Number	Screened Weights, gram					
10	1.1547	1.8947	2.4806	2.6660	3.2694	1.7500
12	1.4000	0.6542	1.5125	1.2279	1.9327	1.2193
14	0.1054	0.0674	0.0411	0.1147	0.0619	0.0358
16	0.0	0.0	0.0040	0.0	0.0	0.0040
18	0.0	0.0020	0.0	0.0119	0.0	0.0
20	0.0037	0.0	0.0	0.0	0.0022	0.0
25	0.0	0.0013	0.0	0.0	0.0011	0.0
30	0.0	0.0	0.0	0.0	0.0	0.0
-30*	0.0021	0.0015	0.0023	0.0	0.0035	0.0089
Median	0.0318	-0.0771	-0.0464	-0.0615	-0.0485	-0.0344
Mean	0.0537	-0.0148	0.0081	-0.0019	0.0079	0.0258
Standard Deviation	0.1803	0.1637	0.1609	0.1404	0.1682	0.2496
Skewness	54.11	71.12	61.17	1.602	67.45	106.8
Kurtosis	6,324.	11,094.	12,906.	888,494.	9,160.	444.5

* Assumed -80 + 100 mesh.

Table X.1. Feed size parameters.

FIGURES X7. to X.13.**Distribution Medians versus Unit Work****FIGURES X.14. to X.20.****Distribution Means versus Unit Work**

X. 7. and X.14.	Quartzite; 0,15,30 kV	p. 123
X. 8. and X.15.	Quartzite; 7.5,22.5 kV	p. 124
X. 9. and X.16.	Mono-Quartz	p. 125
X.10. and X.17.	Poly-Sphalerite	p. 126
X.11. and X.18.	Mono-Sphalerite	p. 127
X.12. and X.19.	Iron Ore	p. 128
X.13. and X.20.	Poly Hematite	p. 129



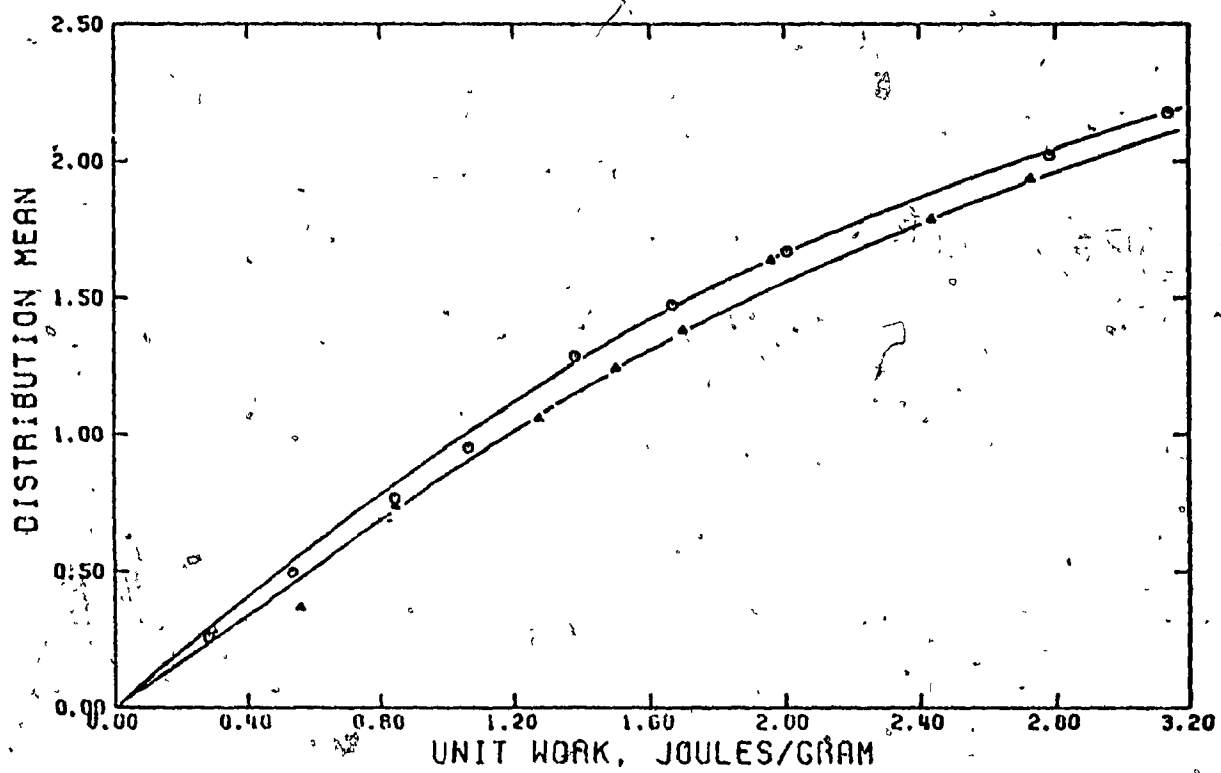
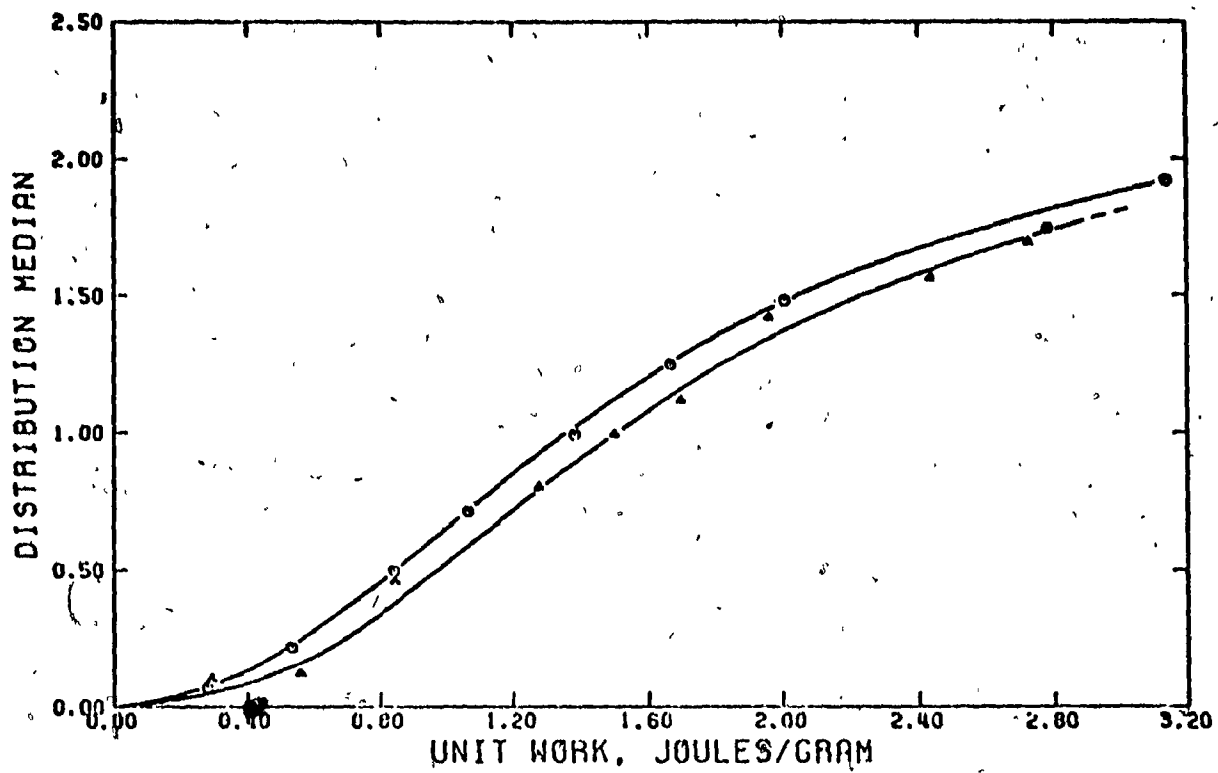
QUARTZITE

KILOVOLTS

○ ZERO

▲ 30.0

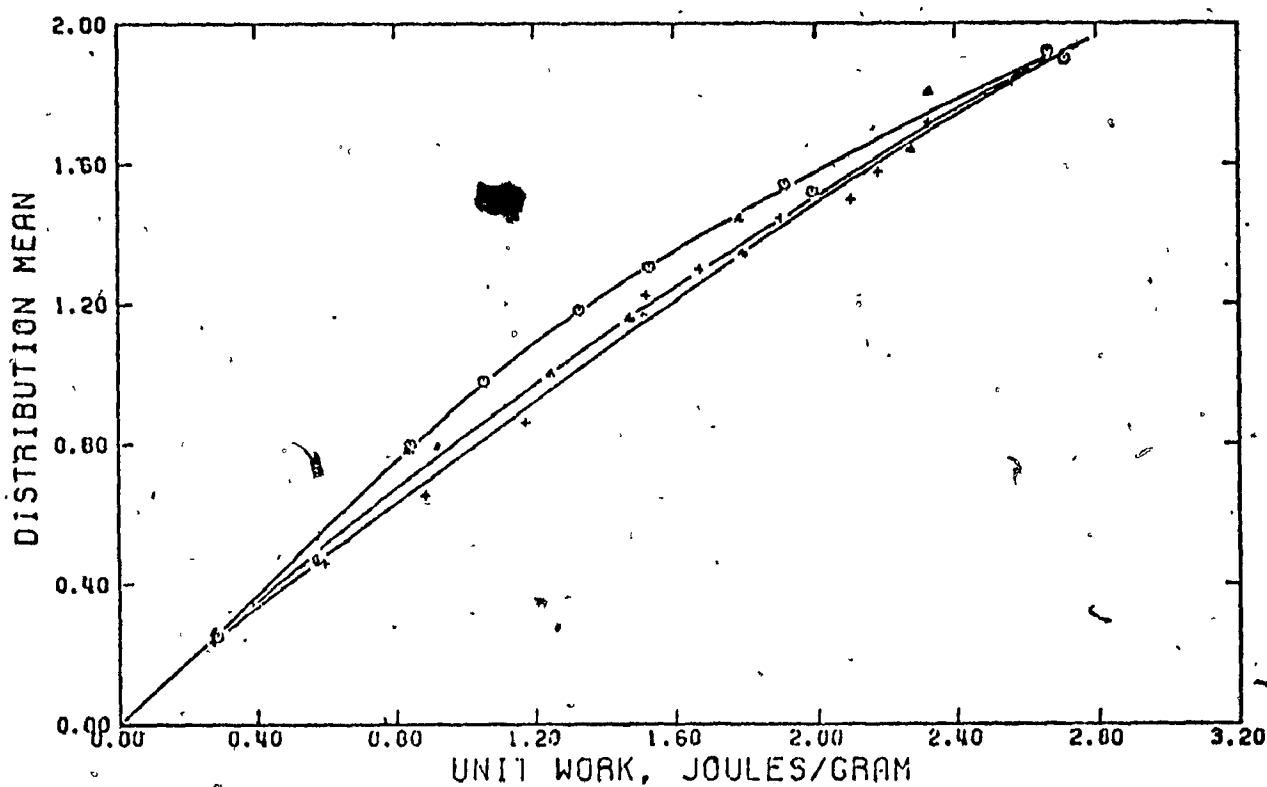
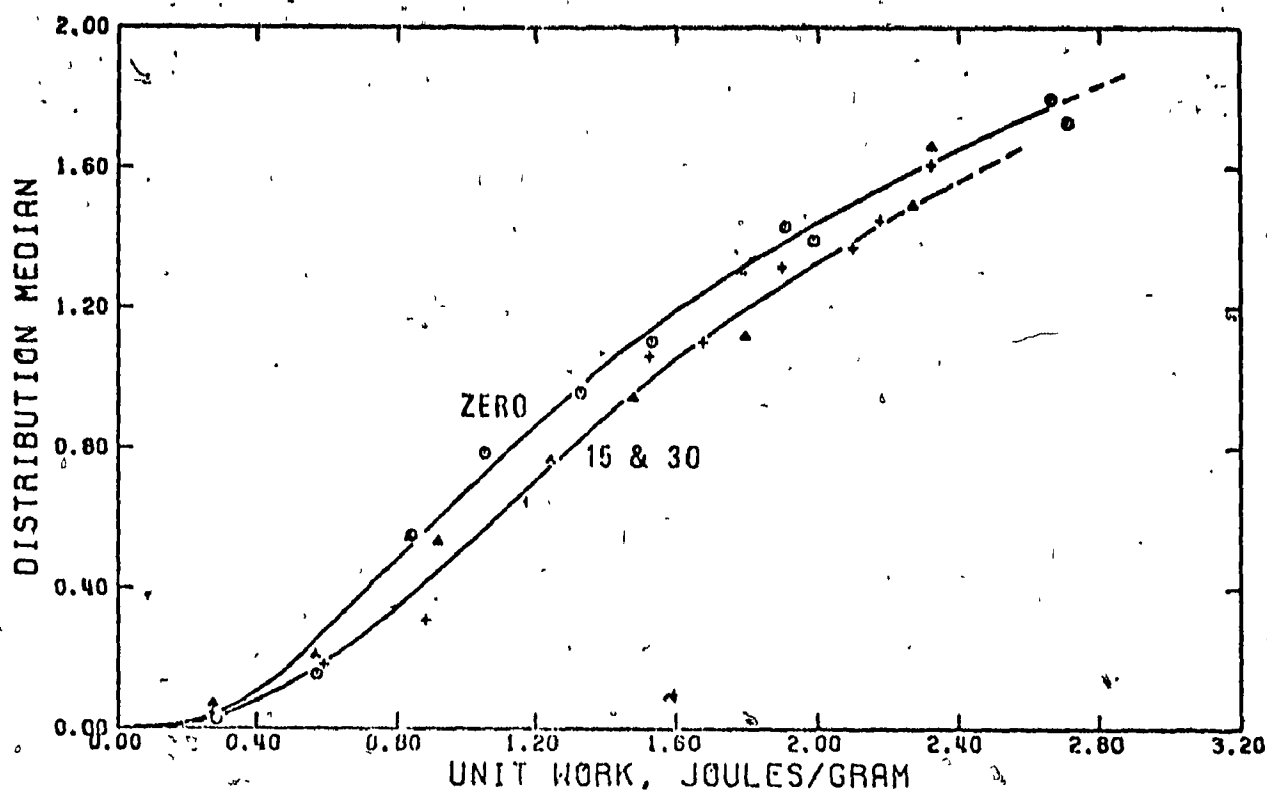
+ 15.0



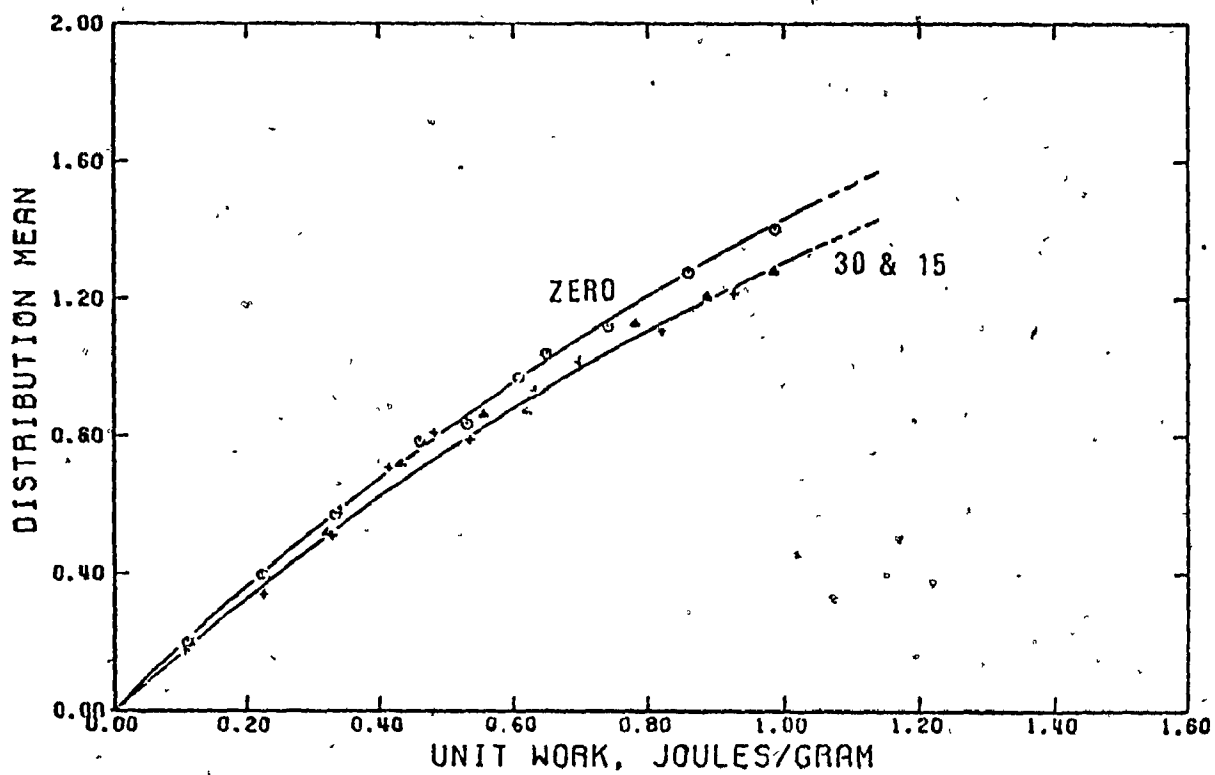
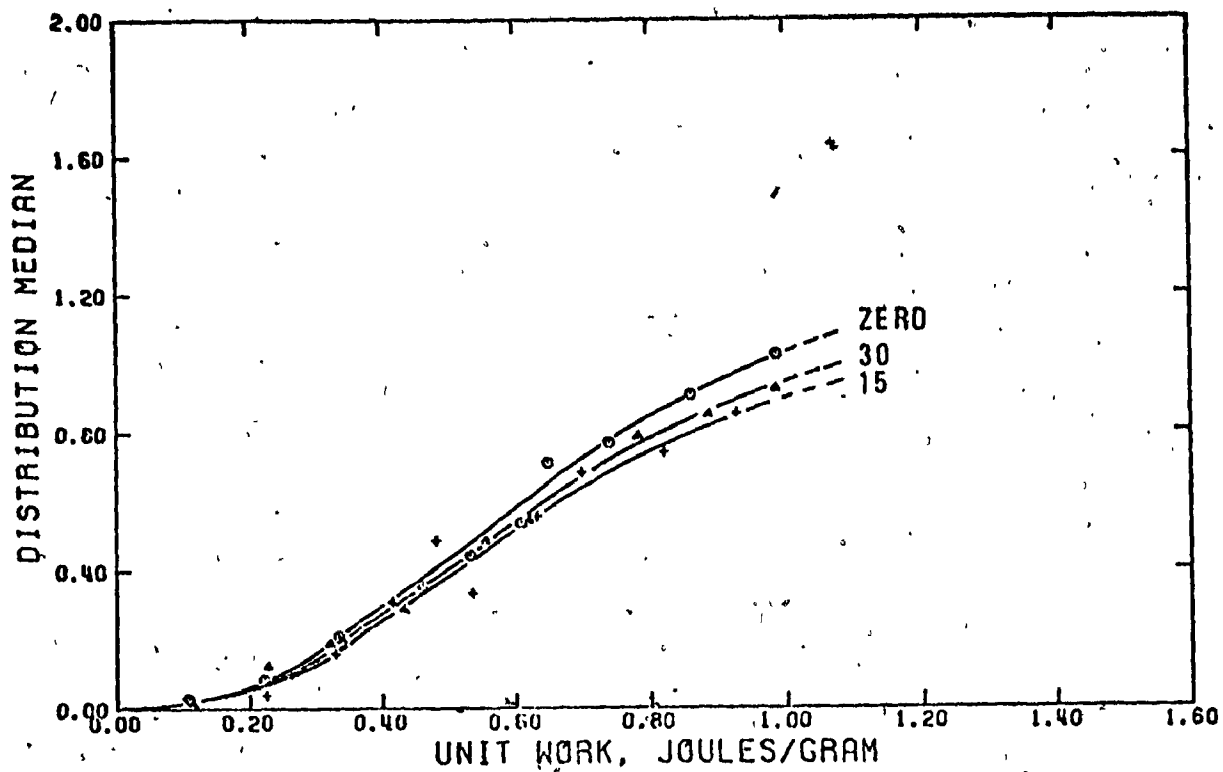
QUARTZITE

KILOVOLTS

○ 7.5 △ 22.5

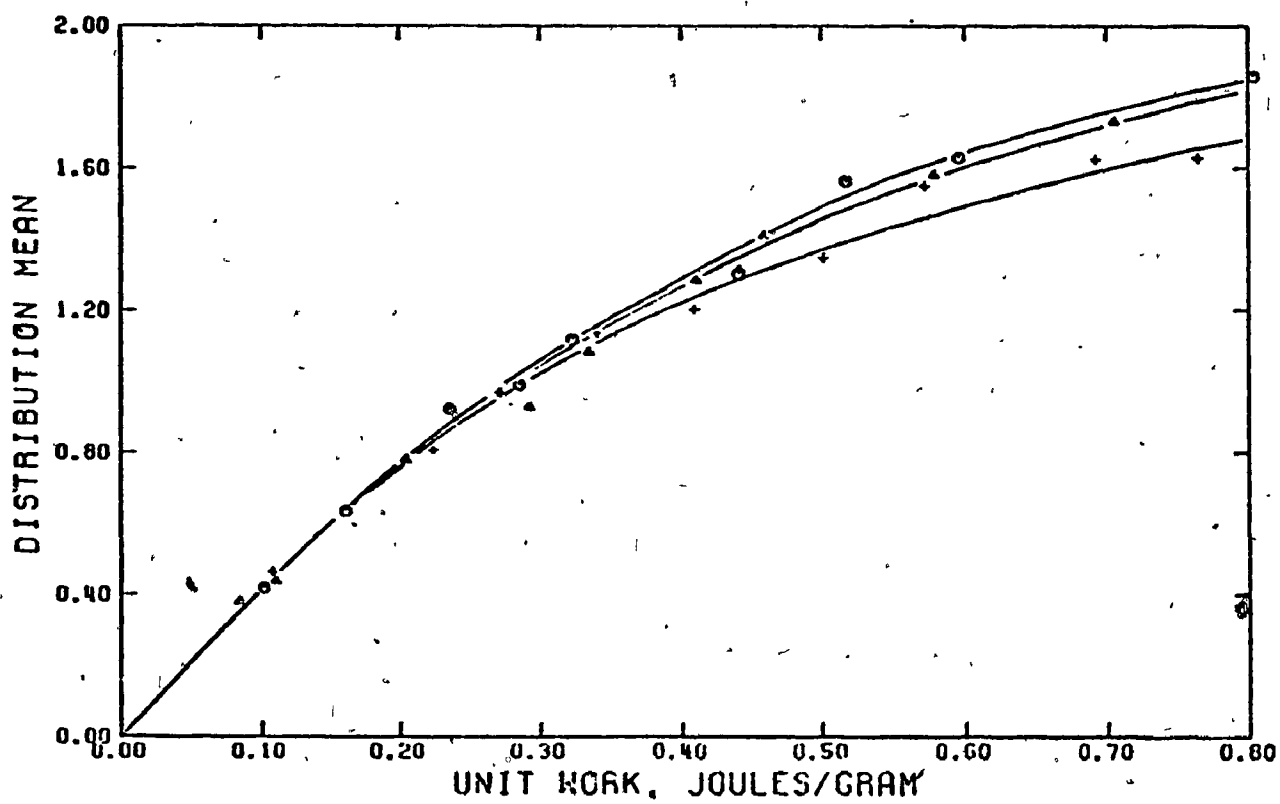
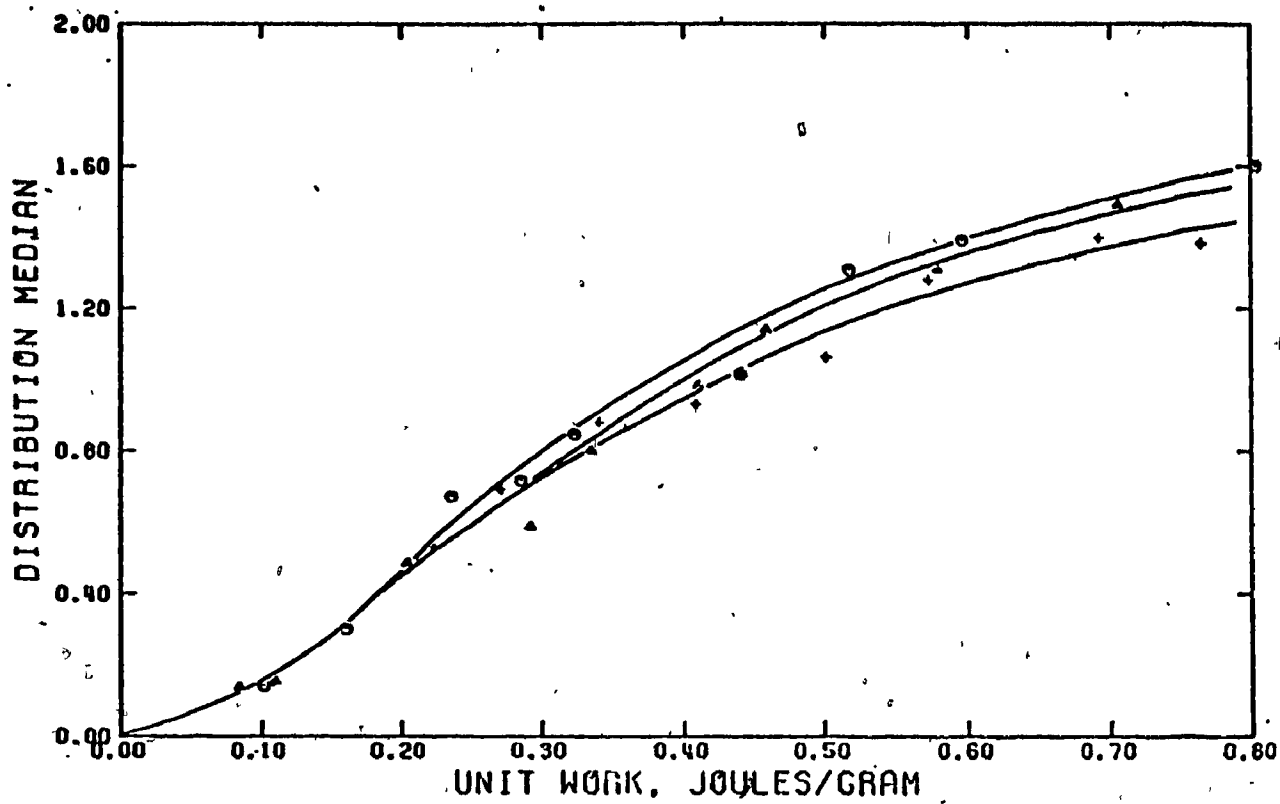


MONO-QUARTZ KILOVOLTS. ○ ZERO ▲ 30.0 + 15.0

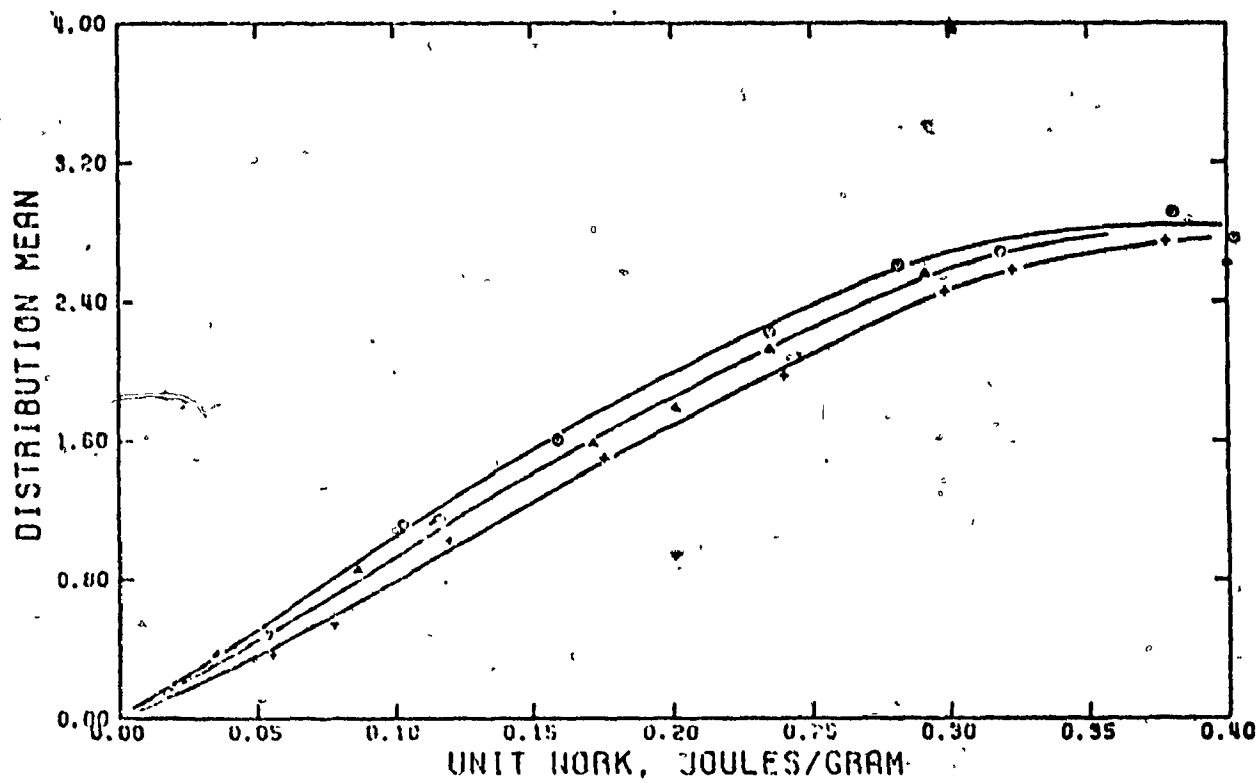
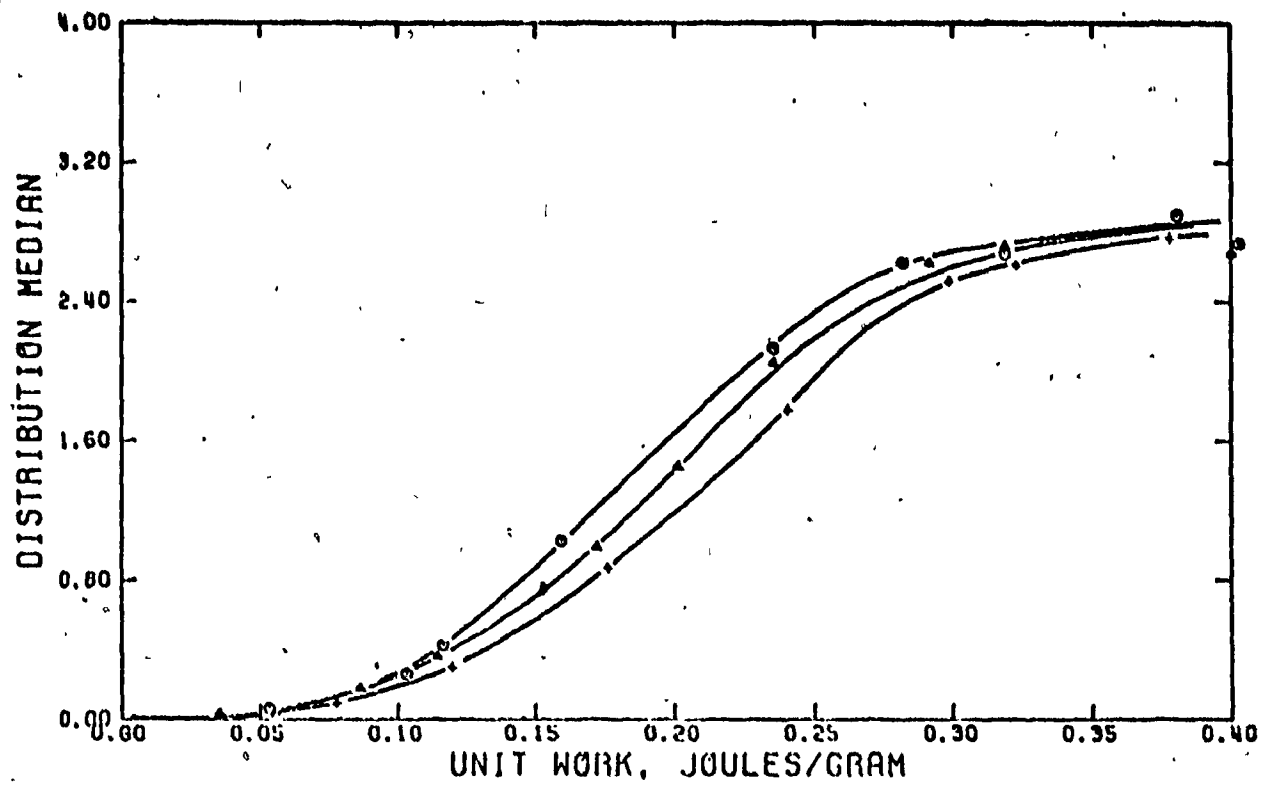


POLY-SPHALERITE KILOVOLTS

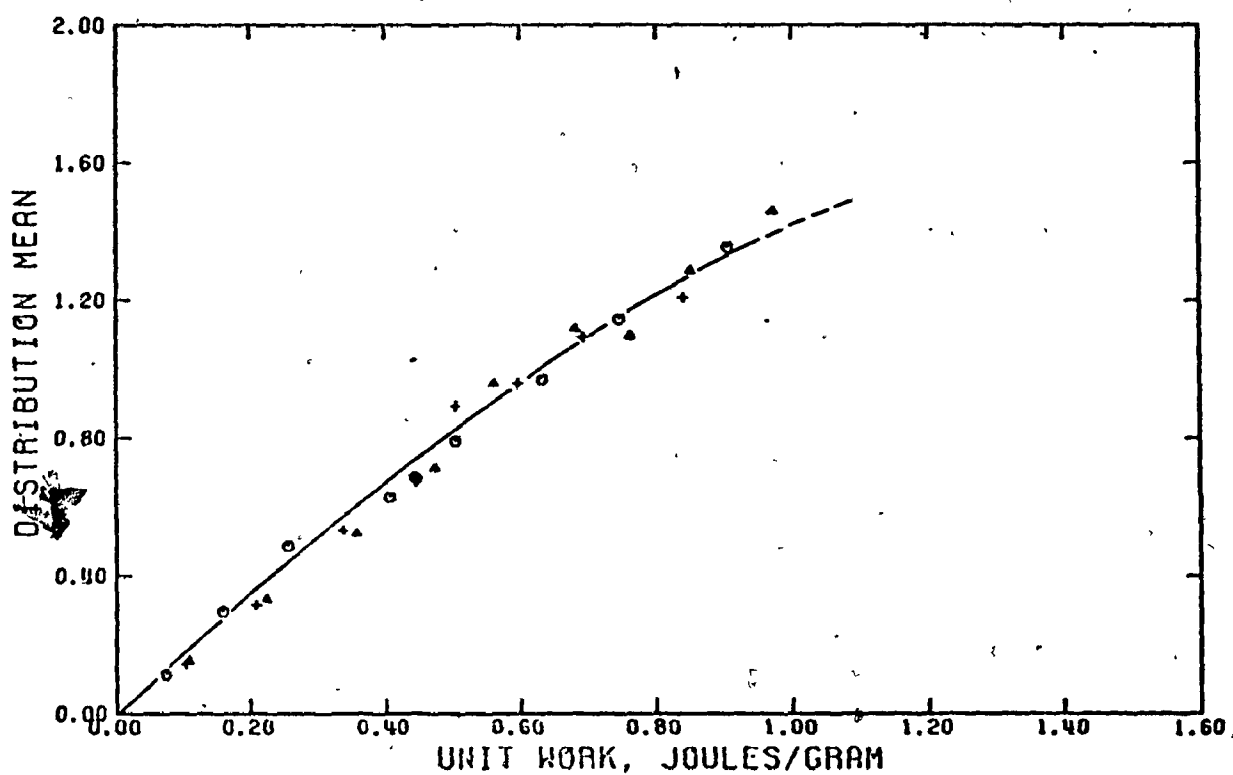
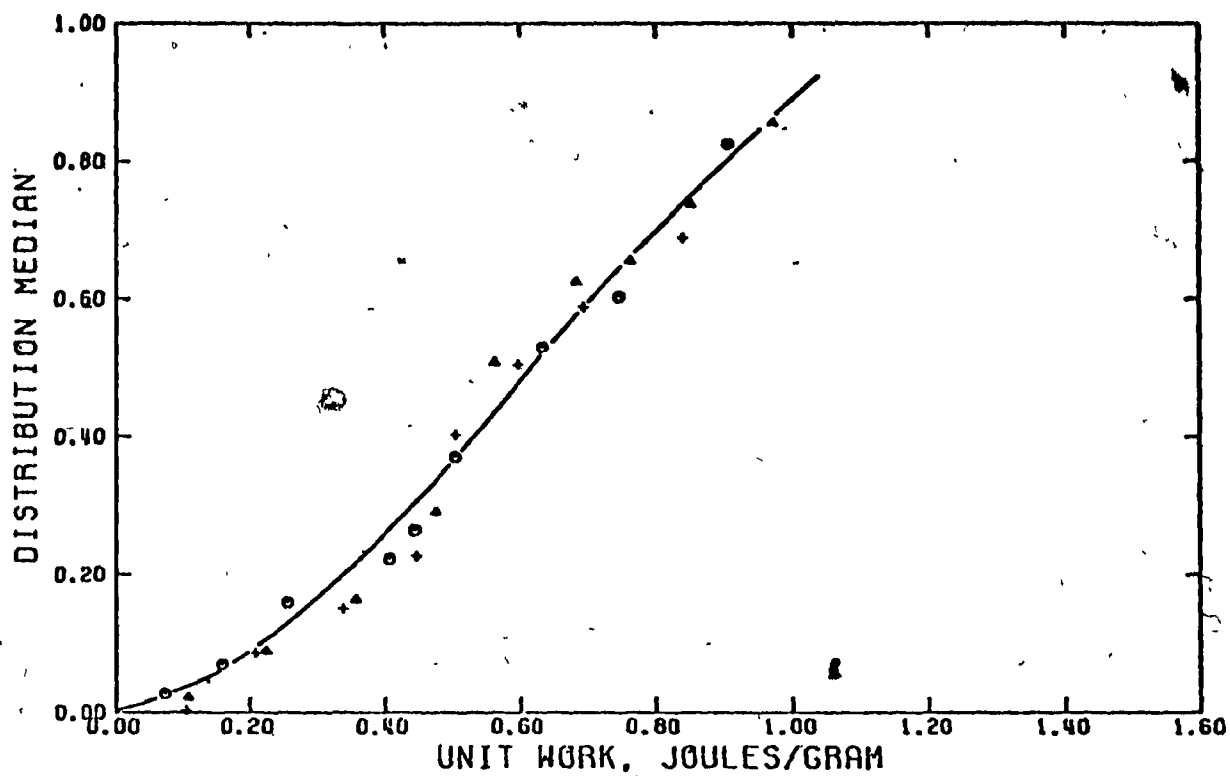
○ ZERO ▲ 30.0 + 15.0



MONO-SPHALERITE KILOVOLTS ○ ZERO ▲ 30.0 + 15.0



IRON ORE KILOVOLTS ○ 0.0 ▲ 30.0 + 15.0



POLY-HEMATITE KILOVOLTS ○ ZERO ▲ 30.0 + 15.0

FIGURES X.21. to X.27.

Standard Deviations versus Unit Work

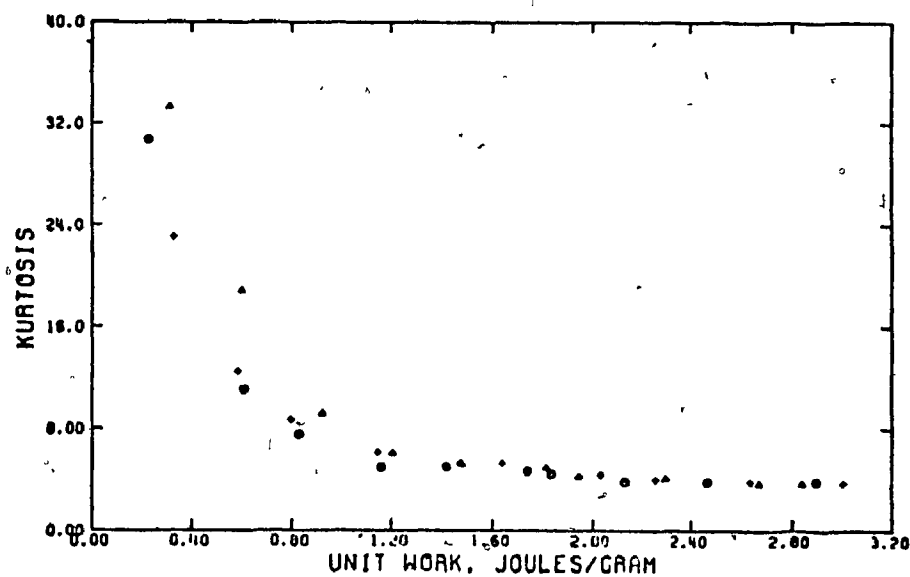
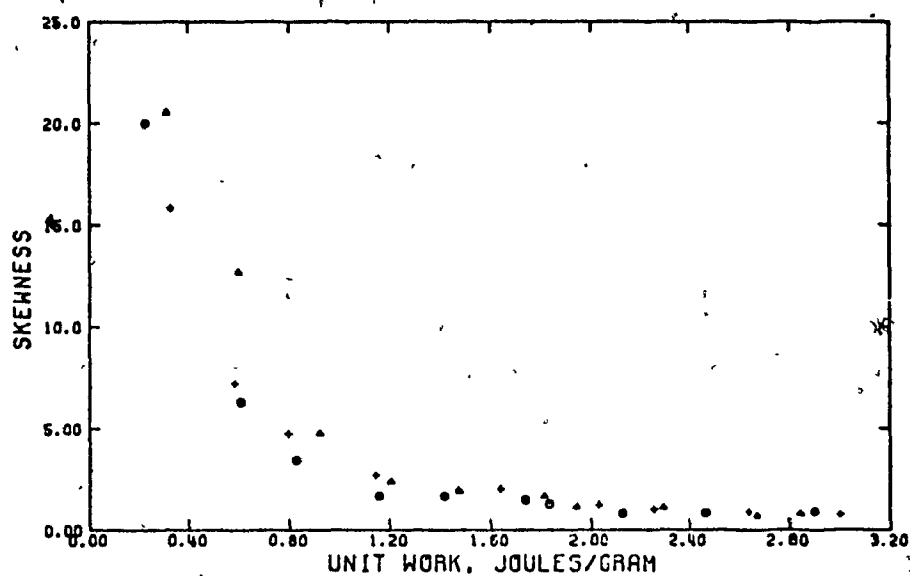
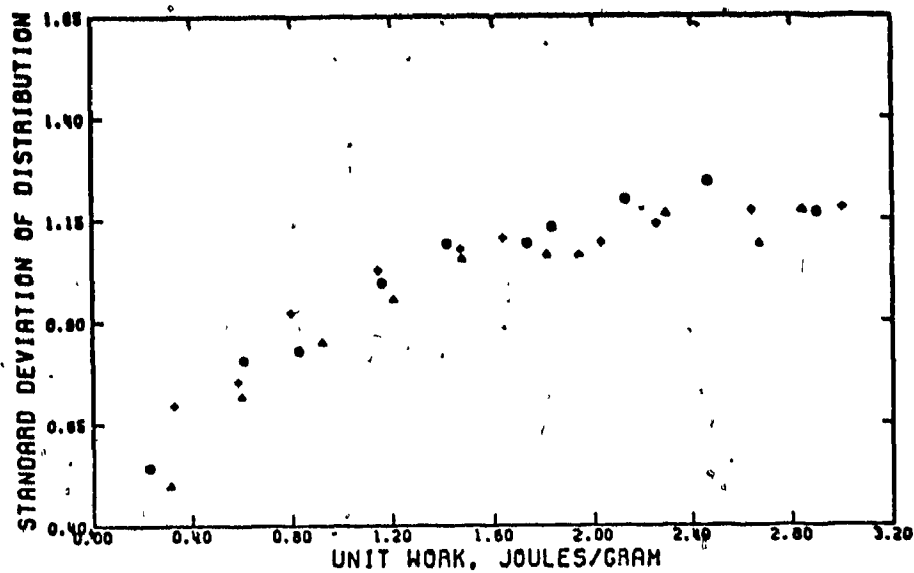
FIGURES X.28. to X.34.

Skewness versus Unit Work

FIGURES X.35. to X.41.

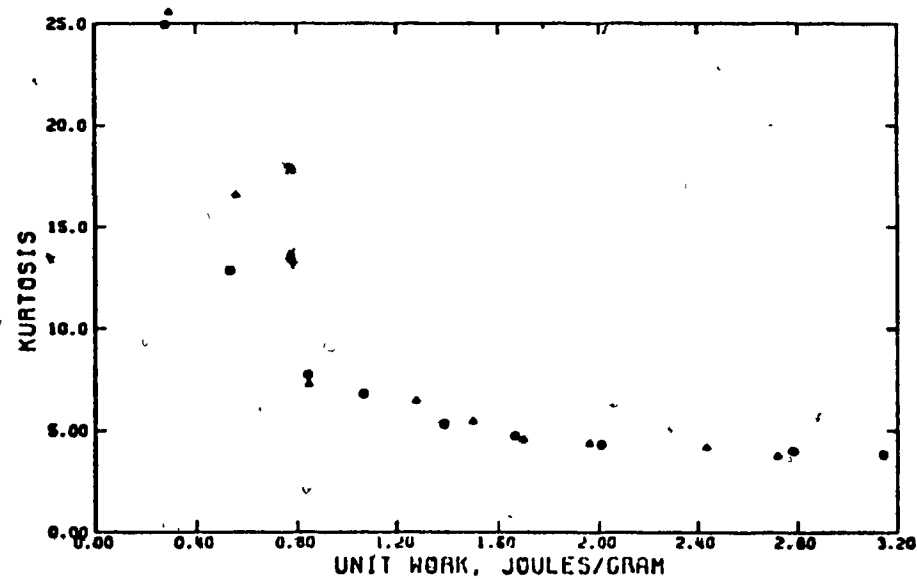
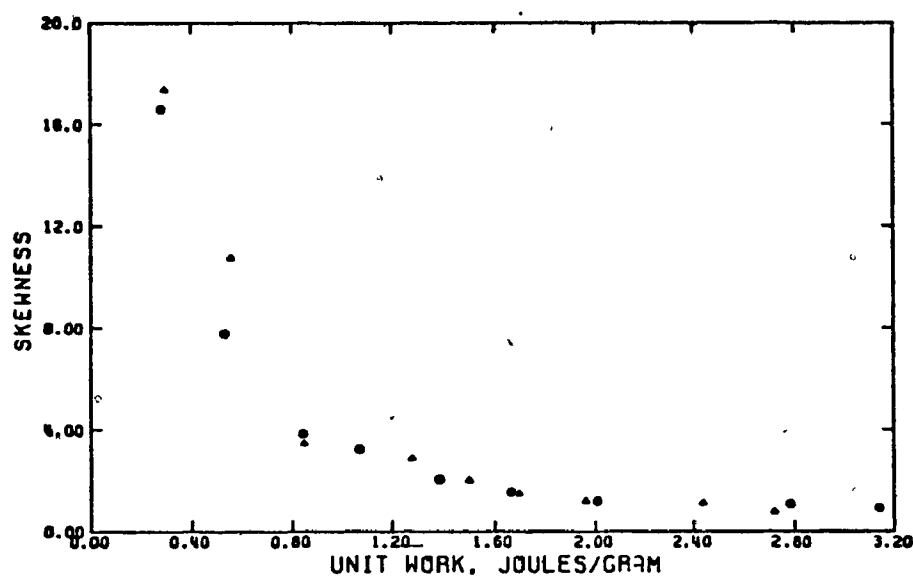
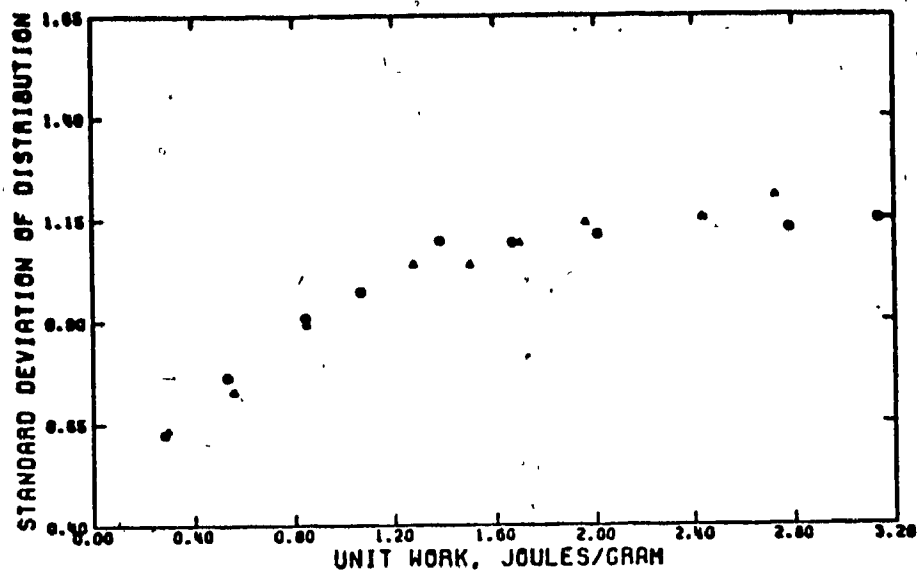
Kurtosis versus Unit Work

X.21., .28. and .35.	Quartzite; 0,14;30 kV	p. 131
X.22., .29. and .36.	Quartzite; 7.5,22.5 kV	p. 132
X.23., .30. and .37.	Mono-Quartz	p. 133
X.24., .31. and .38.	Poly-Sphalerite	p. 134
X.25., .32. and .39.	Mono-Sphalerite	p. 135
X.26., .33. and .40.	Iron Ore	p. 136
X.27., .34. and .41.	Poly Hematite	p. 137

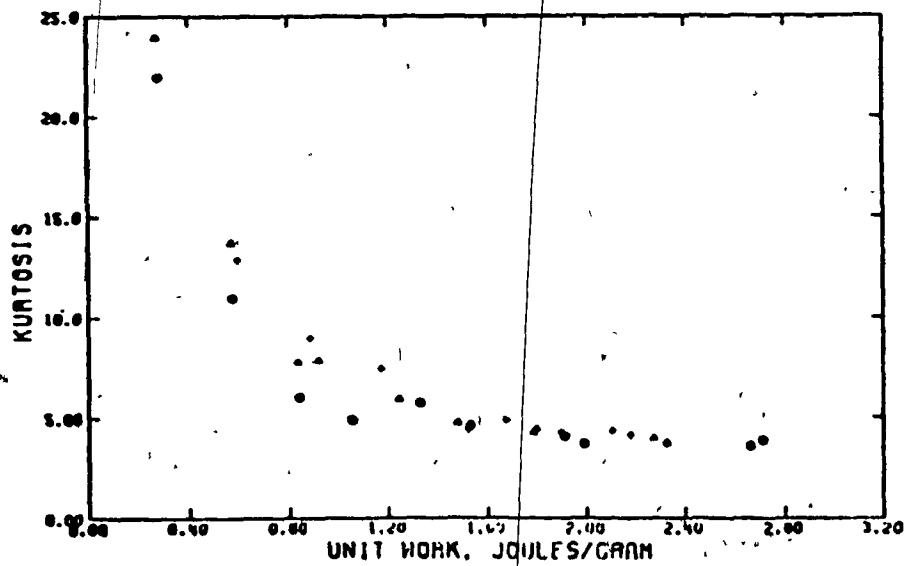
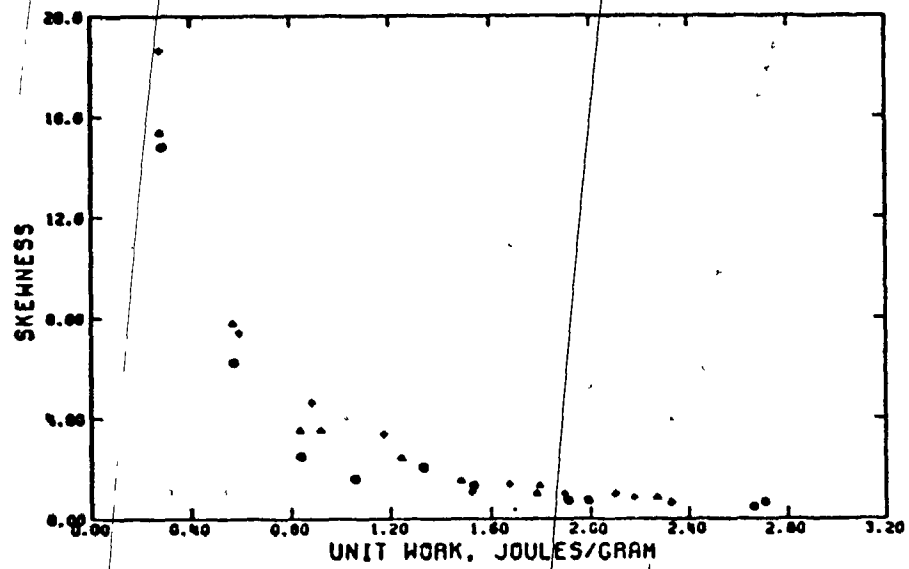
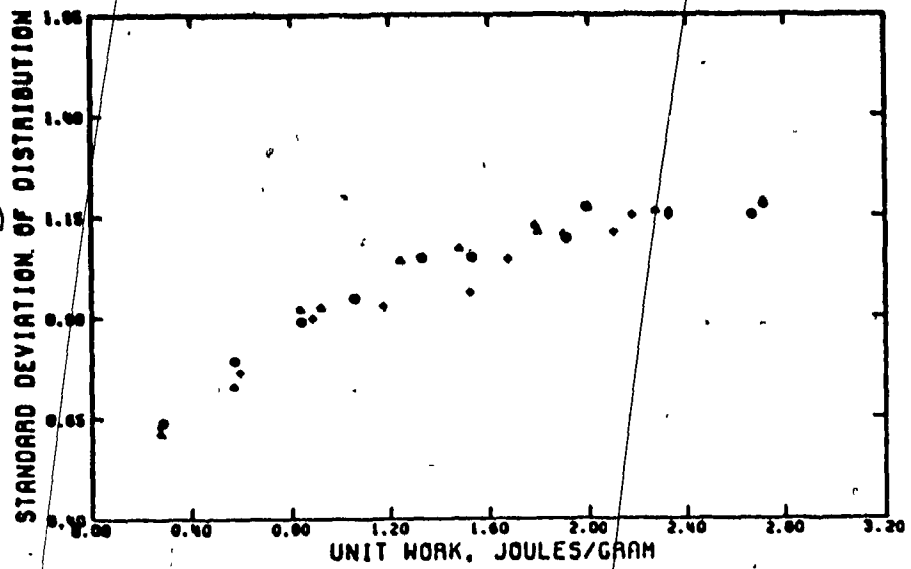


QUARTZITE

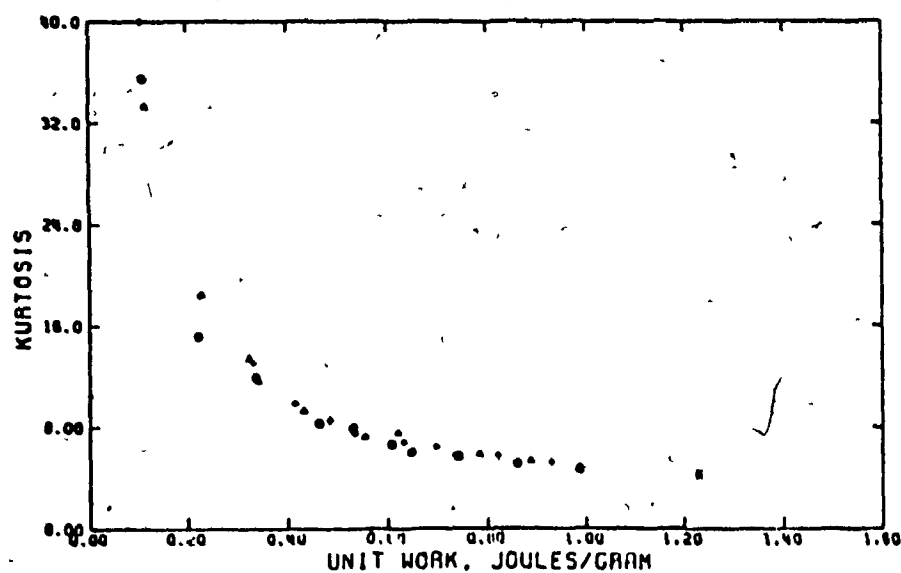
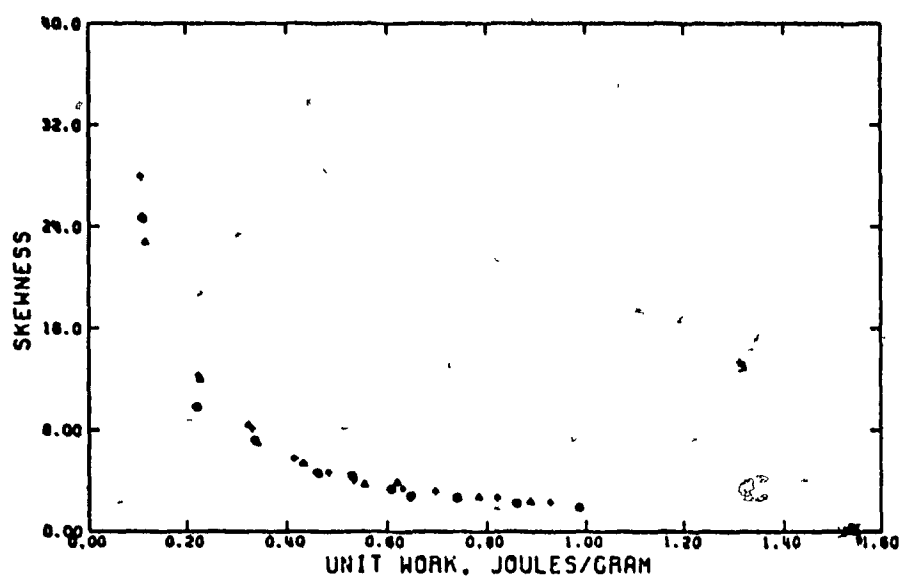
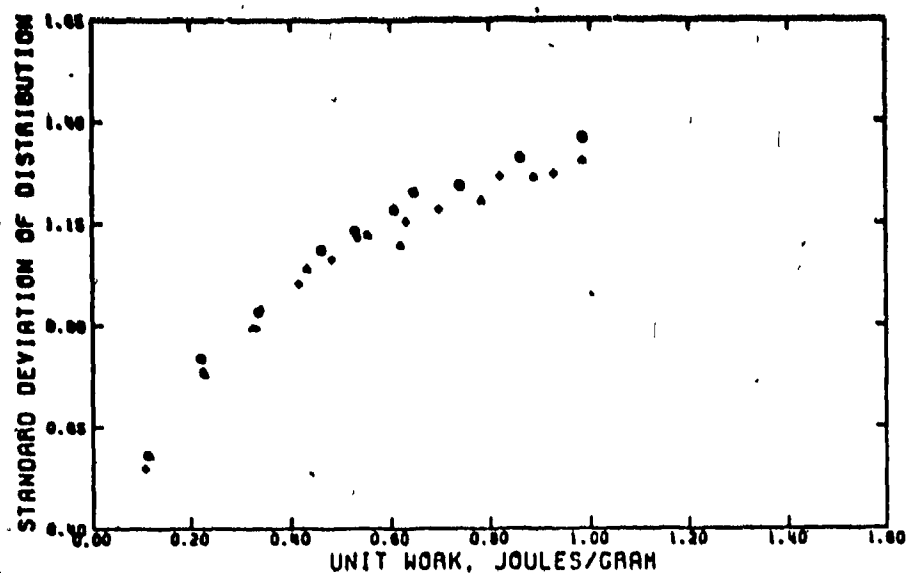
KILOVOLTS : ○ ZERO ▲ 30.0 + 15.0



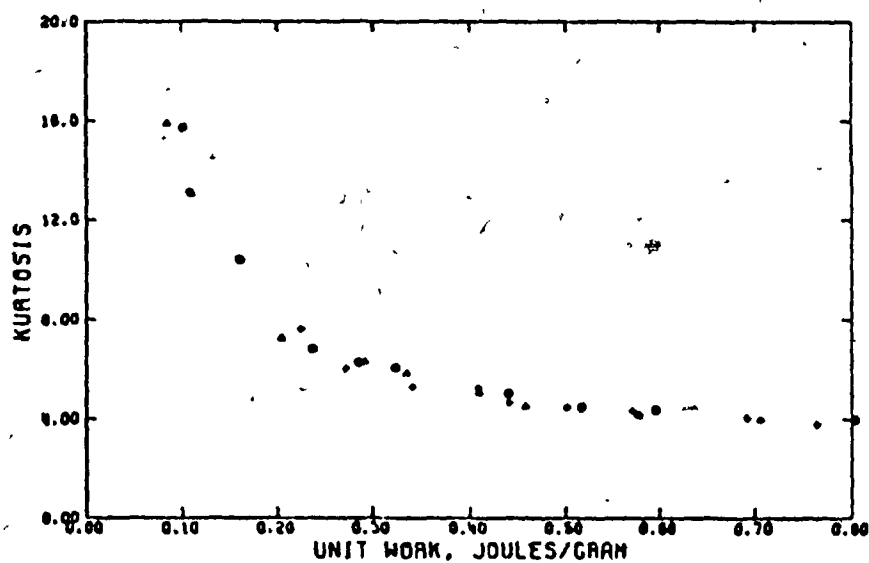
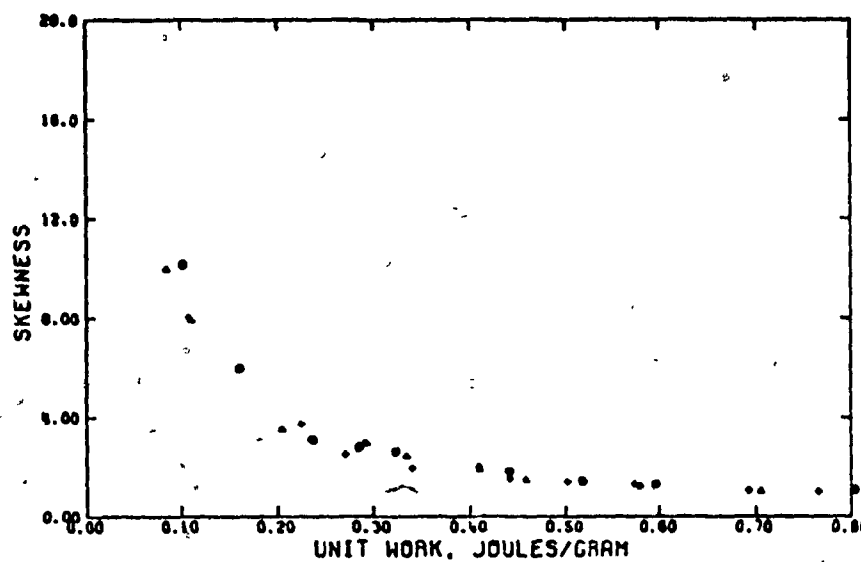
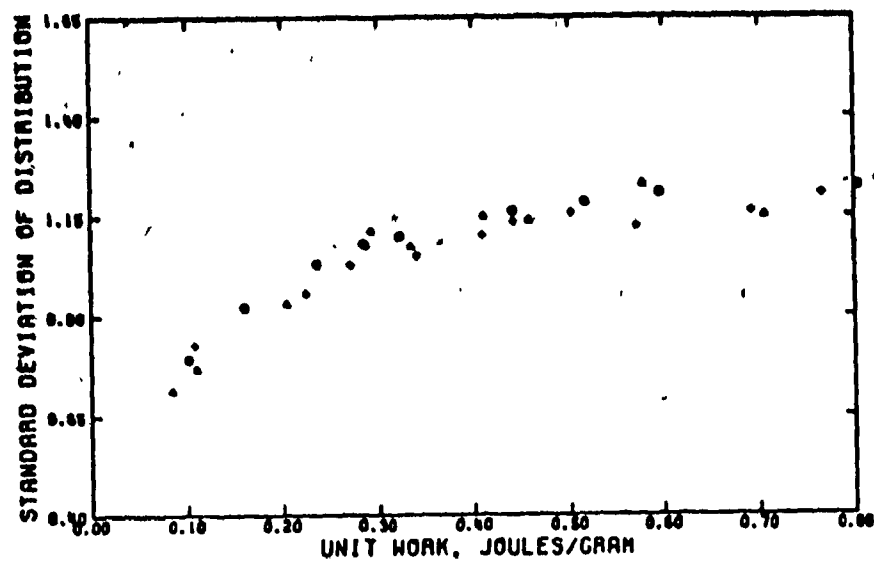
QUARTZITE KILOVOLTS : ○ 7.5 ▲ 22.5



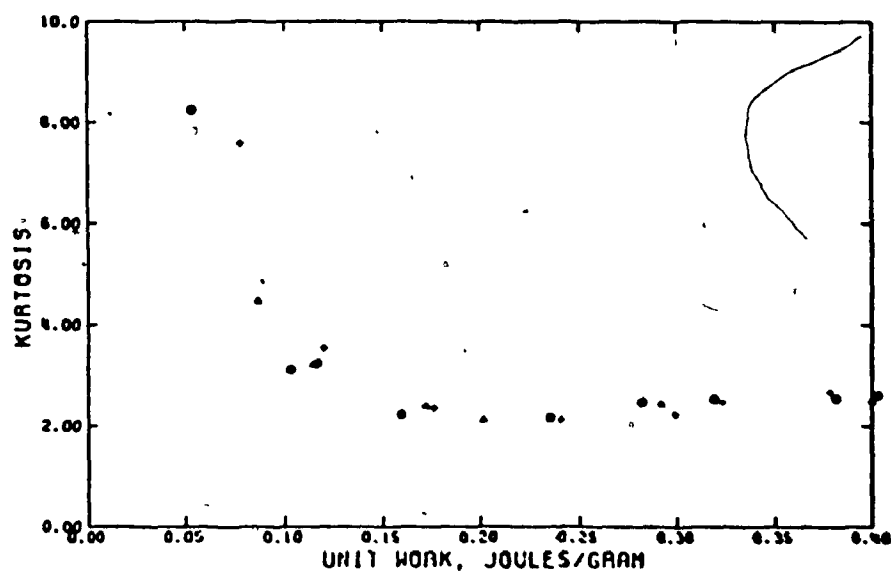
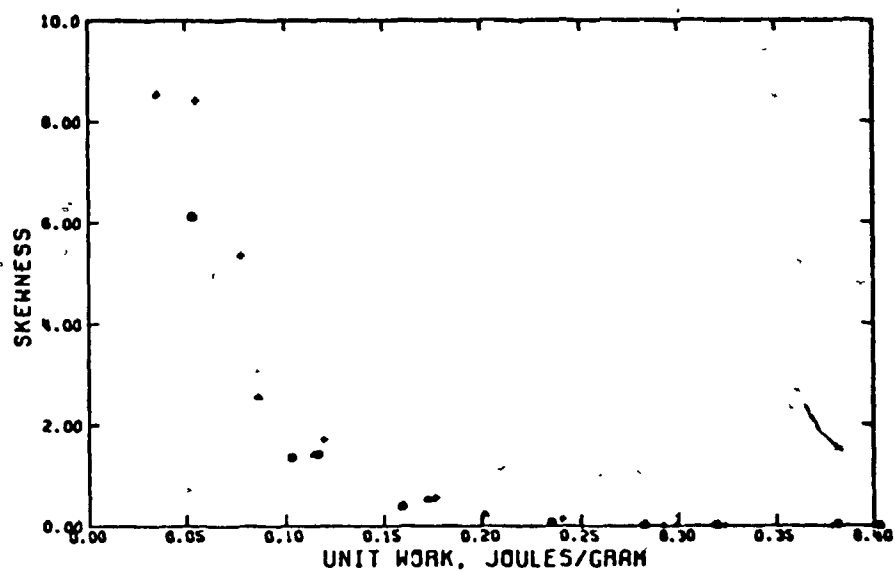
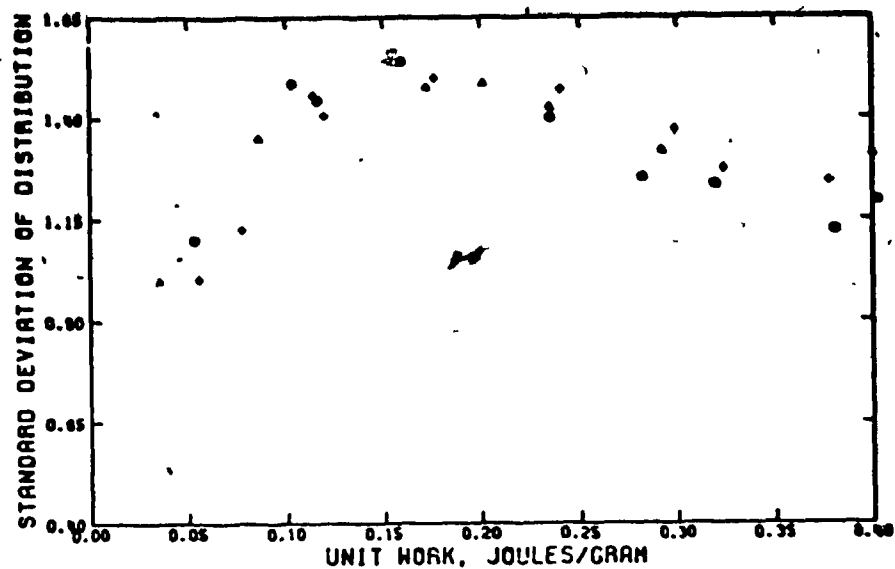
MONO-QUARTZ KILOVOLTS : ○ 0Kv ▲ 10.0 + 15.0



POLY-SPHULERITE KILOVOLTS : ○ 21KV ▲ 36.0 + 16.0

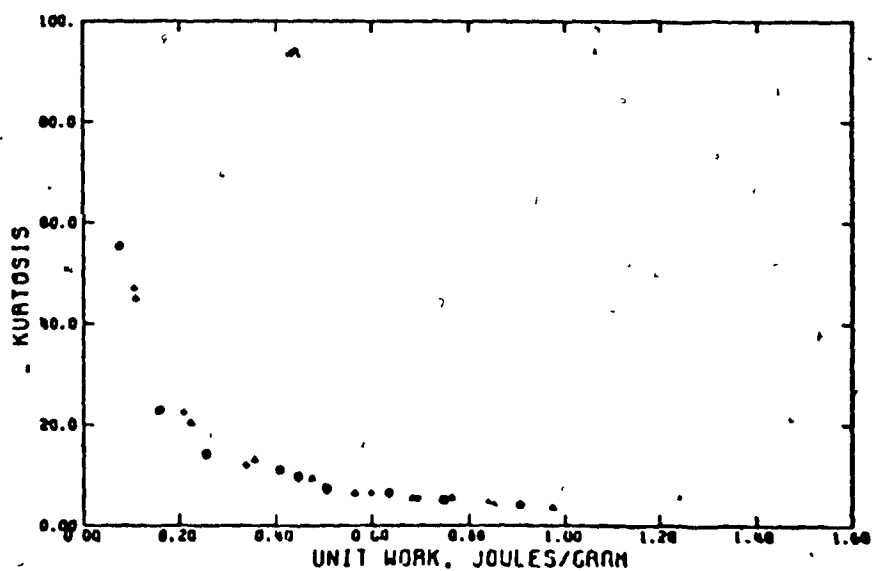
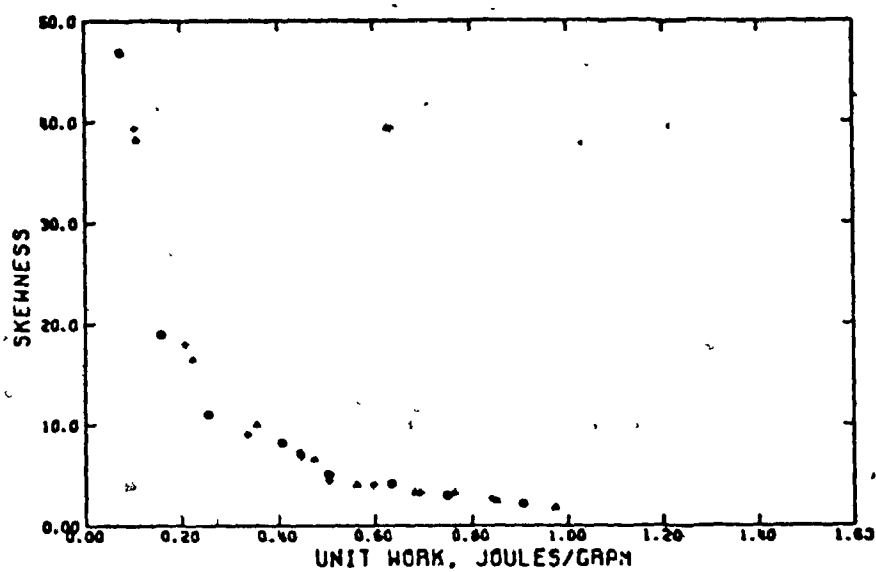
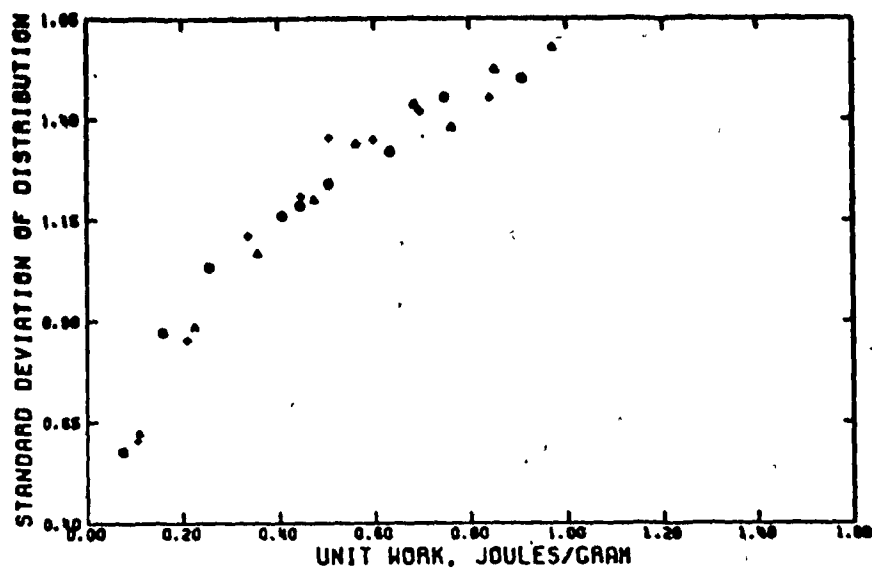


MONO-SPHALERITE KILOVOLTS : ○ 20.0 ▲ 30.0 + 15.0



IRON ORE

KILOVOLTS : ○ 10.0 + 20.0 + 15.0



POLY-METATITE KILOVOLTS : ○ 20.0 ▲ 30.0 + 15.0

appropriate screen interval to find the size value (on the transformed logarithmic scale) corresponding to fifty per cent. This method, although commonly employed (e.g. Schlee and Webster, 1965,67), is ~~imprecise~~, especially with the polymodal distributions encountered in this study and even a precise median value is an inadequate measure of size of a particle distribution which does not retain a constant form. Nevertheless some clear differences are evident between the results obtained under different electric field conditions.

In general, the smoothed curves are sigmoidal, showing small response in the lower unit work region followed by a region of greater near linear response* before final attainment of a maximum value (minimum median size) corresponding to the formation of a packed bed and the effective cessation of comminution.

As with the analyses based on Schuhmann and Rosin-Rammler plots, the results for hematite, Figure X.13., showed no consistent variation between the three levels of applied potential. However, a clear variation is seen with the other five materials. A progressive decrease in comminution

* On the semi-logarithmic plot resulting from the definition of the size units used.

efficiency was again found for quartzite, Figures X.7 and 8., amounting to approximately thirty per cent in the middle of the experimental range. For example, the unit work required to halve the median size of the quartzite feed (from 2.0 to 1.0 mm) is increased from 1.25 to 1.6 J/g.*

In each of the remaining four materials (mono-quartz, mono- and poly-sphalerite and iron ore) a reduction in comminution efficiency in the electric field was also encountered. In the case of iron ore, Figure X.12. and to a lesser extent, with poly-sphalerite, Figure X.10., in the higher unit-work regions, the efficiency is seen to pass through a minimum and to be in part restored at the higher applied voltage, though not regaining the level shown in the absence of a field. The results for mono-quartz, Figure X.9., and mono-sphalerite, Figure X.11., are somewhat scattered so that no conclusion can be drawn from these data about the relative efficiencies resulting from the application of 15 and 30 kV. However, both sets clearly lie below the efficiency curve obtained in zero field.

ii) Means

The mean value is a very much more acceptable

* 1 J/g $\equiv$ 0.278 kWh/tonne.

measure of the overall size as it is based equally on all elements of the distribution. The precision in calculation is limited only by the increment width and, in this study, by the accuracy of the interpolation. It is impossible to evaluate the latter factor (see Appendix IV) but the incremental width could be varied at will to obtain the desired precision. A series of tests at progressively smaller size increments showed that the computed statistics had become essentially constant at and below an increment of 0.01 (log size units), one twenty-fifth of a screen interval. This value was therefore adopted.

As a result, the graphs of distribution mean versus unit work (Figures X.14 to 20), show less scatter than the previous plots and reveal most clearly the effect of the electric field. In general the curves tend to pass smoothly through the origin and are slightly concave downwards, indicating a decrease in the rate at which the mean value changes with increasing work done. Again no change in distribution with change in electrical conditions can be discerned for hematite but the trends noted previously for the other materials are substantiated.

The progressive reduction in efficiency for quartzite

(Figures X.14 and 15) is especially evident in the middle of the work range, approximately 0.4 J/g (23%) more mechanical energy being required to reach a distribution mean value of 1.5 in the field from 30 kV than in the absence of an applied field. Higher percentage differences are encountered at lower unit work levels although the absolute difference is not as great (e.g. an increase of about 0.3 J/g, 32%, is required at a distribution mean value of 1.0, half feed size).

In all the remaining materials a minimum in comminution efficiency is seen, although with the two sphalerite samples the effect only becomes noticeable at work levels greater than 0.4 J/g (Figures X.17 and 18). In each case the curve for 30 kV indicates greater efficiency than that for 15 kV but in no case did the efficiency exceed that obtained with no applied voltage.

The qualitative results of the four measures of product particle size (Schuhmann and Rosin-Rammler size moduli, medians and means) are summarized in Table X.2.

All the previous distribution parameters have been measures of particle size or distribution position. The remaining three computed functions are related to the form

PARAMETER		Schuhmann size modulus	Rosin-Rommeler size modulus	Frequency distribution median	Frequency distribution mean
MATERIAL	VOLTS				
Quartzite	0	A	A	A	A
	7.5	-	B	B	B
	15.0	B	C	C	C
	22.5	-	D	D	D
	30.0	-	E	E	E
Mono-Quartz	0	-	A	A	A
	15.0	-	C	∫	C
	30.0	-	B	∫	B
Poly-Sphalerite	0	-	A	A	A
	15.0	-	∫	C	C
	30.0	-	∫	B	B
Mono-Sphalerite	0	-	A	A	A
	15.0	-	C	∫	C
	30.0	-	B	∫	B
Iron Ore	0	-	A	A	A
	15.0	-	C	C	C
	30.0	-	B	B	B
Poly-Hematite	0	-	∫	∫	∫
	15.0	-	∫	∫	∫
	30.0	-	∫	∫	∫

Note: A, B, C, etc., indicate relative comminution efficiencies (A > B, etc.).

∫ indicates no data.

∫ indicates indistinguishable data sets.

Table X.2. Summary of Distribution Size Results.

of the distribution and are independent of its position.

iii) Standard Deviation

The standard deviation is a measure of the width of the distribution about the mean value and is therefore comparable with the gradient of a cumulative plot. It is, however, a very much more sensitive measure in that all elements of the frequency distribution are used in its calculation.

Figures X.21 to 27 show the variation of standard deviation with increasing unit work. The general form is a smooth curve, concave downwards, passing through the origin (see Table X.1.)). Although in a few cases some tendency to an ordering is suggested (quartzite, for example, apparently tending to lower values of standard deviation with increasing electric field strength, Figures X.21 and 22.), no consistent shift is discernable and it is concluded that no significant field effect has been detected. This is in agreement with the earlier results in which the gradient of cumulative plots was considered constant.

iv) Skewness and Kurtosis

The significance of these parameters is described in Appendix I. Both are measures of the shape

of a frequency distribution, not size, and it was shown earlier (page 120) that both are very sensitive to variations in the extremes of the distribution. Skewness versus unit work graphs are presented in Figures X.28 to 34 and kurtosis versus unit work in Figures X.35 to 41. Both parameters are seen to fall from initially high values and reach or approach equilibrium values at high unit work levels. (This is especially striking in the case of iron ore, Figure X.33, which rapidly attains a skewness value of zero, indicating symmetry about the mean. This value is then maintained at higher values of unit work.) However no significant variation is detected with changing field conditions.

X.3. Liberation

Two approaches were made in an attempt to determine if liberation had been affected by the application of an electric field.

i) Modal analysis

The first method depends on the fact, noted on page 14, that if liberation is enhanced, a mode (peak) will be emphasized in the particle size frequency distribution at a size value corresponding to the natural grain size. The

location and magnitude of the modes of each of the frequency distributions are given in table form in Appendix VI.4.

These results were carefully examined in conjunction with the frequency distributions to determine if any significant changes had resulted from crushing in an electric field.

Special attention was paid to the quartzite data in the region of the grain size mode, 0.63 mm (log size value 1.67) but no consistent differences in the data from the various electrical field conditions were noted.

ii) Float and sink analysis

The results of the float and sink tests on the iron ore are tabulated in Appendix VI.5. and presented graphically in Figure X.42. It is seen that no changes in per cent floats were effected by the application of high voltage.

X.4. Evaluation

A rigorous statistical evaluation of the significance of the detected changes in distribution parameters effected by the application of an electric field in the crushing zone is difficult to devise. No theoretical expressions are available for the relationships between distribution parameters and unit work so that comparisons

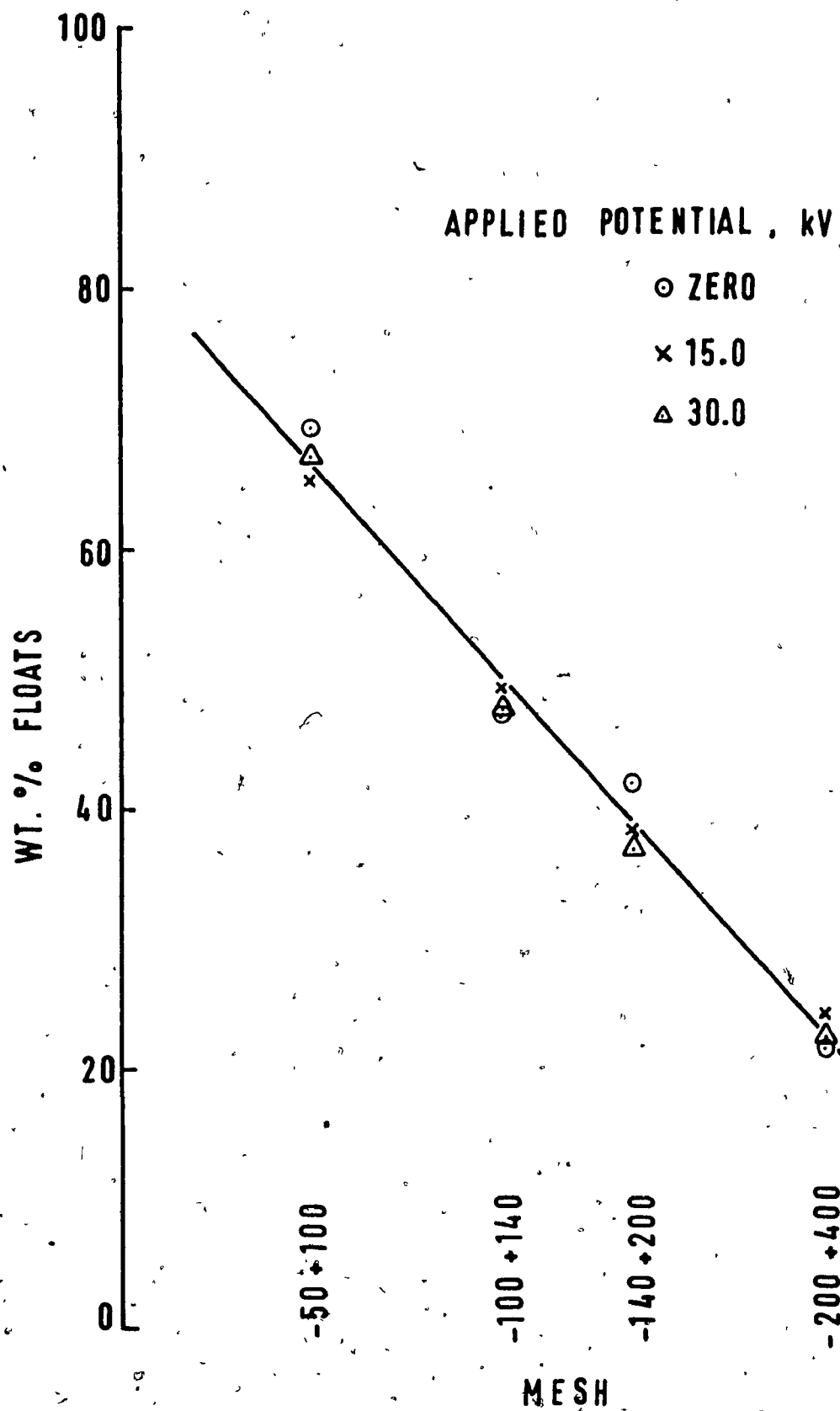


Figure X.42. Float and Sink Test Results

had to be made between empirical curves fitted to the experimental data. The general form of these curves is indicated in Figure X.43. Only the curves of distribution mean versus unit work were tested as a) these curves most clearly showed the effect of the electric field and b) the curves were most amenable to simple mathematical description. (The latter factor was not merely a matter of convenience. The use of a simple expression, a low order polynomial in this case, materially increases the confidence in the derived measure of significance by retaining a high number of degrees of freedom.) The method is as follows.

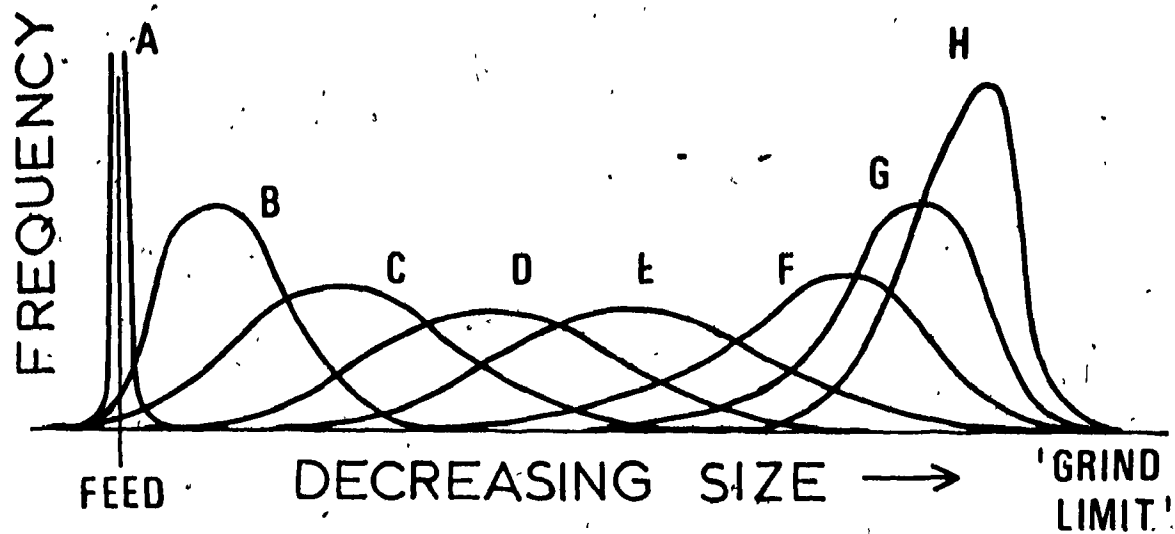
Using a modified* version of the McGill computer routine 'CURVFT' a best-fit low order polynomial, constrained to pass through the origin, was computed for each data set. The program was extended to give a value of the standard deviation, σ , of the data from the fitted curve, defined by

$$\sigma = \sqrt{\frac{\sum (\bar{y} - y)^2}{n - N - 1}} \quad \dots (32)$$

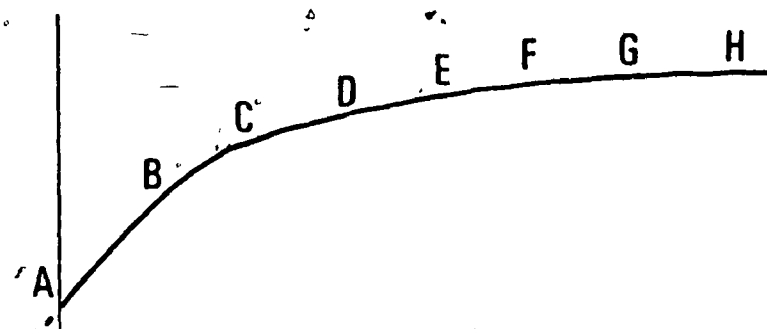
* The program, which has been in use at McGill for over ten years, was found to include an erroneous assumption. A corrected procedure was written by the author and is being incorporated into the McGill library routine.

FIGURE X.43.

General Form of Distribution Parameter versus
Unit Work Relationships



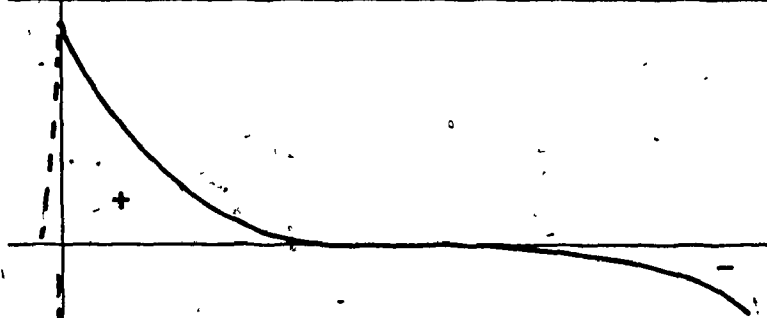
MEDIAN
& MEAN



STANDARD
DEVIATION



SKEWNESS



KURTOSIS



UNIT WORK →

where $\bar{y}$ and y are the computed and experimental distribution mean values respectively, n is the number of data points and N is the order of the fitted polynomial. The denominator denotes the number of degrees of freedom less one, the latter being Bessel's correction for small data sets (Miller and Freund, 1965).

The CURVFT routine uses the sum of squares of deviations ($\sum (\bar{y} - y)^2$) as a measure of goodness of fit. This takes no account of the curve fitting procedure, however, and minimization of the standard deviation was substituted as a preferable criterion.* On this basis little advantage was found in using polynomials of greater than second order. Values of the standard deviations for second order polynomials fitted to the experimental data are given in Table X.4., together with the coefficients of the second order polynomials. The resultant curves are shown in Figures X.44 to 50., the points being those previously shown in Figures X.14 to 20.

* For any line passing through all data points, a fitted polynomial of degree $(n - 1)$ for example, the sum of squares becomes zero, falsely indicating a high degree of confidence. The standard deviation would be infinite, however, indicating the unreasonableness of such a fitted curve.

	kV	UNIT WORK, J/g X	NO. OF POINTS n	C ₁	C ₂	Mean* (x)	STANDARD DEVIATION σ
Quartzite	0		10	1.15652	0.14378	1.48236	0.0698
	7.5		10	1.04995	0.11344	1.38951	0.0440
	15.0	1.6	10	0.99014	0.09069	1.35206	0.0411
	22.5		10	0.94964	0.08067	1.29851	0.0802
	30.0		10	0.82179	0.03745	1.21899	0.0923
Mono-Quartz	0		10	1.02219	0.11664	1.20245	0.0476
	15	1.4	10	0.81380	0.03588	1.06900	0.0511
	30		10	0.90999	0.07150	1.13385	0.0626
Poly-Sphalerite	0		10	1.86647	0.45239	0.95702	0.0186
	15	0.6	10	1.83819	0.57241	0.89685	0.0424
	30		10	1.83418	0.54213	0.90534	0.0321
Mono-Sphalerite	0		9	4.18143	2.35681	1.29548	0.0556
	15	0.4	10	4.15888	2.65337	1.23901	0.0499
	30		10	4.03487	2.21860	1.25897	0.0444
Iron Ore	0		9	12.26977	12.53808	1.95243	0.1297
	15	0.2	8	9.03631	3.87750	1.65216	0.1264
	30		9	11.66270	11.79611	1.86070	0.1468
Poly-Hematite	0		9	1.70951	0.25210	0.93495	0.0395
	15	0.6	8	1.76271	0.33266	0.90505	0.0666
	30		9	1.52620	0.0	0.91572	0.0590

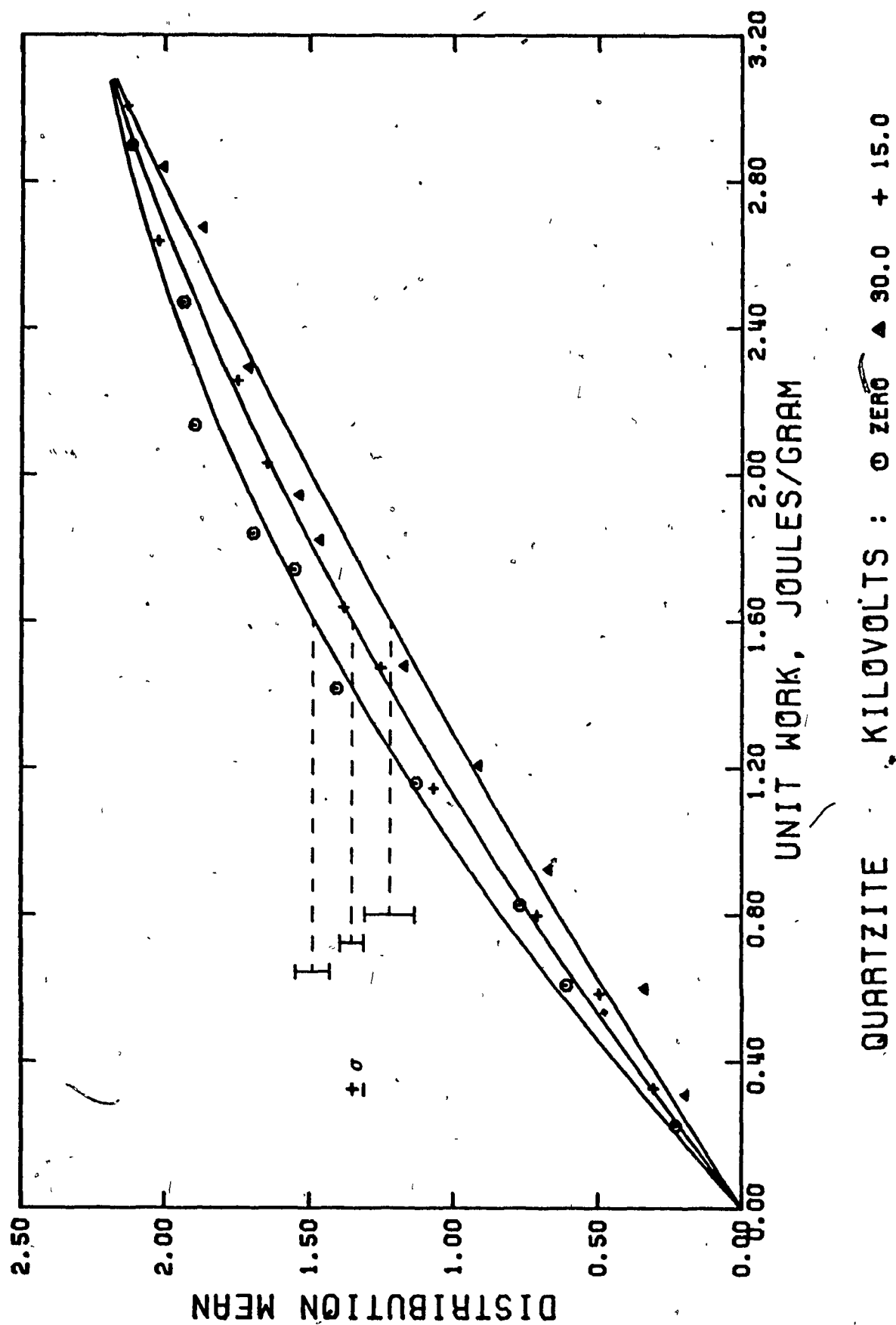
* Mean = $C_0 + C_1 X - C_2 X^2$, $C_0 = 0$

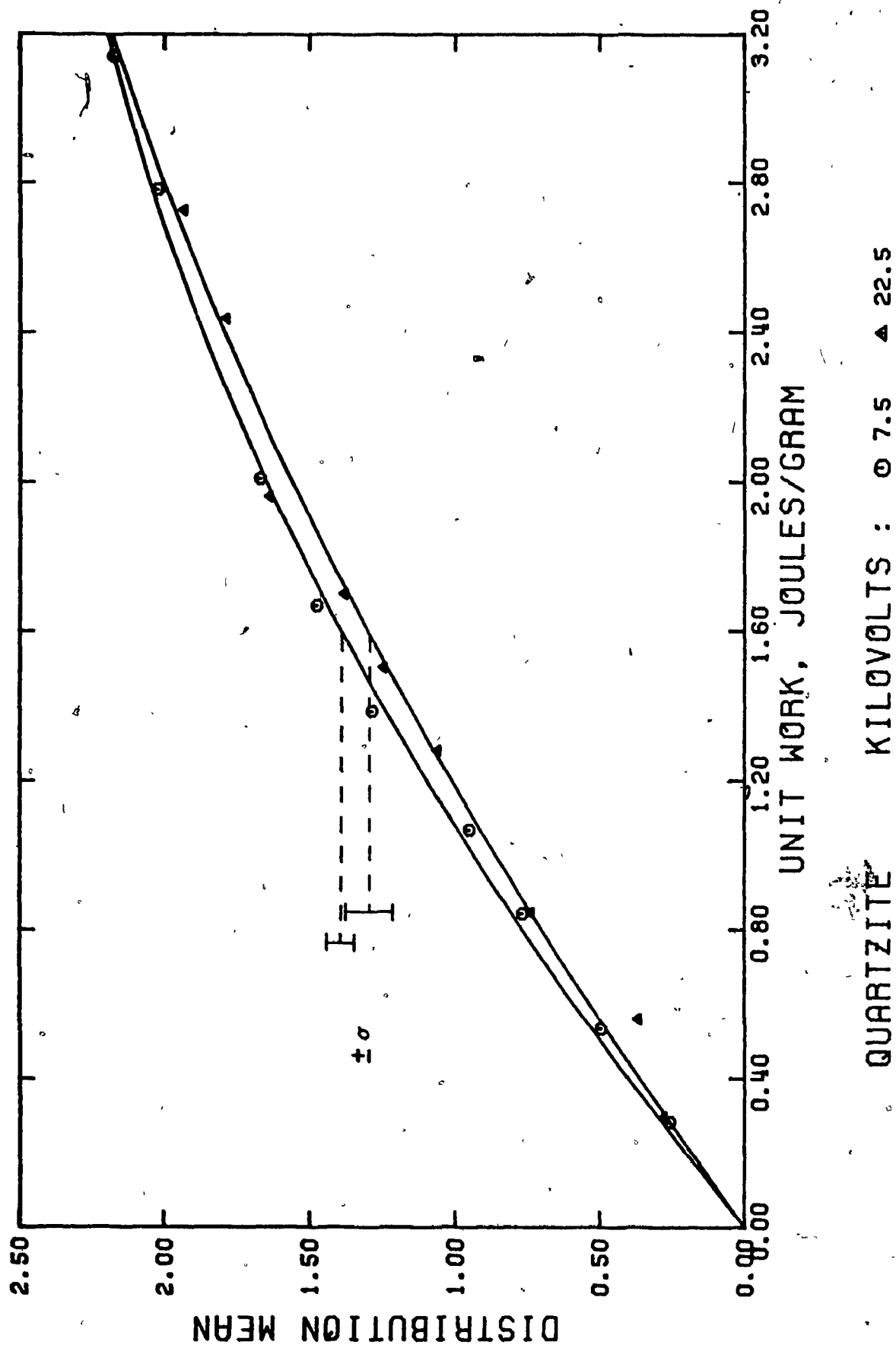
Table X.3. Binomial Fitting to Experimental Data.

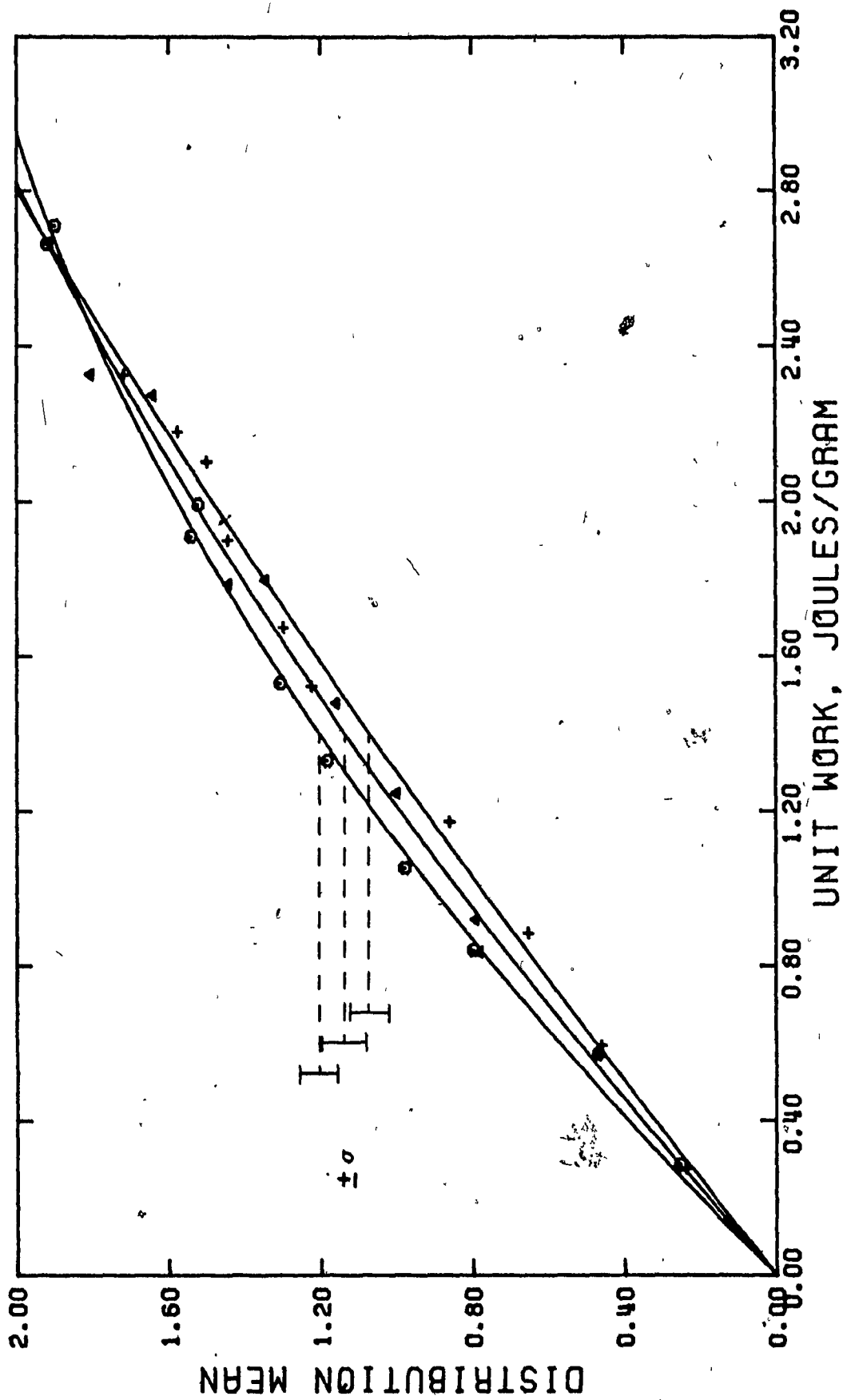
FIGURES X.44 to 50.

Best-fit Binomial Curves to
Means vs. Unit Work Data

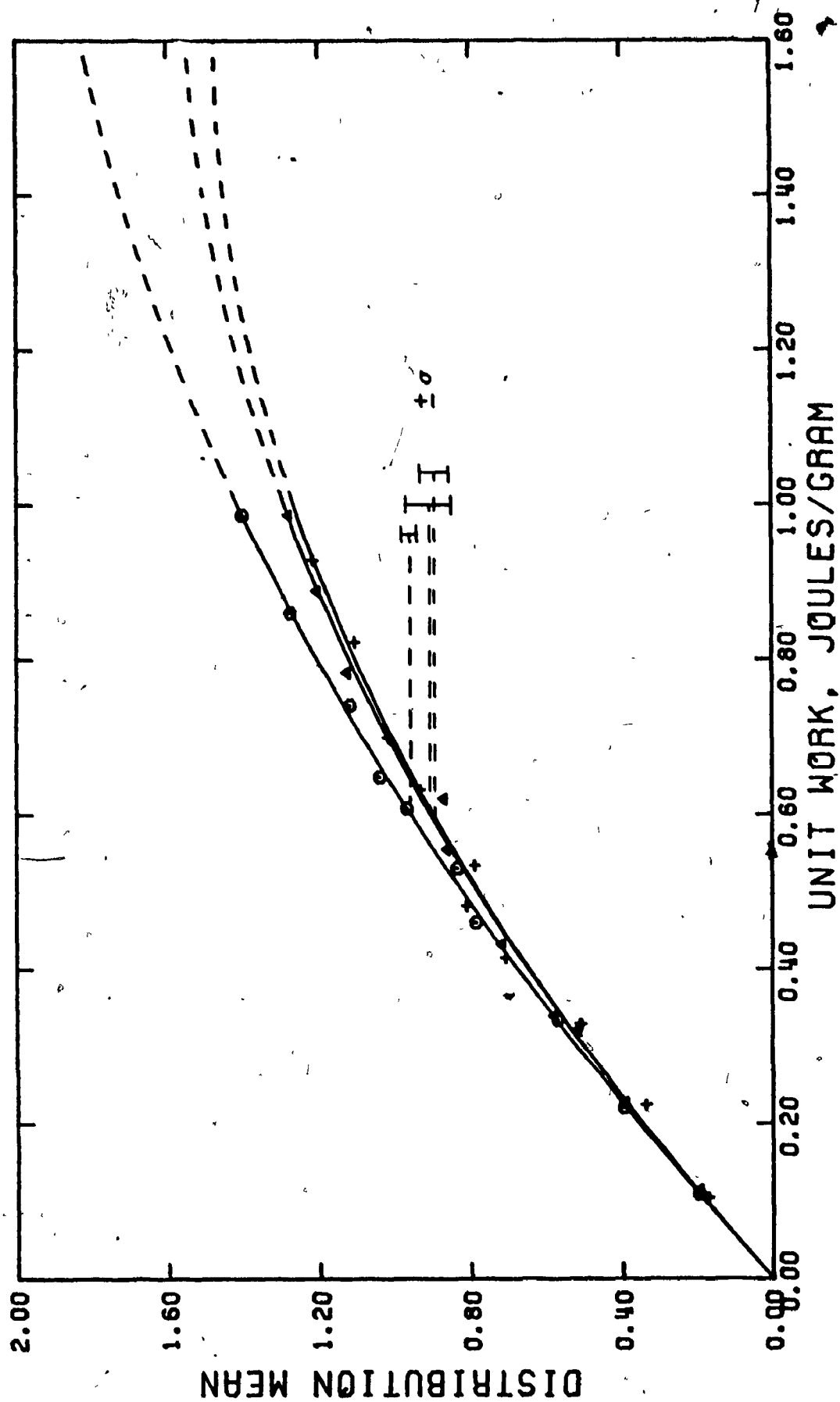
Figure X.44.	Quartzite; 0, 15, 30 kV	page 152
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Figure X.46.	Mono-Quartz	154
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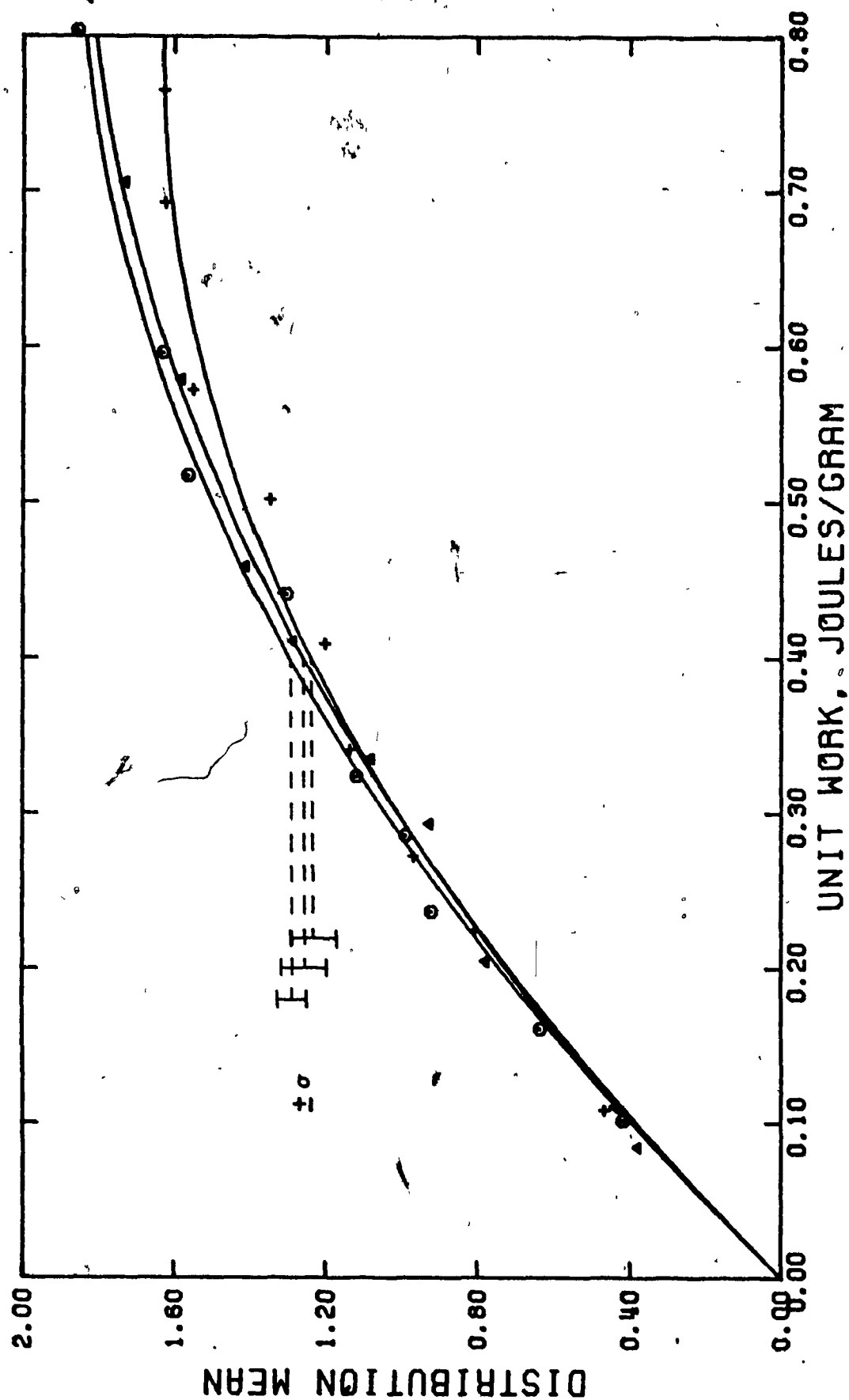




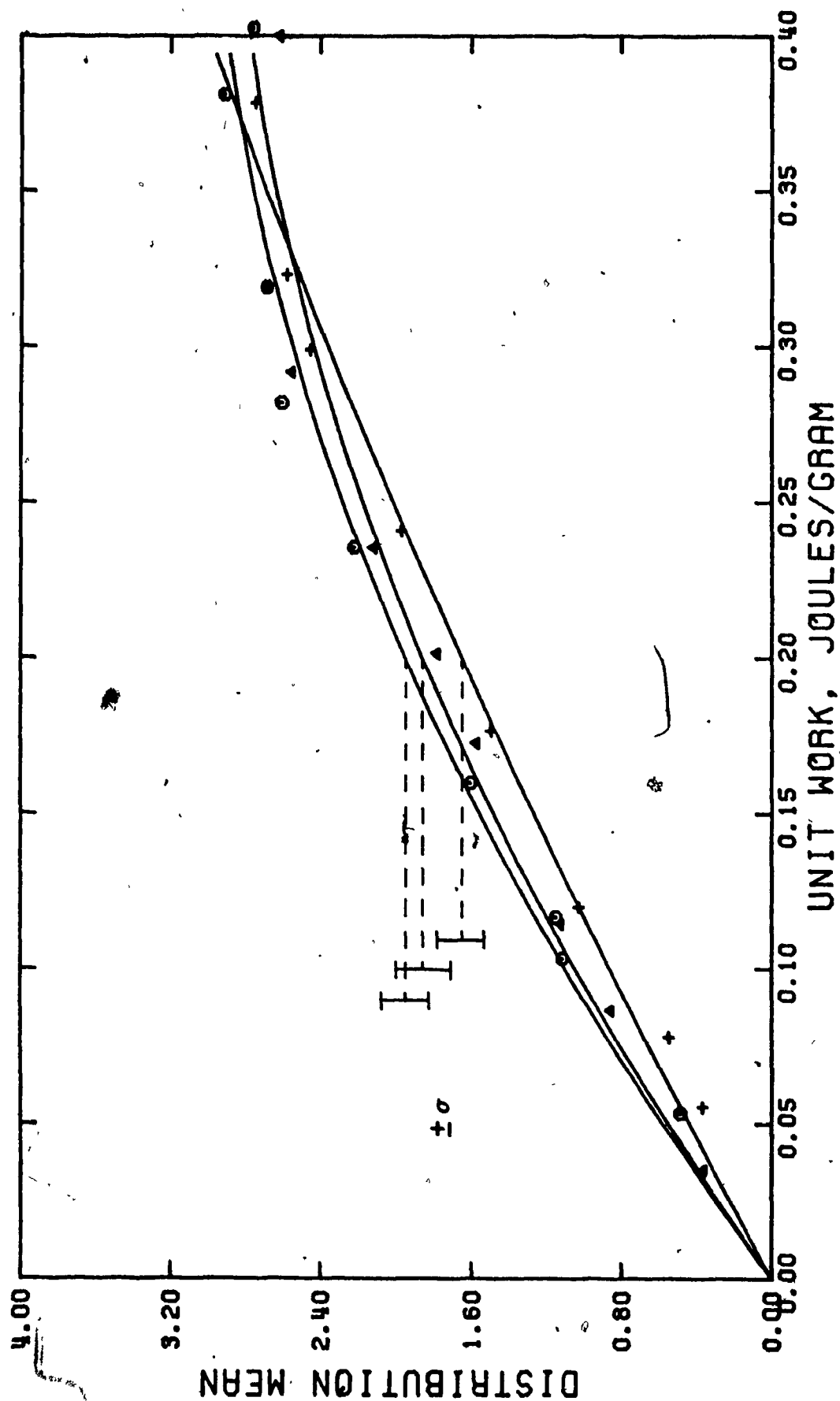
MONO-QUARTZ KILOVOLTS : ○ ZERO ▲ 30.0 + 15.0



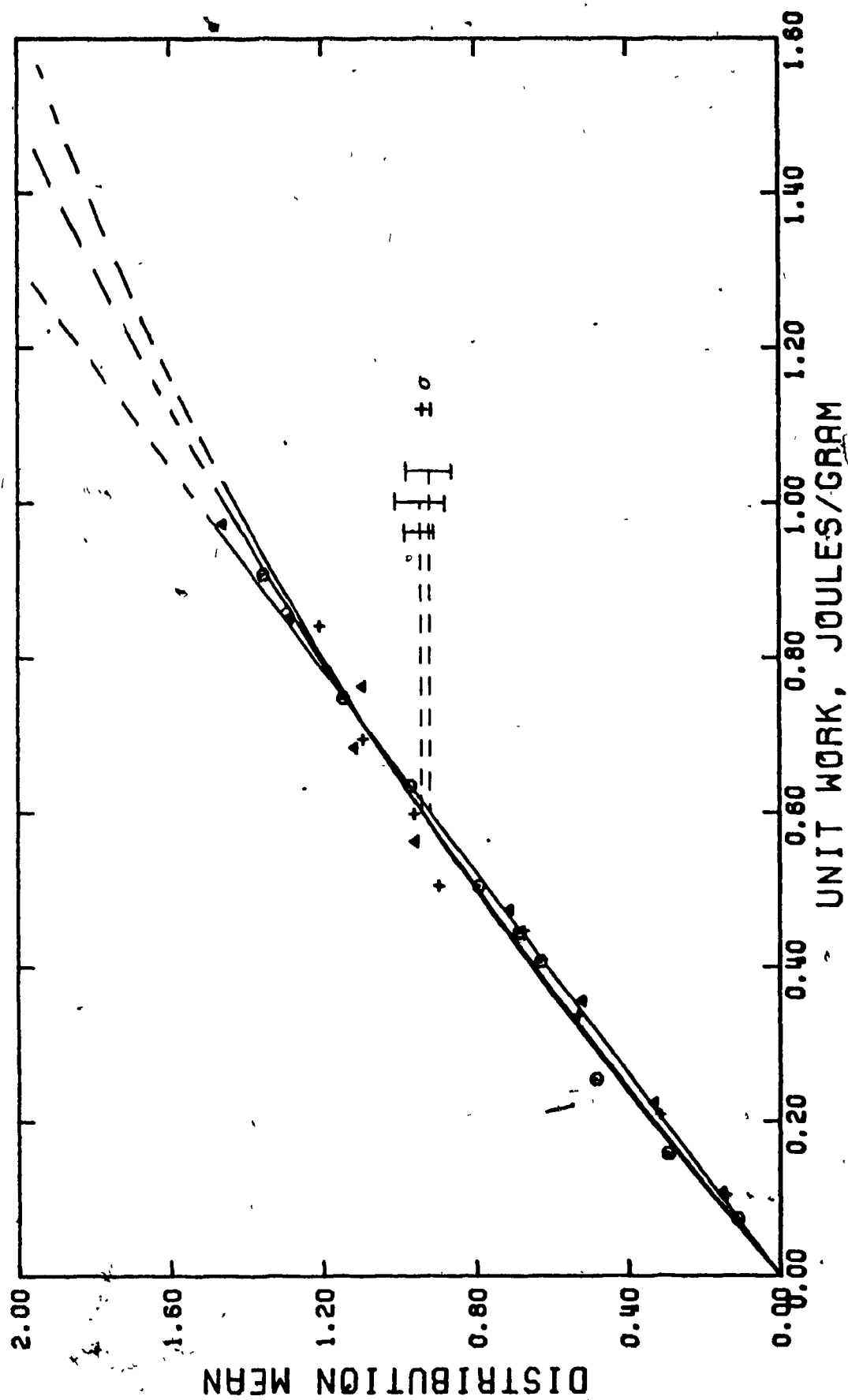
POLY-SPHALERITE KILOVOLTS : ○ ZERO ▲ 30.0 + 15.0



MONO-SPHALERITE KILOVOLTS : ○ ZERO ▲ 30.0 + 15.0



IRON ORE KILOVOLTS : 0 ZERO ▲ 30.0 + 15.0



Standard deviations can properly be considered valid only in the middle of the experimental range. This was the region in which the greatest field effects were observed in almost every case. The bars, $\bar{}$, drawn on the graphs show the standard deviations for each curve and give a qualitative indication of the significance of the noted differences. A quantitative measure was made, based on Student's t test (Moroney, 1951). Values of t were calculated for each pair of curves from the equation:

$$t = \frac{|\bar{x}_1 - \bar{x}_2|}{\sqrt{\left(\frac{n_1 \sigma_1^2 + n_2 \sigma_2^2}{n_1 + n_2 - 2} \right) \left(\frac{1}{n_1} + \frac{1}{n_2} \right)}} \quad \dots (33)$$

where $\bar{x}$ is the mean value of the sample (taken as the computed value of the best-fit curve at mid-range), n is the number of data points and σ is the standard deviation.

The significance of each observed difference was then determined from published tables (Brookes and Dick, 1951; Spiegel, 1961) for $(n_1 + n_2 - 2)$ degrees of freedom. Values of t and the corresponding levels of confidence are given in Table X.5. It is seen that the subjective conclusions presented earlier are substantiated by this test.

MATERIAL	kV	UNIT WORK J/g	n	MEAN ($\bar{x}$)	STD. DEV.	STUDENT'S t / CONFIDENCE LIMIT*				
						0 kV	7.5 kV	15.0 kV	22.5 kV	30.0 kV
Quartzite	ZERO	1.6	10	1.4824	0.0698	-				
	7.5	1.6	10	1.3895	0.0440	3.38/99.5	-			
	15.0	1.6	10	1.3521	0.0411	4.83/99.9	1.87/90.0	-		
	22.5	1.6	10	1.2985	0.0802	5.19/99.9	2.98/99.0	1.78/90.0	-	
	30.0	1.6	10	1.2190	0.0923	6.83/99.9	5.00/99.9	3.95/99.9	1.95/90.0	-
Mono- Quartz	ZERO	1.4	10	1.2025	0.0476	-				
	15.0	1.4	10	1.0690	0.0511	5.73/99.9		-		
	30.0	1.4	10	1.1339	0.0626	2.62/97.5		2.41/30.0		-
Poly- Sphalerite	ZERO	0.6	10	0.9570	0.0186	-				
	15.0	0.6	10	0.8969	0.0424	3.90/99.5		-		
	30.0	0.6	10	0.9053	0.0321	4.18/99.9		0.48/30.0		-
Mono- Sphalerite	ZERO	0.4	9	1.2955	0.0556					
	15.0	0.4	10	1.2390	0.0499	2.21/95.0				
	30.0	0.4	10	1.2590	0.0444	1.50/75.0		0.90/50.0		
Iron Ore	ZERO	0.2	9	1.9524	0.1297					
	15.0	0.2	8	1.6522	0.1264	4.53/99.9				
	30.0	0.2	9	1.8607	0.1468	1.32/75.0		2.93/99.0		
Poly- Hematite	ZERO	0.6	9	0.9350	0.0395					
	15.0	0.6	8	0.9060	0.0666	1.04/50.0				
	30.0	0.6	9	0.9157	0.590	0.77/50.0		0.30/30.0		

* e.g. Confidence level of 95.0. Observed difference would be expected in only 5% of tests if data were drawn from the same population.

Table X.4. Student's t test for Significance of results.

XI. DISCUSSION

XI.1. Introduction

The experimental program was designed to test for and explore a predicted change in comminution efficiency when piezoelectric minerals were crushed while subjected to an intense electric field. However, instead of the expected decrease in the mechanical energy required to achieve a specified degree of size reduction, a decrease in crushing efficiency was generally found. In addition, in several cases the efficiency was seen to pass through a minimum and, at higher field strengths, to improve again, though never quite regaining the level noted in zero field. Quartzite exhibited a substantial decrease in efficiency which became progressively greater with higher field strengths and hematite showed no discernable effect whatsoever.

In this chapter the experimental conditions will first be reviewed briefly, followed by a more thorough consideration of the stresses set up in piezoelectric materials when subjected to fields of the order used in the experiments. Finally, some alternative mechanisms which

may have contributed to the results will be discussed.

XI.2. Calculation of the Electric Field

The electric field experienced by a particle can be determined from equation (30) by substituting appropriate values for particle size, alumina plate thickness and the relative dielectric constants. From Figure VI.8. the average particle size is seen to be approximately 1.0 mm with limits of 2.5 and 0.25 mm. Relative dielectric constants are: for alumina ceramic, 9.8 (Ferreira et al., 1970); quartz, 4.5 (mean values in and perpendicular to optic axis), and sphalerite, 8.3 (both from Parkhomenko, 1971). Total alumina plate thickness (2 x 1/8 inch) = 6.36 mm.

The results for each mineral and particle are given in Table XI.1. Particles experience up to 10^7 V/m with 30 kV applied potential.

Size, mm	0.25	1.0	2.5
Material			
QUARTZITE	300.V	250.V	180.V
SPHALERITE	170.V	150.V	120.V

where V = applied potential in volts.

Table XI.1. Field Strength (V/m) Experienced by Quartz and Sphalerite Particles

XI.3. The Piezoelectric Hypothesis

The simple approach given in Chapter III only took into account the strain produced in one axial direction of a single crystal. As a critical stress criterion was assumed for fracture, no consideration was given to transverse or shear stresses occurring as a result of the applied field. For the same reason, only parallel alignment between the polar axis and the electric field was considered. The effect of adjacent grains was also only touched briefly, no attempt being made at a thorough treatment of the granular interactions in polycrystalline materials. In Chapter I, the stress distribution in a polycrystalline material was shown to be extremely complicated, depending on the relative physical properties of the components, their shape, volumetric abundance, orientation and distribution, the nature of the intergranular bond, and on the mode of stress. It is impossible to account for all these factors satisfactorily but some improvements on the original model can be made as follows.

i) Monocrystalline Particles

No constraint due to neighbouring grains is experienced so that the particle will strain as predicted by

the appropriate piezoelectric equations. The interactions of this strain with that due to the mechanically applied stress will depend upon the crystallographic orientation of the particle with respect to the electric field and the stress direction. Gallagher (1971) showed that fracture occurs along the trajectories of maximum compressive stress, (which are aligned between loading points in the particle) and is therefore due to tensile forces perpendicular to the direction of loading. With irregular particles such as those used in this study, the precise direction of the compressive stress trajectories is not known but, in general, with the single layer of particles tested, they will tend to the vertical (Figure XI.1.). The resultant fracture-

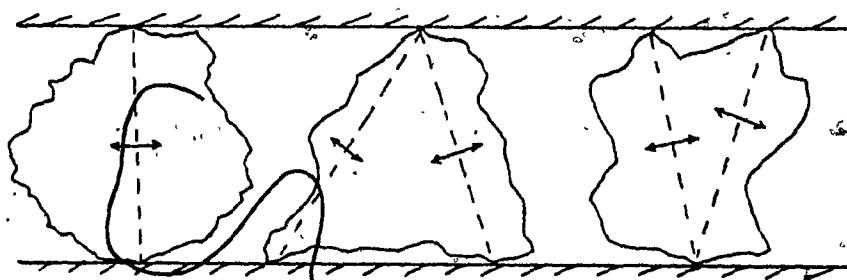


Figure XI.1. Principal Stress Trajectories in Single Particles.

producing tensile stress or strain is therefore in the plane of the crushing platens, perpendicular to the applied field. Thus, only those piezoelectric strains with a component in this plane would be expected to contribute to the fracture

process. Consequently, transverse piezoelectric effects are generally of greater importance than the longitudinal effect.

The longitudinal strain in quartz is given by equation (18) from which the equivalent expression for the longitudinal stress is

$$T_1 = e_{11}E_1 \quad \dots (34)$$

where $e_{11} = 0.19 \text{ C/m}^2$ (Parkhomenko, 1971).

The transverse strain is given by equation (19), from which the transverse stress,

$$T_2 = - e_{11}E_1 \quad \dots (35)$$

Expressions have been derived which permit calculation of modified values for the piezoelectric moduli and constants, d and e , for rotation about one or more coordinate axes (Cady, 1946b). However, in the present study a further transposition is required to determine stresses perpendicular to the field for random orientation of the crystal lattice. The general case is indicated in Figure XI.2.

Referring to the diagram, we have for the

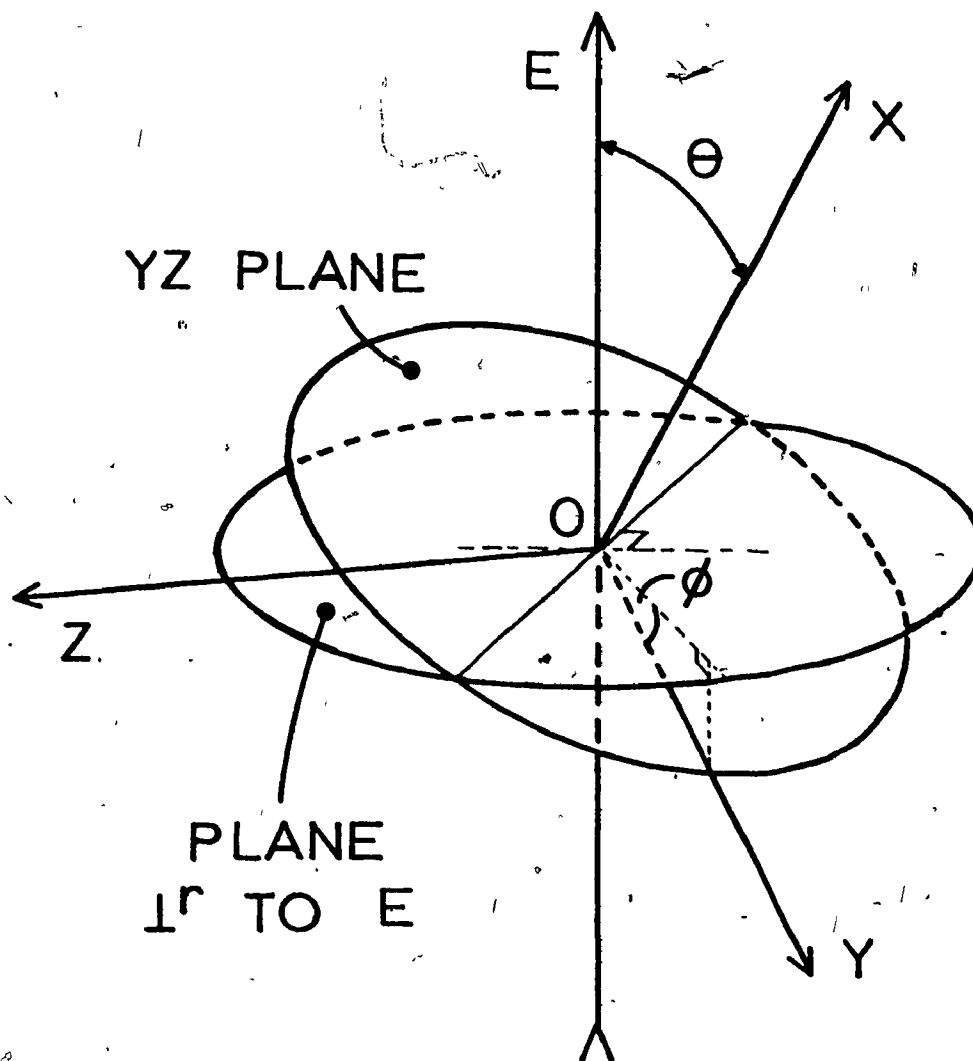


FIGURE XI.2.

Rotation of Axes

longitudinal effect:

$$\text{Component of } E \text{ along X axis} = E \cos \theta \quad \dots (36)$$

$$\text{Resultant stress along X axis, } T_1 = e_{11} E \cos \theta \quad \dots (37)$$

and Component of stress perpendicular to E

$$= e_{11} E \cos \theta \sin \theta \quad \dots (38)$$

where θ is the angle between the polar (X) axis
and the direction of the electric field.

For the transverse effect:

$$\text{Resultant stress along Y axis, } T_2 = -e_{11} E \cos \theta \quad \dots (39)$$

and Component of stress perpendicular to E

$$= -e_{11} E \cos \theta \cos \phi \quad \dots (40)$$

where ϕ is the acute angle between the Y axis
and the plane perpendicular to E.

On rotation of the crystal lattice about the polar axis,

ϕ takes values

$$0 \leq \phi \leq \theta, \quad \theta \leq \pi/2 \quad \dots (41a)$$

$$\text{and } 0 \leq \phi \leq \pi - \theta, \quad \theta > \pi/2 \quad \dots (41b)$$

The angle of θ may take values

$$0 \leq \theta \leq \pi \quad \dots (42)$$

Summing the resolved longitudinal and transverse stresses,

stress is given by:

$$T = e_{11} E \cos \theta \sin \theta - e_{11} E \cos \theta \cos \phi \quad \dots (43a)$$

$$= e_{11} E \cos \theta (\sin \theta - \cos \phi) \quad \dots (43b)$$

Angles θ and ϕ can vary independently, within the limits given by equations (41) and (42), and the variation of ϕ is not a simple function so that a full analysis of stress variation with varying orientation of the crystal lattice may best be accomplished by numerical methods. However, useful information can be obtained by inspection as follows.

As θ increases from zero to π , $\cos \theta$ goes from -1 to +1, taking a value of zero at $\theta = \pi/2$ at which point the entire function (equation (43)) becomes zero. The expression in brackets reflects the greater significance of the transverse effect as $\cos \phi$ is, on average, greater than $\sin \theta$ (as the mean value of ϕ is approximately $\frac{1}{2} \theta$). Consequently, although $(\sin \theta - \cos \phi)$ is symmetrical about $\theta = \pi/2$ and varies between -1 and +1, the mean value is between 0 and -1. The full expression for T thus takes values between $-e_{11} E$ and $+e_{11} E$ and is symmetrical about $\theta = \pi/2$, the mean stress for zero and the magnitude of the mean tensile (or compressive) stress is appreciably less than $e_{11} E$.

In terms of the bed of randomly oriented monocrystalline particles tested, these results show that, whereas some grains should experience tensile stress (of magnitude up to $e_{11}E$) tending to assist comminution, a similar number will experience a compressive piezoelectric stress of equal magnitude which will tend to interact negatively with the mechanically applied stresses, giving apparent strengthening. The number of particles tested was near to one hundred initially and rapidly increased during a test so that it is reasonable to assume that, on average, an equal number of particles were effectively strengthened as were weakened by the piezoelectric effect. No overall effect would therefore be expected with monocrystalline quartz particles.

Sphalerite experiences shear when subjected to an electric field in a plane perpendicular to each polar axis. As mineral fracture occurs as a result of tensile stress (Oka and Majima, 1970; Gallagher, 1971) the shear must be resolved first into tensile and compressive components in the shear plane and at angles $\pm 45^\circ$ from the shear axis (Figure XI.3.).

The appropriate piezoelectric constants are halved by this rotation (Jaffe, 1969) so that we may rewrite

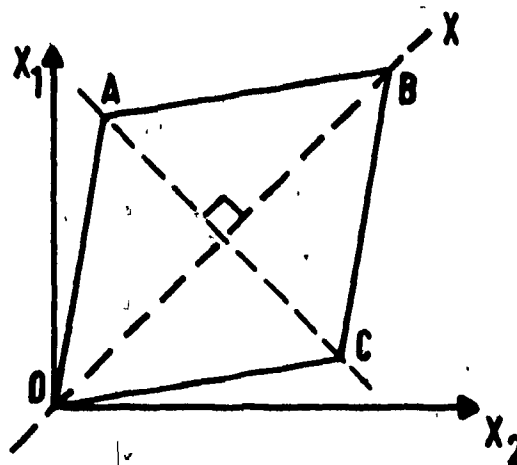


Figure XI.3. Resolution of Shear into Linear Stress or Strain by Rotation of Axes

equations (26) to (28) in terms of the 45° rotated axes OX' etc. as follows.

$$\text{Equation (26), } S_4 = d_{14} E_1$$

$$\text{becomes } S'_1 = \frac{1}{2} d_{14} E_1 \quad \dots (44)$$

$$(27), \quad S_5 = d_{14} E_2$$

$$\text{becomes } S'_2 = \frac{1}{2} d_{14} E_2 \quad \dots (45)$$

$$\text{and (28), } S_6 = d_{14} E_3$$

$$\text{becomes } S'_3 = \frac{1}{2} d_{14} E_3 \quad \dots (46)$$

where S'_i indicates linear strain in the plane perpendicular to direction 'i', directed at 45° to the other two axes (Figure XI.4.), and E_i is the field

component in direction 'i'.

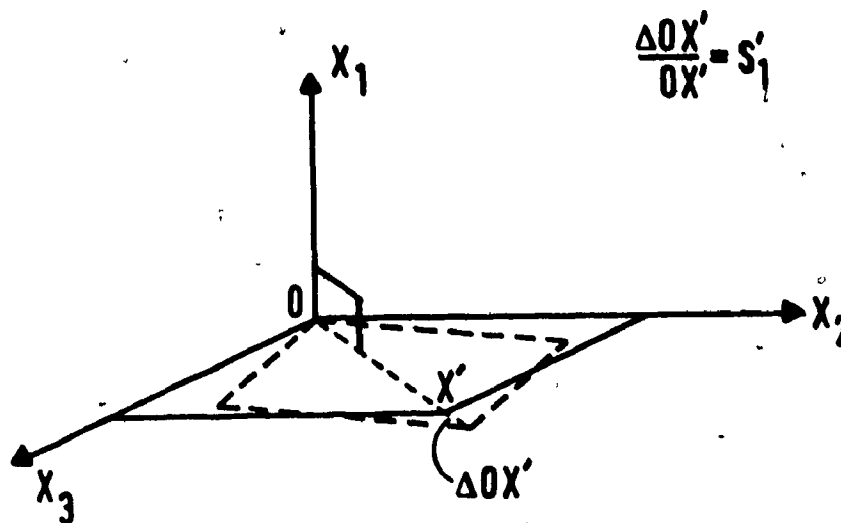


Figure XI.4. Definition of S'_i .

Equivalent expressions may be written relating to the stresses T'_i to the field components E_i by substituting e_{14} for d_{14} throughout. The resultant total stress in any direction, including that of interest here, perpendicular to the field, is given by

$$T = \frac{1}{2} e_{14} E \sum_{i=1}^3 \cos \theta_i \cos \phi_i \quad \dots (47)$$

where θ_i is the angle between axis 'i' and the direction of the field, and ϕ_i is the angle between the resultant stress and the resolved stress direction.

Again, a full analysis of the expression may best be

achieved by numerical methods but the important conclusions can be drawn by inspection.

The maximum value of the summed product is +1, occurring when one axis is parallel with the field ($\cos \theta = 1$) and the remaining axes are in the plane normal to the field. The resultant stress is in the same plane (bisecting the angle between the two axes) so that $\cos \phi = 1$ ($\phi = \text{zero}$) and $T = \frac{1}{2} e_{14} E$.

Due to the symmetry of the cubic sphalerite structure (Figure III.2.), the inverse orientation also results in a stress value $T = \frac{1}{2} e_{14} E$ but with direction rotated through $\pi/2$. (This may be seen by following through with the above analysis for $\theta = \pi$, $\cos \theta = -1$, from which is obtained $T = -\frac{1}{2} e_{14} E$, or compressive stress. It is seen from Figure XI.3. that this coincides with a tensile stress at 90° .)

Zero stress results from an intermediate orientation in which one axis lies in the plane normal to E with the remaining two axes at 45° above and below the plane giving $\theta_2 = 45^\circ$, $\cos \theta_2 = 1/\sqrt{2}$ and $\theta_3 = 135^\circ$, $\cos \theta_3 = -1/\sqrt{2}$. The stresses then cancel.

Tensile strength thus varies between zero and

$\frac{1}{2} e_{14} E$ for sphalerite with varying orientation and, in contrast with quartz, exhibits a finite mean value in this range. Using the value previously quoted for e_{14} of 0.14 C/m² the maximum value corresponds to a stress of

$$\begin{aligned} T &= \left(\frac{1}{2}\right) (0.14) (10^7) \\ &= 7 \times 10^5 \text{ N/m}^2 \quad (= 100 \text{ psi}) \\ &\quad \text{in a field of } 10^7 \text{ V/m*} \end{aligned}$$

No figures are available for the ultimate strength of sphalerite but, by comparison between the crushing curves obtained in this work, values of 1/4 to 1/3 times those for quartzite seem reasonable. The tensile strength may thus be expected to be of the order of 1000 psi, $7 \times 10^6 \text{ N/m}^2$. Hence the calculated maximum tensile stress generated by a voltage gradient of 10^7 V/m is approximately ten per cent of the fracture stress.

ii) Polycrystalline Particles

The analogy between the anticipated piezoelectric stresses and those due to aniso-tropic thermal expansion in polycrystalline materials was drawn earlier. The sense and

* The approximate maximum value of the field experienced by the mineral particles during testing. See section XI.2.

magnitude of thermal stresses in several idealized composite structures have been calculated by a number of workers (Mott and Nabarro, 1940; László, 1943; Timoshenko and Goodier, 1951a; Sokolnikoff, 1956). Newkirk and Sisler (1958) showed the existence of stresses in both phases of Ni-TiC cermets and used Timoshenko's formulae for concentric shells in estimating the hydrostatic stress on the nickel phase. A more satisfactory approach was made by Turner (1946) who considered the general case of thermal anisotropy in a random mixture of heterogeneous isotropic particles. He assumed the hydrostatic stress on any component i to be given by the expression

$$T_i = - (\beta_r - \beta_i) (t - t_0) K_1 \quad \dots(48)$$

where β is the coefficient of volumetric thermal expansion, t_0 and t the initial and final temperatures and K the bulk modulus of elasticity ($= 1/\text{bulk compressibility}$). Subscripts i and r refer to the properties of the ' i 'th component and the resultant mixture respectively. The negative sign is introduced to conform with the convention that tensile stresses are positive.

The stress on a grain is thus considered to be that required to constrain it to an expansion or contraction equal to that

of the aggregate. On the further assumption that the sum of the stresses across any sectioning plane is zero (Laszlo's 'tessellated' stress system) β_r can be formed from

$$\beta_r = \sum_{i=1}^n \beta_i v_i K_i / \sum_{i=1}^n \beta_i K_i \quad \dots (49)$$

where n is the number of components and v is the relative volumetric abundance.

Young's modulus values may be substituted for the bulk moduli provided that the components have similar Poisson's ratios, μ_i ,* and the bulk expansion coefficients may be replaced by the linear coefficients as these are, to a close approximation, directly proportional.

Experimental evidence confirming the theory was provided by Turner (1946) and Kingery (1957) and the latter subsequently (1960c) extended the equations to include polymorphic transformations by substituting $\Delta v / (v_0 \Delta T)$ for β . A similar approach will be used, although the following further modifications must be made. First, Kingery's function replacing β will be re-written as

$$\beta' = \Delta v / (v_0 \Delta E) \quad \dots (50)$$

* Young's modulus, Y , and the bulk modulus are related by the equation $Y = 3K (1 - 2\mu)$ (Timoshenko and Goodier, 1951b).

where β' may be termed the coefficient of volumetric piezoelectric expansion.

Secondly, it is necessary to adapt the approach to include anisotropic materials instead of the heterogeneous aggregates of isotropic materials considered by Turner. Young et al. (1960), Anderson and Bishop (1962) and Alexander (1963) all take the linear expansion coefficient (of polycrystalline uranium) to be the mean of the values parallel to the principal axes. Those values are constant, however, whereas the axial expansions of piezoelectric minerals depend upon field alignment. This variation must be considered in determining appropriate values for β' .

a) Quartz. Referring to Figure XI.2., the linear strains in axes OX, OY and OZ are given (from equation (14)) by

$$S_1 = d_{11} E \cos \theta \quad \dots (51)$$

$$S_2 = - d_{11} E \cos \theta \quad \dots (52)$$

$$\text{and } S_3 = \text{zero} \quad \dots (53)$$

An elemental cube of side h with edges parallel with the axes OX etc. will therefore take up a new volume, v' , given by

$$\begin{aligned}
 v' &= (h + S_1 h)(h + S_2 h)(h + S_3 h) \\
 &= h^3 (1 + S_1 + S_2 + S_3 + S_1 S_2 + S_1 S_3 + S_2 S_3 + S_1 S_2 S_3) \dots (54)
 \end{aligned}$$

But $S_1 = -S_2$ and $S_3 = 0$ (equations (51) to (53)) so that most of the terms vanish leaving

$$v' = h^3 (1 + S_1 S_2) \dots (55)$$

and the change in volume,

$$\begin{aligned}
 \Delta v_a &= v' - h^3 = S_1 S_2 h^3 \\
 &= -d_{11}^2 E^2 \cos^2 \theta h^3 \dots (56)
 \end{aligned}$$

Substituting for d_{11} gives

$$\Delta v_a = -5.35 \times 10^{-24} E^2 \cos^2 \theta h^3$$

Mean volumetric change, for θ varying between zero and 180° , is therefore given by

$$\begin{aligned}
 \Delta \bar{v}_a &= - \frac{5.35 \times 10^{-24} E^2 h^3}{\pi} \int_0^\pi \cos^2 \theta \cdot d\theta \dots (57a) \\
 &= - \frac{5.35 \times 10^{-24} E^2 h^3}{\pi} \left[\frac{1}{2} \theta + \frac{1}{4} \sin 2\theta \right]_0^\pi \\
 &= - \frac{5.35 \times 10^{-24} E^2 h^3}{\pi} \cdot \frac{\pi}{2}
 \end{aligned}$$

$$\therefore \Delta \bar{v}_a = -2.67 \times 10^{-24} E^2 h^3 \dots (57b)$$

Further volumetric changes result from the shear strains given by equations (20) to (22), viz:

$$S_4 = d_{14} E_1 \quad \dots (20)$$

$$S_5 = - d_{14} E_2 \quad \dots (21)$$

$$S_6 = - 2d_{11} E_2 \quad \dots (22)$$

Considering first S_6 , the largest of these strains, letting γ_2 be the angle between the Y axis and the field direction and substituting for d_{11} , we have

$$S_6 = - 4.62 \times 10^{-12} E \cos \gamma_2 \quad \dots (58)$$

The relative change in volume, v'/v , resulting from this strain (see Figure XI.5.) is given by

$$v'/v = h'/h = \cos (S_6) \quad \dots (59)$$

$$= \cos (- 4.62 \times 10^{-12} E \cos \gamma_2)$$

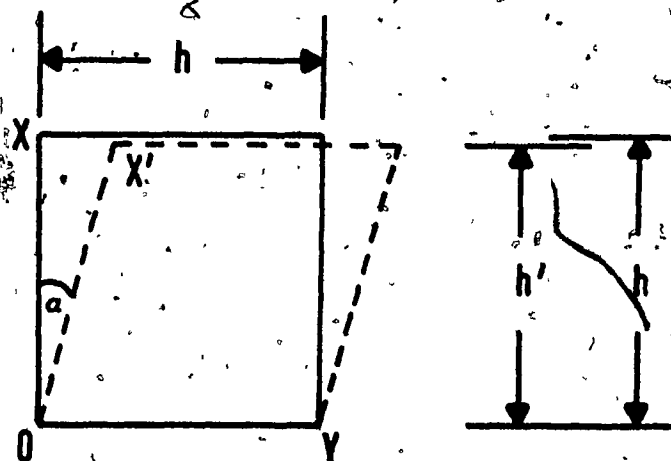


Figure XI.5. Volumetric Effect of Shear Strain.

$$\text{and } \Delta v_b = \cos (-4.62 \times 10^{-12} E \cos \gamma_2) h^3 - h^3 \quad \dots (60)$$

But $\cos x$ may be expanded as

$$\cos x = 1 - \frac{x^2}{2!} + \left(\frac{x^4}{4!} - \dots\right) \quad \dots (61)$$

$$\begin{aligned} \Delta v_b &= - (-4.62^2 \times 10^{-24} E^2 \cos^2 \gamma_2) h^3 / 2 \\ &= - 10.2 \times 10^{-24} E^2 \cos^2 \gamma_2 h^3 \quad \dots (62) \end{aligned}$$

Similarly for S_4

$$\Delta v_c = - 0.727 \times 10^{-24} E^2 \cos^2 \gamma_1 h^3 \quad \dots (63)$$

and for S_5

$$v_d = -0.727 \times 10^{-24} E^2 \cos^2 \gamma_2 h^3 \quad \dots (64)$$

Total volumetric change, Δv_{tot} is thus given by

$$\Delta v_{\text{tot}} = \Delta v_a + \Delta v_b + \Delta v_c + \Delta v_d$$

Care must be taken to carry out this summation over a

geometrically feasible combination of γ values. For

instance, γ_1 and γ_2 cannot simultaneously be less than

45° . However it is evident that the total cannot exceed

$-14 \times 10^{-24} E^2 h^3$ (the approximate value for Δv_{tot} putting

$\theta = \gamma_1 = \gamma_2 = 0$) which gives

$$\Delta v_{\text{max}} = - 14 \times 10^{-10} h^3 \quad \dots (65)$$

for a field of 10^7 V/m.

This is clearly negligible.

b) Sphalerite. Only shear strain is experienced, as given in equations (26) to (28). Mean volumetric change as a result of the strain in any one plane is given, using the procedure followed in equations (58) to (62), by

$$\begin{aligned}\overline{\Delta v_i} &= -\frac{1}{\pi} \int_0^{\pi} \frac{1}{2} (3.18 \times 10^{-12})^2 (E \cos \theta_i)^2 h^3 \cdot d\theta_i \quad \dots (66) \\ &= -\frac{1}{2\pi} \times 10^{-23} E^2 h^3 \int_0^{\pi} \cos^2 \theta_i \cdot d\theta_i \\ &= -\frac{E^2 h^3}{4} \times 10^{-23}\end{aligned}$$

Total mean volumetric change as a result of shear strain in all three planes therefore cannot exceed

$$\begin{aligned}\Delta v_{\text{tot}} &= -\frac{3}{4} E^2 h^3 \times 10^{-23} \quad \dots (67) \\ &= -0.75 \times 10^{-9} h^3 \text{ in a field of } 10^7 \text{ V/m. Thus,}\end{aligned}$$

again, the volumetric change as a result of the field is negligible.

c) Hematite. No strain, and therefore no volumetric change, occurs in an electric field.

Inserting the Δv values (taken as zero) into equation (50) gives β'_i values of zero also. Thus, from

equation (49), β'_r (the bulk expansion of a polycrystalline aggregate due to the converse piezoelectric effect) is zero, as is the average stress experienced by individual grains in the aggregate (equation (48)). Due to the anisotropy of the piezoelectric effect, however, a stress will develop in each direction in which the grain tends to strain.

Equation (48) can be rewritten in terms of linear stresses and modified to apply to the piezoelectric effect, giving

$$T_i = - (a_r - a_i) (E - E_0) \cdot Y \quad \dots (68)$$

where a_r and a_i may be termed the 'coefficients of linear piezoelectric expansion' of the aggregate and component i respectively. The coefficient a_r , in general, may be taken as $\beta_r/3$ and, for each of the minerals considered, is consequently zero. Coefficients a_i , which may be defined (from equation (50)) as

$$a_i = \Delta h_i / (h_0 \Delta E) \quad \dots (69)$$

are equal to the piezoelectric moduli for quartz if the shear stress is ignored. (It was shown earlier that Δh from shear strain is insignificant.) Taking $E_0 =$ zero and $Y = 7.9 \times 10^{10} \text{ N/m}^2$ (Birch et al., 1942) in the XY plane gives, from equation (68),

$$\begin{aligned}
 T_1 &= - (-d_{11}) (10^7) (7.9 \times 10^{10}) \text{ for a field of } \\
 &10^7 \text{ V/m} \\
 &= (2.31 \times 10^{12}) (7.9 \times 10^{17}) \\
 &= 1.82 \times 10^6 \text{ N/m}^2 \quad \dots (70) \\
 &(\approx 265 \text{ psi})
 \end{aligned}$$

Similarly

$$T_2 = -1.82 \times 10^6 \text{ N/m}^2 \quad \dots (71)$$

The tensile stress T , is approximately ten per cent of the tensile strength for quartzite and, as each particle consists of a number of grains, this stress level will be attained or approached in a large proportion of the particles being tested. Fracture is therefore expected to be promoted even though compressive stresses of similar magnitude may be generated at other points within the particle.

With sphalerite the appropriate value of a_i , the piezoelectric expansion coefficient, is taken at 45° to the axes, in the direction of maximum linear deformation. From equations (44), (45) or (46) it is therefore seen that $a_i = \frac{1}{2} d_{14} = 1.59 \text{ pC/N}$. Substituting into equation (68), as was

done with quartz, and using $Y = 5.44 \times 10^{10} \text{ N/m}^2$ (Berlincourt et al., 1963) gives

$$\begin{aligned} T &= (1.59 \times 10^{-12}) (5.44 \times 10^{17}) \\ &= 8.66 \times 10^5 \text{ N/m}^2 \quad \dots (72) \\ &= 125 \text{ psi} \end{aligned}$$

This compares reasonably well with the result of the calculation on page 173 which was based on the piezoelectric constant e_{14} . The value is estimated to be of the order of ten per cent of the fracture stress and, as with quartzite, is expected to be approached at some point in the structure of the majority of polycrystalline particles and to promote fracture.

As hematite exhibits neither volumetric nor linear response to an imposed electric field no stresses will be generated in the pure sample and no change in the comminution characteristics was anticipated. In iron ore the hematite phase will experience a stress as a result of the silica deformation, however, and will modify the stress pattern. The magnitude of the stress can be estimated from the modified Turner's expressions. Equation (49) gives $\beta_r =$ zero (as $\beta_{Qtz} = \beta_{Hem} = 0$) so that $\alpha_r =$ zero, as before, and (from equation (68)-)

$$T_{\text{Qtz.}} = (a_i E Y)_{\text{Qtz.}}$$

which is identical to equations (70) and (71). That is, the magnitude of the stresses in the quartz phase of iron ore are the same as those generated in quartzite.

Using equation (68) for the hematite phase gives $T = \text{zero}$ as a_{Hem} is zero in all directions. This is evidently incorrect and it is apparent that the equation should be written:

$$T_{\text{Hem.}} = (-a_i)_{\text{Qtz.}} (EY)_{\text{Hem.}}$$

That is, the stress that is required to overcome the tendency to strain of the adjacent quartz grain. Unfortunately, no value for $Y_{\text{Hem.}}$ has been found so the magnitude of $T_{\text{Hem.}}$ cannot be evaluated.

The calculations carried out in this section have shown that the original estimation of the stress generated in piezoelectric materials as a result of an imposed field was only significantly in error in the case of mono-crystalline quartz. The stresses in that material have been shown to cancel in a randomly oriented bed containing a sufficient number of particles. This is assumed to be true for the experimental

work described in this thesis in which the number of particles tested simultaneously generally exceeded one hundred. The comparable cancelling of stresses of opposite sense generated within the grain structure of quartzite has been considered unimportant as, by assuming a critical stress criterion for fracture, it is the maximum (tensile) stress developed within a body which determines the initiation of fracture. It should be noted, furthermore, that even if alternative criteria are adopted (such as Weibull's statistical theory (1939) or Chen and Marovelli's average stress theory (1966)) no explanation of the observed strengthening and subsequent strength reversal is obtained. It is therefore evident that mechanisms other than the piezoelectric effect must be sought to explain the observed phenomena.

XI.4. Alternative Mechanisms

i) Relaxation of Residual Stresses

It was suggested (section VIII.2.ii.) that the strengthening observed in quartzite in the initial experiments might be attributable to relaxation of residual stresses. Photographic evidence that such stresses were indeed present was given (Figure VIII.7) and the subsequent

tests were, in part, designed to test this possibility. It was predicted that if stress relaxation were taking place the effect would only be observed in polycrystalline anisotropic materials. Polycrystalline because residual stresses cannot be sustained in a free crystal. Anisotropic because only anisotropic thermal expansion was thought capable of generating stresses which could be released by a crystallographically oriented phenomenon such as the converse piezoelectric effect. It was further predicted that a strength reversal might be observed if residual stresses of opposite sense set up.

In general the results of the subsequent tests failed to support the hypothesis. Some strengthening was observed in the sample of cubic (i.e. isotropic) sphalerite and appreciable strengthening was also found with monocrystalline quartz. In addition, no reversal in the strengthening effect was found with quartzite, though it was observed with the other materials! The reversal in the strengthening trend seen in the results for iron ore may be fortuitous in view of the same observation in the materials in which no residual stresses can be present and an alternative explanation should be sought. However it is interesting to note that the strengthening effect in quartzite was considerably greater than with the other materials so that it is conceivable

that the relaxation mechanism may be a contributing factor to the strengthening of this material, in addition to the phenomenon which gave rise to the changes in the other samples. The possible interaction between residual and piezoelectric stresses in quartz will therefore be considered further.

If it is assumed that quartzite, like iron ore, is formed at a temperature above the $\alpha \rightarrow \beta$ transformation temperature (Miles, 1954), it is seen from Figure II.4. that the contraction in the Z axial direction of a free crystal would be 1.75 per cent and in all directions in the XY plane would be 1.0 per cent on cooling to room temperature. Thus there is, or tends to be, a relative foreshortening of the crystal in the Z direction. In a polycrystalline matrix, in which each grain is limited by the surrounding grains to homogeneous strain intermediate between the extreme values, stresses will be set up proportional to the difference between this intermediate value and the unconstrained value. Thus a tensile stress will be developed along the Z axis and compressive stresses in the XY plane. It is the relaxation of these stresses on heating which is credited with the strengthening observed when iron ore is heated to 400 - 500°C (Lean, 1963; see also page 30).

The linear strains resulting from the converse piezoelectric effect in quartz were considered earlier. It was shown that a) the net strain in the^o XY plane is zero for all orientations, that is, that the strain developed in one direction is precisely countered by a strain of opposite sign perpendicular to it and, b) that the linear strain in the Y direction, which arises from shear perpendicular to the XY plane, is extremely small and is always one of contraction. It is therefore evident that the only intermediate interaction between the residual thermal stresses and the induced piezoelectric stress would be a very small reinforcement of the tensile stress in the Y direction. This would result in further weakening, not the observed strengthening, but the piezoelectric strain is so much smaller than the thermal strain that no effect can realistically be expected.

ii) Triaxial Stresses

Uniaxial stress conditions are employed in most crushing and grinding operations and in comminution testing. That is, the rock sample is loaded along one axis and unconstrained in directions perpendicular to that axis. The stress-strain values quoted in Chapter I were obtained under uniaxial stress conditions.

Triaxial conditions, in which the applied stresses in all three axial directions are significant, are encountered in underground (in situ) situations and have, therefore, been the subject of research by geologists and mining engineers. Two main effects have been noted. First, it is found that the ultimate strength of a brittle rock is dependent upon the minor stress. (The intermediate stress value is of lesser importance and testing is usually carried out by jacketing the specimen.) Figure XI.6, adapted from the results of Bieniawski (1967) shows a typical set of results. It is seen that the ultimate compressive strength

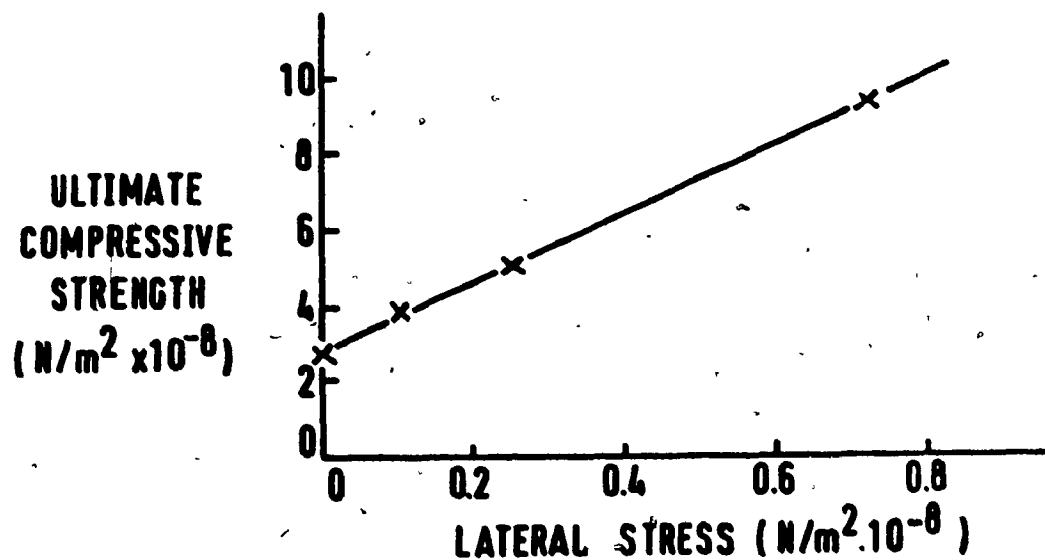


Figure XI.6. The Effect of Confining Pressure on the Ultimate Compressive Strength of Transvaal Quartzite. (After Bieniawski (1967).)

is very sensitive to confining pressure. Scholz (1973) suggested that if a net decrease in volume resulted from piezoelectric strain the effect might be the equivalent of triaxial compression and that strengthening would be expected initially, possibly followed by weakening as the linear strain effects (the 'mismatch' idea) became more significant. It was demonstrated earlier that volumetric changes due to piezoelectric strain are indeed negative but are trivial compared with the linear effect. However, in view of the noted sensitivity to confining pressure, this possibility will be examined.

From Bieniawski's results (Figure XI.6.), a hydrostatic pressure of 10^2 N/m^2 gives rise to a thirty-five per cent increase in compressive strength (from 2.8 to $3.8 \times 10^8 \text{ N/m}^2$). The volumetric change associated with this hydrostatic pressure can be calculated from the expression, given in Birch et al. (1944), viz:

$$-v/v_0 = 27 \times 10^{-7} P - 24 \times 10^{-12} P^2 \quad \dots (74)$$

where P is the hydrostatic pressure in bars (1 bar = 10^5 N/m^2).

$$\text{Hence, } -v/v_0 \approx 2.7 \times 10^{-4} \quad \dots (75)$$

This, although small, is some 10^5 times greater than the

volumetric strain developed in an electric field so that it is clear that the latter factor could make no significant contribution to the observed strengthening.

The second effect sometimes noted as a result of the application of triaxial stresses is the onset of plastic deformation. This effect is greatly enhanced at elevated temperatures and low strain rates, as it is in metals (Barrett, 1952). With most minerals, the effect is negligible under normal conditions, Friedman (1972) has identified tectonic stresses of geological age in sandstones, for example, although some exceptions have been found. Stanton and Willey, for instance, have demonstrated stress relaxation in galena (1970) and sphalerite (1971). In the latter case relaxation only took place at elevated temperatures, however, and was observed progressively over a number of days. It is evident, therefore, that plastic deformation was not a factor in the experimentation described in this thesis.

iii) Surface Charge Effects

The effect of surfactants on mineral strength was mentioned in section II.2. and Westwood's explanation, based on the mobility of dislocations originating in the surface, was introduced. He has recently (1973) demonstrated that

surface hardness and mineral strength are a function of surface charge (which may be modified by adsorbed species), strength being at a maximum at the zero point of charge.

In discussions with the author, it was postulated that induced electric charge on the mineral particles as a result of the application of an electric field may have had an analogous effect to the adsorption of surfactants, namely a change in surface potential and the resultant modification of dislocation mobilities. Considering first the case of quartz, the theory has a number of attractive aspects.

When quartz (or any other oxide mineral) is immersed in water, adsorption of hydroxyl and hydrogen ions gives rise to a surface charge. The relative amounts adsorbed depend upon the relative ionic concentrations in solution (i.e. pH) and on the nature of the mineral. For each mineral, there is a characteristic pH at which adsorption of anions and cations is equal and the resultant charge is zero. This is the zero-point-of-charge mentioned above. For quartz, the zero-point-of-charge is about pH 2 (Gaudin and Fuerstenau, 1955). At higher pH levels (OH^- concentrations) the surface exhibits a net negative charge.

As no attempt was made to exclude atmospheric

moisture from the particles it is probable that adsorption occurred and that a negative charge was developed on the quartz surface. According to Westwood's theory, this would result in a lowering of the mineral strength. On subjecting the quartz particles to an intense positive electric field it is envisaged that the negative surface charge is reduced, leading to an apparent strengthening. Furthermore, an increase in the field intensity would be expected to increase the mineral strength progressively as the negative surface charge was reduced until the mineral possessed no net surface charge. An increase in field intensity beyond this point would then be expected to give rise to a lowering of mineral strength as the particle surface became positively charged. The theory thus provides an explanation of the decrease in comminution efficiency and of the attainment of a minimum value and subsequent reversal.

Unfortunately, several aspects remain unexplained by this qualitative theory, nor can a quantitative theoretical treatment be made. It is not evident, first of all, why quartzite should not show the same strength reversal as is seen with mono-quartz. Nor is it possible to explain the lack of response of hematite, which has a zero-point-of-charge at pH 8.5 (Parks and de Bruyn, 1962) and which would therefore

be predicted to show a decrease in strength from an induced positive charge. There is also a very large difference between the magnitude of the applied potential (measured in kilo-volts) and the electrochemical potential of the mineral surface (measured in milli-volts), and it is not at all clear to what extent these will interact.

None of the mechanisms described above provide very satisfactory explanations for the experimental results. It is most probable, therefore, that some other phenomenon has been detected, although the observed effects may be the result of an interplay of phenomena. For instance, it is conceivable that the initial strengthening is the result of the reduction in surface charge while the subsequent reversal occurs when piezoelectric stresses become predominant. Such suggestions must be regarded as purely conjectural, however, and it is acknowledged that no one theory has been found to explain the experimental data.

XII. SUMMARY, CONCLUSIONS, CLAIMS AND

SUGGESTIONS FOR FURTHER RESEARCH

XII.1. Summary and Conclusions

Six rock samples, in the form of -8 +12 mesh particles, have been mechanically crushed whilst subjected to intense electric fields in an attempt to observe changes of comminution efficiency and product characteristics predicted on the basis of the piezoelectric properties of the component minerals. A decrease in efficiency was found with all samples except polycrystalline hematite and no changes in product characteristics (form of size distribution or degree of liberation) were detected with any of the materials. The hematite sample showed no response whatsoever to the influence of the electric field and all but quartzite of the remaining materials exhibited a maximum in strength at an intermediate level of applied potential. Higher field strengths gave rise to an improvement in comminution efficiency but levels achieved in zero field were not regained.

In view of these discrepancies between the experimental and predicted results, the theoretical basis for

the hypothesis was reviewed and refined. In general the original, simplified approach was seen to result in over-estimation of the magnitude of the average piezoelectric stresses but no basis was found for revising the predicted comminution effects. Alternative mechanisms were therefore sought in an attempt to explain the results. Three possibilities were examined. Only one, a surface charge effect analogous to that produced by surfactants, was thought to be feasible and even with that theory several inconsistencies were noted.

It is therefore concluded that:

- i) For the materials tested and for field strengths of up to 10^7 V/m no improvement in efficiency or effectiveness of comminution is achieved by crushing in an electric field.
- ii) On the contrary, optimum comminution conditions occur in zero field.
- iii) The hypothesis initially put forward, that of piezoelectric stresses, appears disproved, although it is possible that the effect has been masked by other phenomena.
- iv) The experimental data cannot be explained in terms of residual elastic stress relaxation, nor were volumetric changes of importance.
- v) It is possible that the observed change in materials

strength may be attributable to a charge effect akin to the so-called Rehbinder effect as explained by Westwood, but several discrepancies are noted.

XII.2. Claims to Original Research

The following aspects of this study are believed by the author to be original.

- i) The initial hypothesis that piezoelectric materials would exhibit changes in comminution behaviour when subjected to an electric field.
- ii) The calculation of the magnitude of field strength required to generate stresses or strains significant in terms of the fracture process.
- iii) The design and construction of a crushing cell in which mineral particles could be subjected to electric fields of up to 10^7 V/m during comminution.
- iv) The use of alumina ceramic material in the dual role of electrical insulator and extremely hard crushing face.
- v) Comminution of quartzite, monocrystalline quartz, mono- and polycrystalline sphalerite, iron ore and polycrystalline hematite in electric fields of up to 10^7 V/m.

In addition, the interpolation procedure used in

analysis of particle size distributions (Appendix IV) was developed by the author. Other techniques used in product analysis were not in themselves original although the extensive use of computer facilities is unusual in this type of study. All computer programs, except for the occasional use of standard sub-routines, were designed and written by the author.

XII.3. Suggestions for Further Research

The results of the experimentation described in this thesis are obviously disappointing, especially in that no improvement in comminution characteristics was achieved. However, a number of aspects might repay further attention.

i) In view of the improvement in efficiency observed at higher field strengths with mono-quartz and iron ore (and to a lesser extent, with both sphalerite samples), further testing at even higher field strength values is indicated. This could best be carried out using a higher voltage potential source but preliminary tests could be carried out by simply replacing one of the alumina-faced platens with a hardened steel type used in the initial tests. Adequate insulation should still be provided by the remaining alumina plate and the potential gradient in the mineral particles would be approximately doubled.

ii) The surface charge hypothesis should be examined experimentally. Two approaches are suggested. Firstly, tests similar to those described in this thesis may be repeated but with the polarity of applied potential reversed. The magnitude of the electric field would not be affected by this change but the potential with respect to ground would become negative. Secondly, direct measurements of surface hardness (by indentation or by oscillatory pendulum techniques) could be made over a range of field conditions.

iii) As differences were noted between the response of mono-quartz, quartzite and iron ore, other siliceous materials might be tested to determine any pattern of behaviour which might provide an insight into the controlling mechanisms.

APPENDICES

A.I. REPRESENTATION OF SIZE

DISTRIBUTION DATA

A.I.1. Introduction

"It is desirable that size analyses be expressed in such a form, either numerically or graphically, that comparisons can be made readily" (Schuhmann, 1940). Taggart (1945) gave more than a dozen empirical methods and interest has revived in the last decade, mainly in connection with comminution modelling. Among the recent approaches are the fitting of Pearson's (1895) gamma and beta distribution functions (St. Clair, 1969; St. Clair and Brown, 1972) and quasi-theoretical expressions developed by Gilvarry (1961), Gaudin and Meloy (1962), Harris (1968), Meloy and Gumtz (1969) and Everell et al. (1971). The three methods used in this study will be described.

A.I.2. The Schuhmann Plot

Probably the most common way of displaying screen analysis data is the log-log plot of Y , the cumulative weight fraction (or per cent) less than size X , versus X . This is the method advocated by Schuhmann (1940) after whom

it is named.*

Data yielding a straight line when plotted in this way may be described by the equation

$$Y = (X/K)^n \quad \dots (A.1)$$

where K, the size modulus, is the intercept at $Y = 1$ (i.e. 100% passing) and n is the gradient of the plot, known as the dispersion modulus.

Taking logarithms gives

$$\log Y = n \log X - n \log K \quad \dots (A.2)$$

Hence a plot of $\log Y$ against $\log X$ will yield a straight line of gradient n and intercept (at $Y = 1$ or 100 per cent) of $n \log K$. Considerable deviation from linearity is usually observed at values of Y greater than 60% and it is not rare to find published papers in which only the finest ten per cent or so is appropriately fitted by a straight line (e.g. Charles, 1957), although this is not always obvious due to the considerable foreshortening of the logarithmic plot at higher Y values. The use of the Schuhmann size modulus, K, in such cases is clearly of doubtful validity (Lynch, 1958;

* The method has also been attributed to other workers (Harris, 1971) and is frequently used without attribution, and even used inadvertantly, as in $\log Y$ vs. mesh number plots.

Nagahama et al., 1969) but the method offers great simplicity and is therefore commonly used.

A.I.3. The Rosin-Rammler Plot

More common in Europe and of wide use in coal preparation, is the method proposed by Rosin and Rammler (1933) who gave:

$$R = 100 \exp \left[- bX^n \right] \quad \dots (A.3)$$

where $R = 1 - Y$ and b and n are constants.

R is the 'residue' (i.e. the cumulative fraction retained) on screen aperture X .

Orr and Dallavalle (1959) use this form* but a more common and convenient form is

$$R = \exp \left[- (X/X')^n \right] \quad \dots (A.4)$$

where X' , the Rosin-Rammler size modulus, is the aperture value corresponding to $R = 36.8$ per cent ($Y = 63.2$ per cent).

This may be transformed for plotting as follows:

$$i) \text{ Invert, } \frac{1}{R} = \exp (X/X')^n \quad \dots (A.5)$$

* R is misdefined as the weight fraction $< X$ by Orr and Dallavalle.

$$\text{ii) Take logs., } \ln \left(\frac{1}{R} \right) = (X/X')^n \quad \dots (\text{A.6})$$

$$\text{iii) Take logs. again, } \ln \ln \left(\frac{1}{R} \right) = n \ln X - n \ln X' \quad \dots (\text{A.7})$$

Hence a plot of the 'Rosin-Rammler function', log-log reciprocal R, against log X will be linear with gradient n. Putting n equal to zero or $X = X'$ gives $R = 1/e$ ($Y = 1 - R = 63.2$ per cent). The X value at this point is conventionally taken as the size modulus of the distribution and corresponds to the distribution mode.

The function is very similar to the Schuhmann expression at low values of Y (less than about fifty per cent) but at higher values the scale is much less crowded and frequently gives a much better fit. In addition, it has recently been shown (Austin, 1971/72; Austin et al., 1972; Kapur, 1972) that the function can be theoretically derived from comminution rate equations. Harris (1971) has pointed out that the same expression, under the names of the Alyavdin and Weibull functions, is encountered in other fields and has made available a multi-purpose chart, thus removing the main disadvantage to the use of the method in North America. In this study, however, use was made of the computer plotter facility.

A.I.4. Frequency Distribution Analysis

The methods mentioned above share the following drawbacks:

- a) a prescribed function, rather than a general curve, is fitted to the data;
- b) the cumulative plot is relatively insensitive to short-range changes in size distribution; and
- c) all the expressions considered apply only to unimodal frequency distributions.

The (non cumulative) frequency distribution can be used to overcome these difficulties as it is very sensitive to particle size (Brown et al., 1958; Harris, 1971) and amenable to mathematical description without imposing a pre-determined function. Although the method is standard procedure in the geological sciences, especially in defining sediments (e.g. Spencer, 1963; Schlee and Webster, 1965,67; Griffiths, 1967; McBride, 1971), it is rarely encountered in comminution studies. Exceptions are Brown et al. (1958), Nagahama et al. (1969) and St. Clair and Brown (1972).

The frequency distribution is usually described by the four parameters - Mean, Standard Deviation, Skewness and

Kurtosis, which are calculated from the first four moments of the distribution as follows.

The data, with upper and lower bounds $X_{\max}$ and $X_{\min}$, is divided into n groups, $F_1, F_2, \dots, F_n$, on equal class intervals, w . F_i is the frequency, or weight per cent, in interval ' i '. Then the total frequency (total weight per cent) is given by

$$T = \sum_{i=1}^n F_i \quad \dots (A.8)$$

The first moment is then defined as

$$M_1 = \sum_{i=1}^n F_i (X_{\min} + (i - 0.5) w) / T \quad \dots (A.9)$$

and the ' j 'th moment,

$$M_j = \sum_{i=1}^n F_i (X_{\min} + (i - 0.5) w - M_1)^j / T$$

where $j = 2, 3, 4$.

The distribution parameters are then given by:

$$\text{Mean} = M_1 \quad \dots (A.11)$$

$$\text{Standard Deviation} = \sqrt{M_2} \quad \dots (A.12)$$

$$\text{Skewness} = M_3 / M_2^3 \quad \dots (A.13)$$

$$\text{and Kurtosis} = M_4 / M_2^2 \quad \dots (A.14)$$

The mean and standard deviation have units of length, skewness and kurtosis are dimensionless.

The mean corresponds to the 'centre of gravity' of the distribution and thus is a measure of position, that is, of average particle size.

The standard deviation is a measure of the spread about the mean, that is the dispersion of particle sizes. It thus corresponds to the gradient of a cumulative distribution.

Skewness is an indication of the symmetry of the distribution. A value of zero indicates symmetry about the mean, positive values indicate a long tail on the side of values greater than the mean and vice versa.

Kurtosis is generally referred to as a 'measure of peakedness', although that description is challenged by Baker (1968). A normal (Gaussian) curve has a kurtosis of 3.0* and a uniform distribution has a kurtosis of 1.8. In general curves with a more pronounced 'peak' than a normal curve have kurtoses greater than 3 and vice versa.

* Kurtosis is sometimes defined as $(M_4 / M_2^2) - 3$ for this reason.

A.III. POLYMODAL SIZE DISTRIBUTIONS AND THE CALIBRATION OF SCREENS

A.II.1. Introduction

The consistently polymodal forms of the frequency distributions could be explained in terms of a regular variation in effective screen apertures from the nominal values. This would be especially noticeable with the $4\sqrt{2}$ series used in which the difference between screens is not great. Consequently an independent check was made on a product sample and the method subsequently extended to calibrate the screens.

A.II.2. Projected Image Size Analysis

The -8+40 mesh fraction of quartzite sample number 148 was rescreened into three portions, -8+16, -16+25 and -24+40 and each portion weighed. The -25+40 mesh portion was riffled to obtain a smaller sample, also weighed, for convenience in the subsequent sizing.

Each portion in turn was placed on the glass object plane of an overhead projector (the type commonly employed in lecture rooms) and the image projected onto a screen, giving a magnification of approximately ten times. (The precise

magnification was not determined at this stage as it was only required to obtain a relative frequency measure.) The 'second dimension', the separation of the closest pair of parallel lines enclosing the particle image (see Figure A.1.) was determined for each particle by orientation of a piece of graph paper.

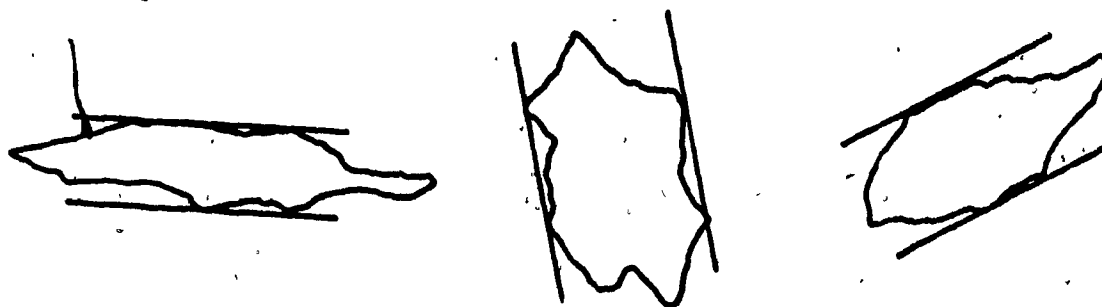


Figure A.1. The 'Second Dimension' of a Projected Image.

This dimension was used as, assuming the particles to be lying in a stable position with their minimum thickness parallel to the light path, it corresponds most closely to the dimension governing screening. With the two finer samples, sufficient particles were included by counting only those in opposite quadrants of the projection screen. The results were converted to a weight (or volume) per cent basis by multiplying by the cube of the mean size of increment (Table A.1) and plotted as a histogram in Figure A.2. It is seen that the bimodal nature of this portion of

Projected image size increment, mm	Mean size, mm	-8+16 mesh (0.9722 g)	-16+25 mesh (0.8221 g)	-25+40 mesh (0.4388 g)	Corrected (b) = (b) x $\frac{571}{291}$	Corrected (c) = (c) x $\frac{0.4388}{0.0964}$ x $\frac{310}{157}$	Total particles, N = (a) + (d) + (e)	Relative frequency, F = $ND^3 \times 10^{-3}$
	D	(a)	(b)	(c)	(d)	(e)	N	F
27-28	27.5	1					1	20.8
26-27	26.5	1					1	18.6
25-26	25.5	1					1	16.6
24-25	24.5	3					3	44.1
23-24	23.5	1					1	13.0
22-23	22.5	7					7	79.7
21-22	21.5	7					7	69.6
20-21	20.5	8					8	68.9
19-20	19.5	11					11	81.6
18-19	18.5	10					10	63.3
17-18	17.5	8					8	42.9
16-17	16.5	9					9	40.4
15-16	15.5	7					7	26.1
14-15	14.5	16					16	48.8
13-14	13.5	16					16	39.4
12-13	12.5	16	6		11.8		27.8	54.3
11-12	11.5	15	16		31.4		46.4	70.6
10-11	10.5	9	31		60.8		69.8	80.8
9-10	9.5	2	56		109.9		111.9	95.9
8- 9	8.5		80		157.0		157.0	96.4
7- 8	7.5	128	67	3	131.5	27.0	158.5	66.9
6- 7	6.5		30	18	58.9	161.8	220.7	60.6
5- 6	5.5		5	46	9.8	413.4	423.4	70.4
4- 5	4.5			65		584.2	584.2	53.2
3- 4	3.5		291	21		188.7	188.7	8.1
2- 3	2.5			4		36.0	36.0	0.6
1- 2	1.5							
0- 1	0.5							
					157			

Table A.1. Size Analysis by Projection.

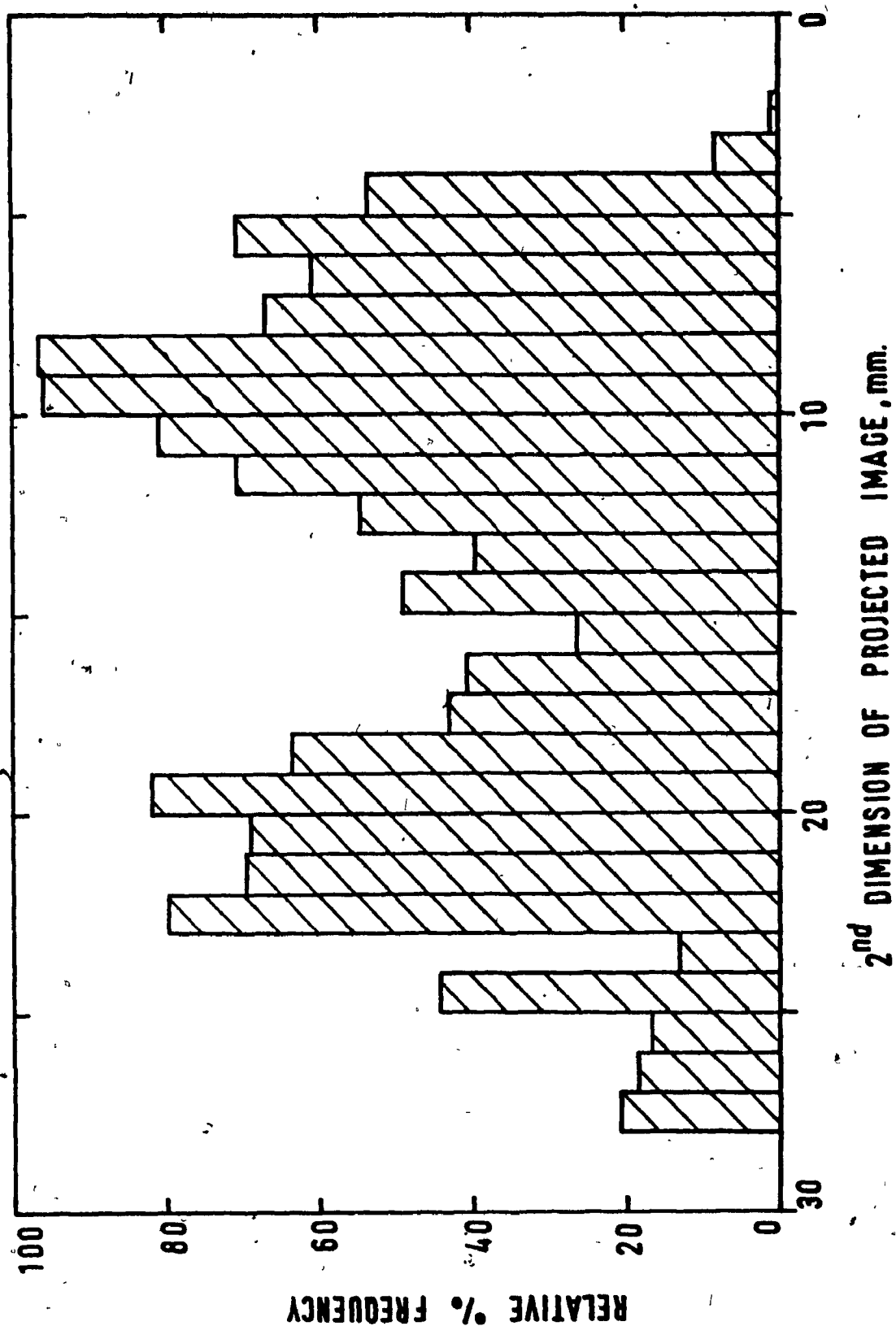


FIGURE A.2.

Bimodal Distribution of -8+40 Particles.

the total size distribution, as indicated by the interpolated screen analysis, is verified.

A.II.3. Screens Calibration

As the projected image method provided a convenient check on the distribution of particle sizes it was decided to extend the method to determine the effective aperture of each screen in the series. Checks on the calibration of screens have been reported previously, using different methods, by Andreason (1928) and St. Clair and Brown (1972). A sample of crushed quartzite was screened and the frequency distribution of approximately one hundred particles from each fraction determined in similar manner to that described above. The magnification was determined in each case, however, and photomicrographs of the fine fractions (-40 mesh) were used as projected images could not be measured satisfactorily.

The mean and standard deviation for each fraction were calculated and the effective cut-points defined and determined as the intercepts between adjacent normal curves having the same parameters. The entire calculation was carried out on the computer, the intercept being determined by iteration, but the basis for the procedure is shown

graphically in Figure A.3. A good fit is seen between the calculated curves and the histograms, thus justifying the procedure. It is interesting to note the large degree of overlap between the fractions from adjacent screens.

The effective apertures determined in this way are plotted against mesh number in Figure A.4. The theoretical line is also given and it can be seen that the method results in an appreciable overestimate of the aperture sizes. By multiplying by a factor* (approximately 0.85 for the photomicrograph results and 0.76 for the projection results) all points are found to lie close to the theoretical line. Although there is a small amount of variation about the line, no regular variation which could give rise to the observed polymodal distributions is seen. It is therefore concluded that the polymodal form was a true function of the product distribution.

It is interesting to conjecture briefly on the mechanism giving rise to the modes. It was noted earlier that a mode will be observed in sizes corresponding to the

* It is usual to find discrepancies of this nature between results from different measuring techniques (Laws et al., 1963) necessitating the use of a constant of proportionality.

FIGURE A.3.

Determination of the Effective Screen Aperture

PERCENTAGE
IN CLASS

10-20 #
16-18 #

20
-25
-20
-15
-10
-5
0

-18+20 MESH
-16+18 MESH

mm.

0.6 0.8 1.0 1.2 1.4 1.6

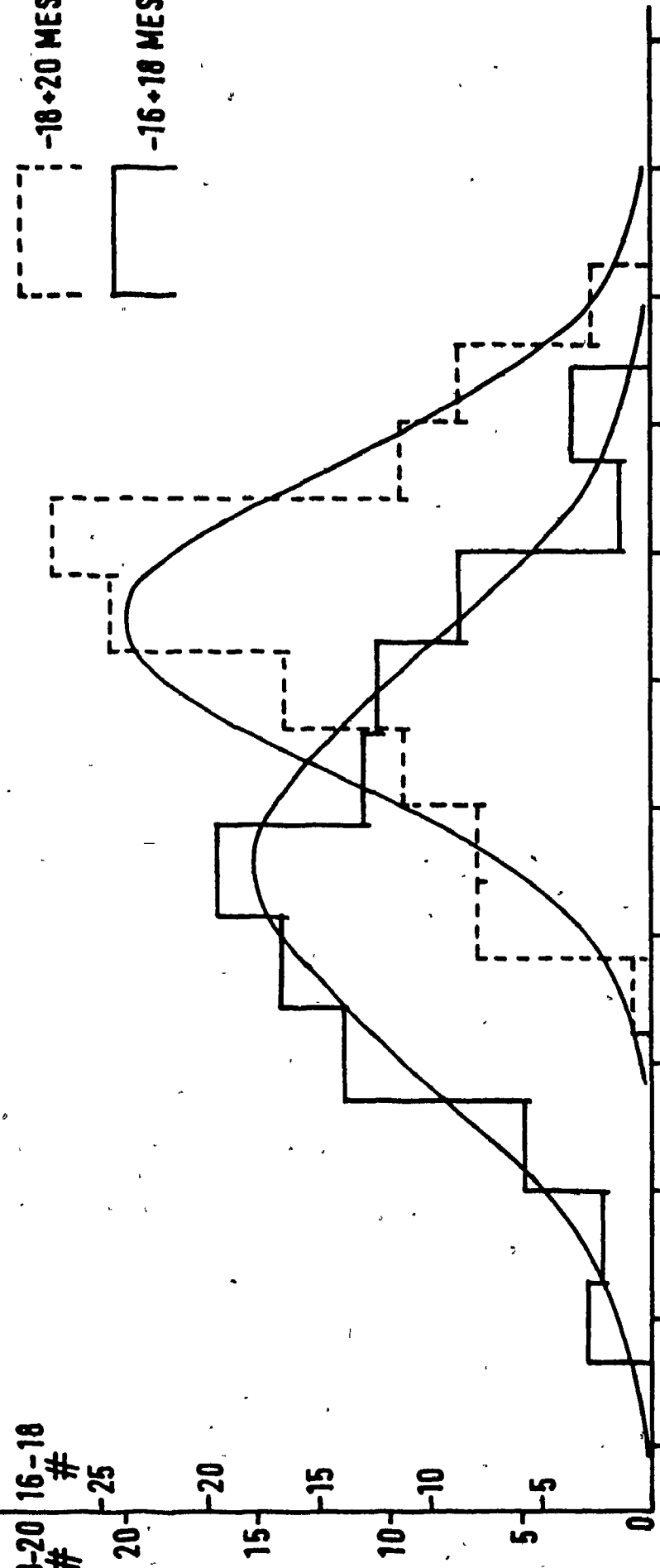
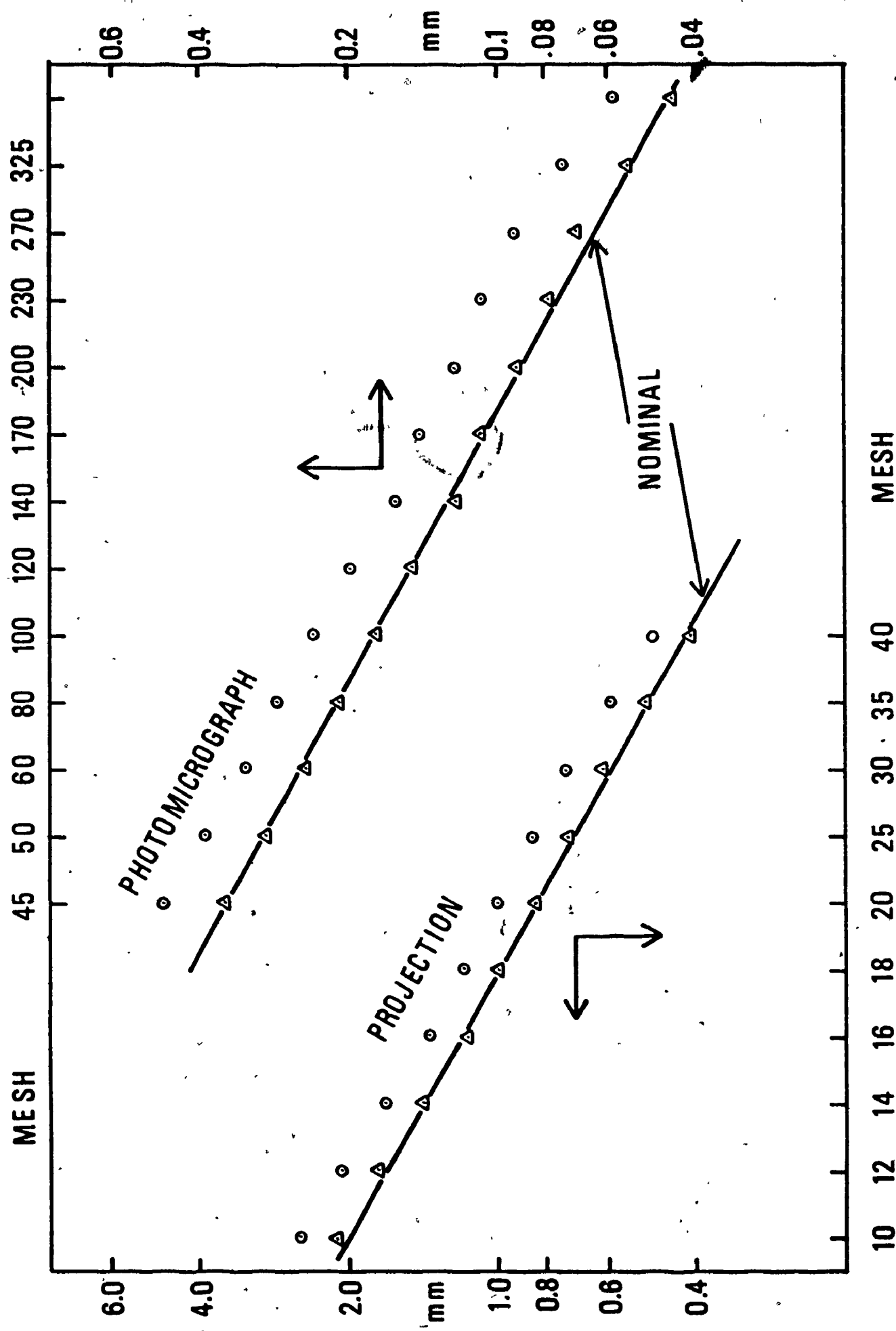


FIGURE A.4.

Apparent and Corrected Screen Aperture Values

Experimental ○

Corrected Δ



natural grain size if inter-granular fracture occurs but this cannot be the explanation here as similar distributions were observed with the mono-crystalline materials. A probable explanation is that at each fracture event the broken particle yields two or three large fragments, giving the second mode (the first corresponds to the feed size) plus dust. Successive fracture events give geometrically similar products so that the sizes corresponding to the modes tend to be in a constant ratio. The peaks are therefore evenly spaced on the logarithmic plot. Fracture patterns of this nature have been observed previously (Gilvarry and Bergstrom, 1961; Bergstrom, 1963; Gilchrist, 1967) but do not appear to have been so clearly demonstrated before.

A.III. GRAIN SIZE ANALYSIS

The natural grain size distribution of the quartzite was determined for use in the attempt to detect liberation changes. Grain size measurement from thin or polished section is considered by Griffiths (1967), Mueller (1967), Gifkins (1970) and Textoris (1971). Due to the random way in which the grains are sectioned, the apparent grain size is less than the true grain size, although this may be no disadvantage if similar sections are to be compared. If a measure of the true grain size is required, the shape factor must be known or assumed, leading to calculated values of 1.5 to 2.5 times the observed values (Gifkins, 1970). Occasionally, however, it is possible to obtain a direct measure of the three-dimensional structure. Williams and Smith (1952) describe an X-ray technique applicable to metals and Friedman (1958, 62) has published an empirical relationship between thin-section and screen analysis values for a series of calcareous sandstones which he achieved by dissolving the cement in acid and screening the liberated grains. Friedman's relationship has been adopted in this study on the assumption that the grain shapes are similar in the two rocks.

Friedman's expression, rounded to two decimal places, may be written:

$$X_{\text{calc.}} = 0.38 + 0.90 X_{\text{obs.}} \quad \dots (\text{A.15})$$

where $X_{\text{obs.}}$ is the maximum visible dimension of the sectioned grain and $X_{\text{calc.}}$ is the corresponding calculated passing aperture.

X values are expressed in terms of the geological phi scale,

$$\phi = -\log_2 d \text{ mm.}$$

The relationship was used as follows:

i.) Using a microscope with a rotatable eyepiece scale, the maximum apparent dimension of almost four hundred grains was determined.

ii) Cumulative per cent values were calculated and are plotted in Figure A.5. Cement material (approximately seven per cent of the total) was considered to fall into the finest size increment.

iii) A number of values were read-off from the cumulative curve, converted to screen size equivalent using Friedman's relationship (this was done graphically) and re-plotted, giving the corrected cumulative curve of Figure A.5.

iv) Difference values corresponding to the $\sqrt[4]{2}$ screen series were read from the corrected curve and are also

plotted in Figure A.5., giving the frequency distribution curve for the grain sizes.

Steps (i) and (ii) are detailed in Table A.2.

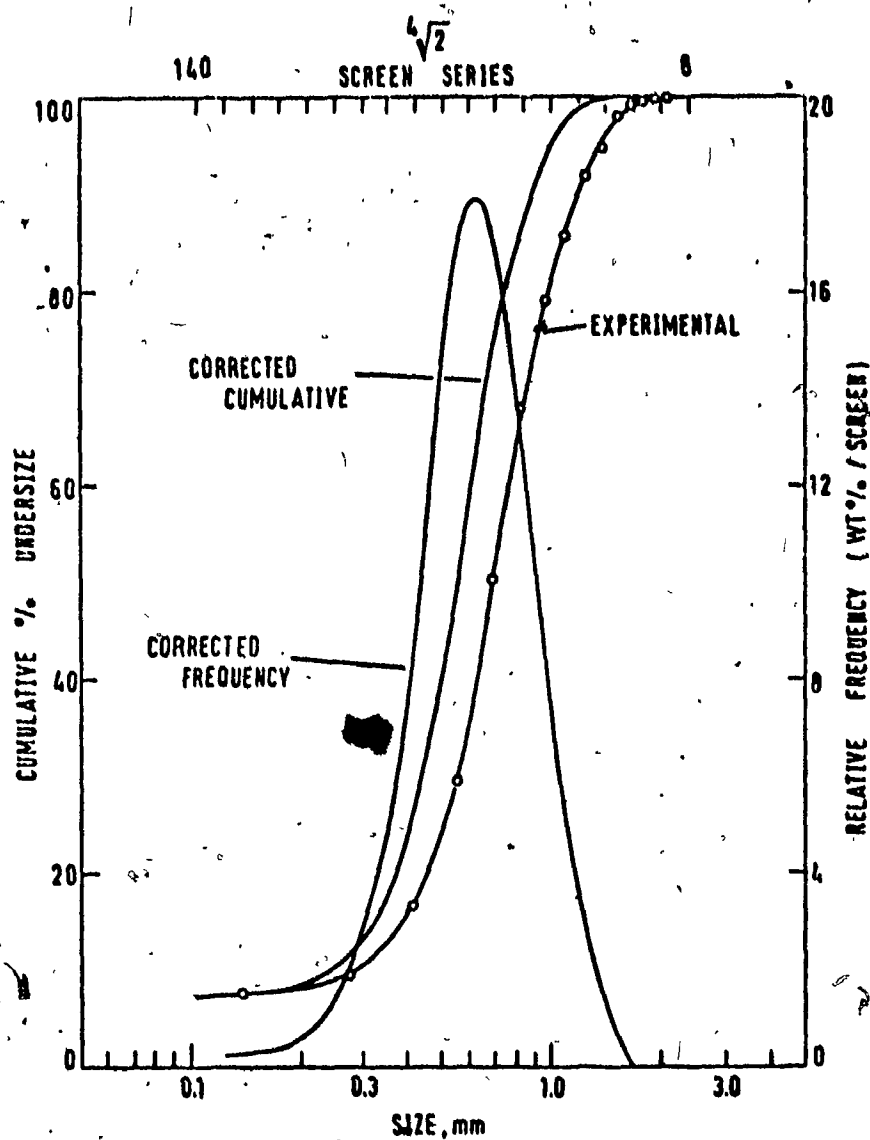


Figure A.5. Friedman-Corrected Grain Size Curves

Microscope Scale Interval (1 unit = 0.278 mm)		Size Increment, mm	No. of grains (cement included in first increment)	Per cent of Total Number	Cumulative per cent undersize
0 - 0.5	0 - 0.139	0.139 - 0.278	31	7.53	7.53
0.5 - 1.0	0.139 - 0.278	0.278 - 0.417	8	1.94	9.47
1.0 - 1.5	0.278 - 0.417	0.417 - 0.556	29	7.05	16.52
1.5 - 2.0	0.417 - 0.556	0.556 - 0.696	53	12.86	29.38
2.0 - 2.5	0.556 - 0.696	0.696 - 0.835	86	20.87	50.25
2.5 - 3.0	0.696 - 0.835	0.835 - 0.974	73	17.72	67.97
3.0 - 3.5	0.835 - 0.974	0.974 - 1.11	46	11.16	79.13
3.5 - 4.0	0.974 - 1.11	1.11 - 1.25	27	6.56	85.69
4.0 - 4.5	1.11 - 1.25	1.25 - 1.39	26	6.32	92.01
4.5 - 5.0	1.25 - 1.39	1.39 - 1.53	12	2.91	94.92
5.0 - 5.5	1.39 - 1.53	1.53 - 1.67	13	3.15	98.07
5.5 - 6.0	1.53 - 1.67	1.67 - 1.80	5	1.21	99.28
6.0 - 6.5	1.67 - 1.80	1.80 - 1.94	1	0.24	99.52
6.5 - 7.0	1.80 - 1.94	1.94 - 2.08	1	0.24	99.76
7.0 - 7.5	1.94 - 2.08		1	0.24	99.76
			412	100.00	

Table A.2. Quartzite Grain Size Plotting

A.IV. INTERPOLATION

An interpolation procedure was sought which would give a smooth curve through the screen analysis data and from which could be determined values for calculation of statistical parameters describing the distribution. A new method was developed which gives a curve identical to that given by Snyder's continuous parabolic method (1961) but by a considerably simpler and more general route. The curve is symmetrical in forward and backward interpolation, has a continuous first difference (i.e., is 'smooth') and has been shown by Snyder to compare satisfactorily with known functions. No absolute test of an interpolation method can be made, but the generated curve is acceptable to the eye and, of course, is unbiased. A significant advantage over the Snyder method is that it is not limited to evenly spaced data points.

The method will be described with reference to Figure A.6. Interpolation is to be carried out in interval $N - O$. The steps are i) Paraboli A and B are calculated through the points MNO and NOP. (MNOP are successive data points.)

ii) For each desired x interpolation value, the y values, y_A and y_B , on the two paraboli are determined.

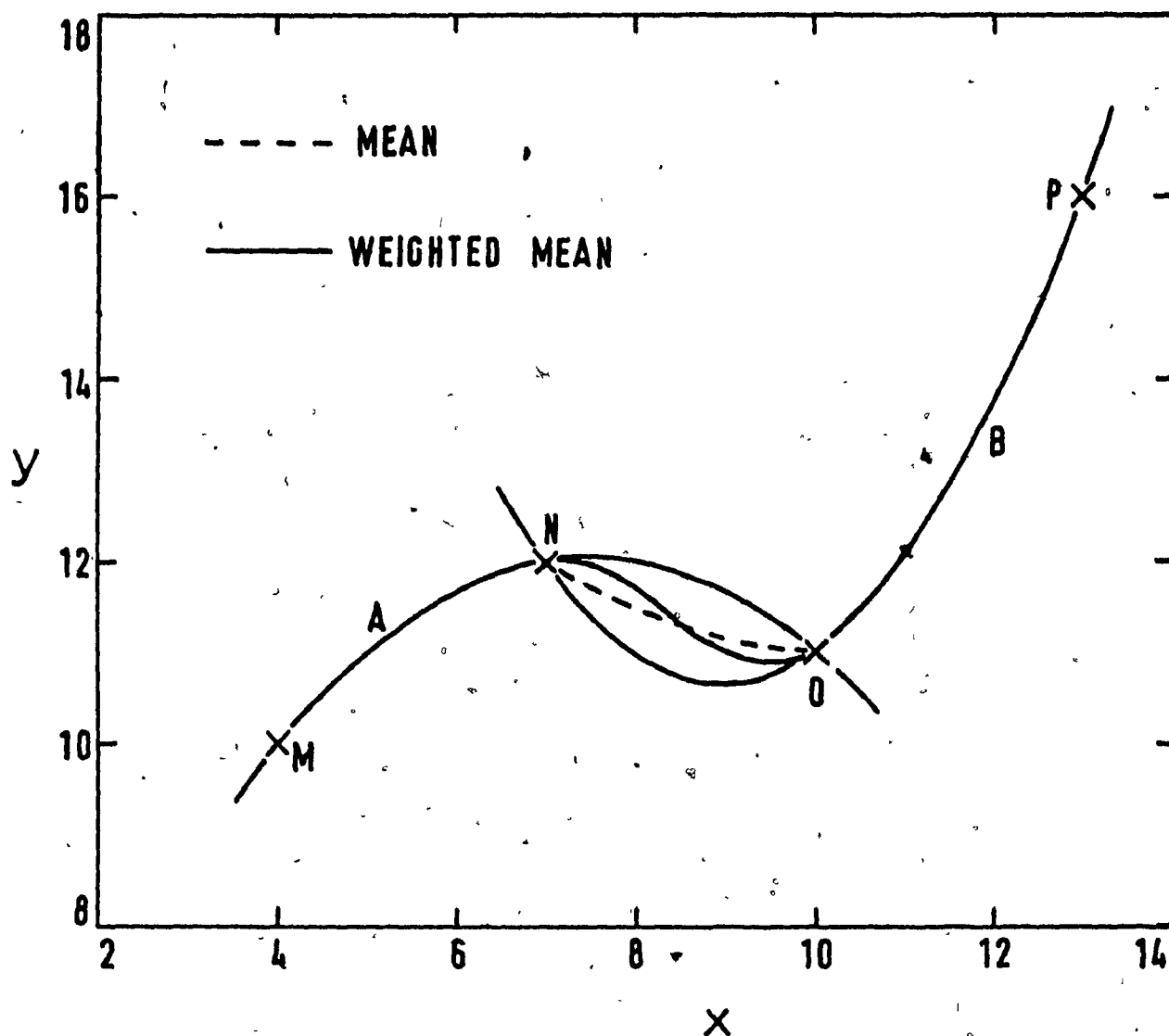


FIGURE A.6.

Weighted Mean Parabolic Interpolation

iii) The interpolated y value is calculated as the weighted mean of the independent y values. Weighting is varied linearly across the interval $N - 0$, y_A being weighted 100 per cent at N and zero at 0 , etc.

The method requires at least two data points on either side of the interpolation point. It is, therefore, necessary to modify the procedure at each end of a data set. The method adopted in this study was to assume additional points at unit spacing on the X axis.

The parabola through three points, (x_1, y_1) , (x_2, y_2) and (x_3, y_3) is usually calculated by solving the three simultaneous quadratic equations:

$$y_i = a + b x_i + c x_i^2, \quad i = 1, 2, 3. \quad \dots (A.16)$$

for the constants a , b and c .

A preferable computational form is given from the method of divided differences. Hamming (1962) gives the expression:

$$y = y_1 + (x - x_1) \left\{ [x_2, x_1] + (x - x_2) [x_3, x_2, x_1] \right\} \dots (A.17)$$

where the terms in square brackets are defined as follows

$$[x_2, x_1] = (y_2 - y_1) / (x_2 - x_1) \quad \dots (A.18)$$

$$\text{and } [x_3, x_2, x_1] = \left\{ [x_3, x_1] - [x_2, x_1] \right\} / (x_3 - x_2) \dots (\text{A.19})$$

In the case that $x_3 - x_2 = x_2 - x_1 = 1$, that is points at unit spacing in x , equation (A.17) can be written:

$$y = y_1 + (x - x_1)(y_2 - y_1) + \frac{(x - x_1)(x - x_1)(y_3 - 2y_2 + y_1)}{2}$$

... (A.20)

which is the form used by Snyder (1961). Hamming's full form (A.17) was used in this study as it was intended to use the program for non-uniformly spaced data points. In terms of Figure A.6. the expression may be written:

i) Parabola A

$$y_A = y_M + (x - x_M) \left\{ A_A + (x - x_N)(B_A) \right\} \dots (\text{A.21})$$

$$\text{where } A_A = (y_N - y_M) / (x_N - x_M)$$

$$\text{and } B_A = ((y_O - y_M) / (x_O - x_M)) - A_A / (x_O - x_N)$$

ii) Parabola B

$$y_B = y_N + (x - x_N) \left\{ A_B + (x - x_O)(B_B) \right\} \dots (\text{A.22})$$

$$\text{where } A_B = (y_O - y_N) / (x_O - x_N)$$

$$\text{and } B_B = ((y_P - y_N) / (x_P - x_N)) - A_B / (x_P - x_O)$$

Subscripts A and B denote the parabola being considered and subscripts M, N, O and P denote the data points as shown.

The weighting factor is given by

$$\text{WEIGHT} = (x_0 - x) / (x_0 - x_N) \quad \dots (\text{A.23})$$

and the interpolated y value by

$$y_{\text{interp.}} = (y_A \times \text{WEIGHT}) + (y_B \times (1 - \text{WEIGHT})) \quad \dots (\text{A.24})$$

A.V. COMPUTER PROGRAMS

Except for the use of elementary sub-routines (for example, for the determination of moments of a distribution), all programs were written by the author. The main programs used are given in the following pages. Each print-out contains comment cards to facilitate comprehension.

1. Rosin-Rammler Analysis and Plotting Pages 226-228
2. Frequency Distribution Analysis
 introducing Interpolation and Plotting 229-235
3. Screens Calibration - Fitting of Normal
 Curves and Iterative Determination of
 Intercepts 236-237
4. Plotting Distribution Parameters versus
 Unit Work 238-240

```

C
C  ROSIN-RAMMLER ANALYSIS AND PLOTTING.
C

      DIMENSION X(26),Z(30,10),RR(26),RAXIS(16,2)
      RR(25)=0.0
      RR(26)=1.0
      DO 1 I=1,30
      DO 1 J=1,10
1     Z(I,J)=0.0
      CALL PLOTON
      CALL PLOT(-5.0,1.0,-3)

C
C  READ NO. OF SEPARATE DATA SETS, I.E. NO. OF GRAPHS.
C
      READ(5,2)NPLOTS
2     FORMAT(12)

C
C  READ SCREEN APERTURE VALUES. (AS DETERMINED BY EXPT. IN THIS CASE).
C
      READ(5,3)(X(I),I=1,24)
3     FORMAT(5F10.4)

C
C  READ ANNOTATION VALUES FOR R-R SCALE AND LOCATE POSITIONS ON AXIS.
C
      READ(5,3)(RAXIS(I,1),I=1,16)
      SHIFT=3.0*ALOG10(ALOG(100.0/99.5))
      R=3.0*ALOG10(ALOG(100.0/36.79))-SHIFT
      RAXIS(1,2)=0.0
      DO 4 I=2,16
4     RAXIS(I,2)=3.0*ALOG10(ALOG(100.0/(100.0-RAXIS(I,1))))-SHIFT
      N=0
      DO 11 NPLUT=1,NPLOTS

C
C  SAMPLE NAME, NO. OF SAMPLES (MAX. 10), APPLIED POTENTIAL.
C
      READ(5,5)T,Y,P,E,NSAM,VOLTS
5     FORMAT(4A4/12/A4)

C
C  DRAW AND LABEL AXES AND CAPTIONS.
C
      CALL PLUT(10.0,0.0,0.0,-3)
      CALL PLUT(0.0,RAXIS(16,2),2)
      CALL PLUT(6.0,RAXIS(16,2),2)
      CALL PLOT(6.0,0.0,0.0,2)
      D=1.0/3.0
      CALL LGAXS(0.0,0.0,0.0,23,HPARTICLE SIZE (MICRONS),-23.6,0.0,0.0,30.0,0)
      DO 6 I=1,10
      H=RAXIS(I,2)-0.05
      CALL NUMBER(-0.45,H,0.1,RAXIS(1,1),0.0,1)
      CALL DASH(6.0,RAXIS(1,2),5.9,RAXIS(1,2),0.0)

```

CONTINUED.....

```

6 CALL DASH(0.0,RAXIS(1,2),0.1,RAXIS(1,2),0.0)
  CALL SYMBOL(-0.55,1.55,0.15,40HWEIGHTX PASSING (ROSIN-RAMMLER FUNC
XTION),90,0.40)
  CALL SYMBOL(0.55,8.7,0.15,T,0.0,4)
  CALL SYMBOL(1.15,8.7,0.15,Y,0.0,4)
  CALL SYMBOL(1.75,8.7,0.15,P,0.0,4)
  CALL SYMBOL(2.35,8.7,0.15,E,0.0,4)
  CALL SYMBOL(0.7,8.45,0.15,VOLTS,0.0,4)
  CALL SYMBOL(1.45,8.45,0.15,9HKILOVOLTS,0.0,9)
  CALL SYMBOL(7.0,4.0,0.1,9HUNIT WORK,0.0,9)
  CALL SYMBOL(6.9,3.82,0.1,11HJOULES/GRAM,0.0,11)
  B=ALOG10(30.0)
  F=(ALOG10(1700.0)-B)*3.0
  G=(ALOG10(2360.0)-B)*3.0
  FF=F+0.03
  CALL SYMBOL(FF,2.0,0.1,4HFEED,0.0,4)
  CALL DASHY(F,RAXIS(16,2),F,0.0,2)
  CALL DASHY(G,0.0,G,RAXIS(16,2),2)
  RM=R+0.05
  CALL DASHY(1.5,R,6.0,R,2)
  CALL NUMBER(1.5,RM,0.12,63.2,0.0,1)

C
C   FOR EACH SAMPLE: READ I.D., WEIGHT(GM), WORK DONE (IN-LB/GM).
C
  DO 11 K=1,NSAM
    READ(5,3)(Z(I,K),I=1,3)

C
C   CONVERT W.D. TO JOULES/GRAM.
C
    Z(3,K)=Z(3,K)/(8.8507*Z(2,K))

C
C   READ AND SUM SAMPLE WEIGHTS.
C
    READ(5,3)(Z(I,K),I=4,28)
    DO 7 I=5,28
      7 Z(I,K)=Z(I,K)+Z(I-1,K)
    DO 8 I=4,27
      IF(Z(I,K).EQ.0.0)Z(I,K)=0.0001

C
C   DETERMINE CUMULATIVE % RETAINED.
C
    Z(1,K)=(1.0-(Z(1,K)/Z(28,K)))*100.0
    IF(Z(1,K).EQ.0.0)Z(1,K)=0.01

C
C   DETERMINE R-R FUNCTION VALUE.
C
    8 RR(I-3)=3.0*ALOG10(ALOG(100.0/(100.0-Z(1,K))))-SHIFT

C
C   WRITE VALUES FOR POSSIBLE SCHUMMANN PLOT.
C
    IF(MOD(N,50).EQ.0)WRITE(6,9)(X(I),I=1,24)
    9 FORMAT('1'//T10,'APERTURE, MICRONS'//' NO. ' .24F5.0//T10,'CJ MULA
XTIVE ATX PASSING'//)
    WRITE(6,10)Z(1,K),Z(1,K),I=4,27)

```

CONTINUED.....

N=N+1
10 FORMAT(F6.0,2X,24F5.1)

C
C *MARK* = CODE FOR PLOTTING SYMBOL - DIFFERENT FOR EACH SAMPLE.
C

MARK=K
IF(K.GT.6) MARK=K+2
DO 11 I=1,24
XL=(ALOG10(X(I))-Q)*3.
IF(RR(I).LT.0.) GO TO 12
IF(RR(I).GT.RAXIS(16,2)) GO TO 12

C
C PLOT POINTS.
C

7
CALL SYMBOL(XL,RR(I),0.05,MARK,0.0,-1)
12 IF(I.GT.1) GO TO 11
HH=3.7-K*0.2
HG=HH+0.05

C
C DRAW-UP KEY.
C

CALL SYMBOL(7.10,HG,0.1,MARK,0.0,-1)
CALL NUMBER(7.38,HH,0.1,2(3,K),0.0,3)
11 CONTINUE
CALL ENDPLT
STOP
END

C
C FREQUENCY DISTRIBUTION ANALYSIS INCLUDING INTERPOLATION, MOMENT AND
C MODAL ANALYSIS ETC. AND CURVE PLOTTING.
C

DIMENSION DATA(37,13),F(3500),Q(3),W(10),ANS(4),PEAKS(10,20)
DIMENSION XARRAY(3500),YARRAY(3500),ID(10,2),R(3)
COMMON CALC(3500,11)

C
C INITIALISE ARRAYS = ZERO
C

DO 1 I=1,37
DO 1 J=1,13
1 DATA(I,J)=0.0
DO 2 I=1,3500
DO 2 J=1,11
2 CALC(I,J)=0.0
DO 3 I=1,10
DO 3 J=1,20
3 PEAKS(I,J)=0.0

C
C READ NO. OF DATA SETS
C

READ(5,4)NSET
4 FORMAT(12)

C
C READ MIN. 'X', INTERPOLATION INCREMENT (MIN=0.0025), MAX. 'X'.
C

READ(5,6)(Q(I),I=1,3)

C
C READ MESH NOS., APERTURES (MM) AND MEAN 'X' OF RETAINED PRODUCT.
C

READ(5,6)((DATA(I,J),J=1,3),I=4,27)
6 FORMAT(3F10.5)
DATA(28,3)=Q(3)

C
C READ SUBROUTINE OPTION CODES : '1'=GO, '0'=NO GO.
C

READ(5,7)IMOMEN,IMODES,IPLOT
7 FORMAT(3I2)
LOOP=0
99 IF(LOOP.EQ.NSET)GO TO 127
LOOP=LOOP+1

C
C READ MATERIAL, PLOTTING FACTORS (FUNCTIONS OF UNIT WORK), NO. OF
C SAMPLES (MAX=10) AND APPLIED POTENTIAL.
C

READ(5,8)T,Y,P,E,WFACT,D,NSAM,VOLTS
8 FORMAT(4A4,2F4.2/12/A4)

C
C DETERMINE 'X' VALUES FOR INTERPOLATION -ENTER INTO ARRAY 'CALC'
C

CONTINUED.....

```

C      M=8/0(2)+1
      DO 9 I=1,M
9      CALC(I,1)=(I-1)*0(2)-1.
C
C      ENTER LOOP FOR EACH SAMPLE IN TURN; READ ID. WT. WD AND SCREENED WTS.
C
      DO 10 KOUNT=1,NSAM
      K=KOUNT+3
      READ(5,11)(DATA(I,K),I=1,3)
      READ(5,11)(DATA(I,K),I=4,28)
11      FORMAT(5F10.4)
C
C      DETERMINE UNIT WORK, A) KWH/TONNE, B) JOULES/GRAM
C
      DATA(31,K)=DATA(3,K)/(31.86+DATA(2,K))
      DATA(32,K)=DATA(3,K)/(8.8507*DATA(2,K))
C
C      SUM WEIGHTS, DETERMINE MEDIAN AND TOTAL XWT LOSS
C
      DATA(29,K)=0.0
      DO 12 I=4,28
      SUM=DATA(29,K)+DATA(I,K)
12      DATA(29,K)=SUM
      PCT=SUM/100.
      SUM2=0.0
      I=3
13      SUM1=SUM2
      I=I+1
      SUM2=SUM1+DATA(I,K)/PCT
      IF(SUM2.LT.50.)GO TO 13
      DATA(33,K)=(DATA(I,3)+0.125)-((SUM2-50.)/(SUM2-SUM1))*0.25
C
      DATA(30,K)=(DATA(2,K)-DATA(29,K))/DATA(2,K)*100.
C
C      DETERMINE COORDINATES OF TWO POINTS EITHER SIDE OF INTERPOLATION
C      POINT - INCLUDE LIMITING VALUES AND EXTENSION POINTS AS NECESSARY
C
      L=4
      LL=1
      I=0
14      I=I+1
      IF(CALC(I,1).LE.0(1))GO TO 14
      IF(CALC(I,1).GE.0(3))GO TO 29
15      IF(CALC(I,1)-DATA(L,3))18,16,17
16      CALC(I,KOUNT+1)=DATA(L,K)
      L=L+1
      LL=1
      GO TO 14
17      L=L+1
      LL=1
      GO TO 15
18      IF(LL.EQ.0)GO TO 28
      IF(L-5)19,20,21

```

CONTINUED.....

```

19  X1=Q(1)-1.
    Y1=0.0
    X2=Q(1)
    Y2=0.0
    GO TO 23
20  X1=Q(1)
    Y1=0.0
    GO TO 22
21  X1=DATA(L-2,3)
    Y1=DATA(L-2,K)/PCT
22  X2=DATA(L-1,3)
    Y2=DATA(L-1,K)/PCT
23  IF(L-27)26,25,24
24  X3=Q(3)
    Y3=0.0
    X4=Q(3)+1.
    Y4=0.0
    GO TO 27
25  X4=Q(3)
    Y4=0.0
    GO TO 36
26  X4=DATA(L+1,3)
    Y4=DATA(L+1,K)/PCT
36  X3=DATA(L,3)
    Y3=DATA(L,K)/PCT
C
C  DETERMINE Y AT X ON TWO PARABOLIC THROUGH ADJACENT POINTS. (YA & YH)
C
27  AA=(Y2-Y1)/(X2-X1)
    BA=((Y3-Y1)/(X3-X1))-AA/(X3-X2)
    AB=(Y3-Y2)/(X3-X2)
    BB=1-((Y4-Y2)/(X4-X2))-AB/(X4-X3)
28  LL=0
    YA=Y1+((CALC(1,1)-X1)*(AA+(CALC(1,1)-X2)*BA))
    YB=Y2+((CALC(1,1)-X2)*(AB+(CALC(1,1)-X3)*BB))
C
C  TAKE WEIGHTED MEAN
C
    WEIGHT=(X3-CALC(1,1))/(X3-X2)
    CALC(1,KOUNT+1)=(YA*WEIGHT)+(YB*(1-WEIGHT))
    IF(CALC(1,KOUNT+1).GE.0.)GO TO 14
    CALC(1,KOUNT+1)=0.0
    GO TO 14
29  IF(IMOMEN.EQ.0)GO TO 31
C
C  CARRY OUT MOMENT ANALYSIS
C
    DO 30 I=2,M
30  F(I)=CALC(1,KOUNT+1)
    F(1)=0.0
    R(1)=-1.0
    R(2)=Q(2)
    R(3)=7.0
    CALL MOMEN(F,R,5,ANS)

```

CONTINUED.....


```

DATA(34,K)=ANS(1)
DATA(35,K)=SQRT(ANS(2))
DATA(36,K)=ANS(3)**2/ANS(2)**3
DATA(37,K)=ANS(4)/ANS(2)**2
31 IF(IMODES.EQ.0)GO TO 10
C
C CARRY OUT MODAL ANALYSIS
C
NPEAK=0
CALL MODES(PEAKS,M,NPEAK,KOUNT)
ID(KOUNT,2)=NPEAK
10 CONTINUE
32 IF(IPL0T.EQ.0)GO TO 34
C
C PLOT SIZE DISTRIBUTION.
C
DO 33 I=1,NSAM
33 W(I)=DATA(32,I+3)
CALL ACPL0T(M,XARRAY,YARRAY,Q,W,WFACT,NSAM,T,Y,P,E,VOLTS,D,LOOP,NS
*ET)
C
C WRITE INPUT AND COMPUTED DATA
C
34 DO 35 I=1,NSAM
35 ID(I,1)=DATA(1,I+3)
WRITE(6,100)(ID(I,1),I=1,NSAM)
100 FORMAT('1'//T16,'-----' * EXPERIM
XENTA_ DATA * -----'//T11,'SAMPLE
XNUMBER .....',I6,9I8)
N3=NSAM+3
WRITE(6,101)(DATA(2,J),J=4,N3)
101 FORMAT(/T11,'WEIGHT BEFORE CRUSHING, (GM.) ....',10F8.4)
WRITE(6,102)(DATA(3,J),J=4,N3)
102 FORMAT(T11,'WORK DONE, (INCH-POUNDS) .....',F7.2,9F8.2)
WRITE(6,103)
103 FORMAT(/T16,'-----' * SCREEN ANAL
XYES * -----'//T15,'MESH',T28,'N
* XOMINAL',T72,'SAMPLE WEIGHTS, GM.'/T14,'NUMBER APERTURE (MM)'//)
DO 104 I=4,27
MESH=DATA(I,1)
104 WRITE(6,105)MESH,DATA(1,2),(DATA(1,J),J=4,N3)
105 FORMAT(T15,I3,F16.3,T44,10F8.4)
WRITE(6,106)(DATA(28,K),K=4,N3)
106 FORMAT(T14,'-400',T44,10F8.4)
WRITE(6,107)(DATA(29,K),K=4,N3)
107 FORMAT(/T16,'-----' * COMPUTED O
XATA * -----'//T11,'TOTAL SCREEN
XED WEIGHT, (GM.) ....',10F8.4)
WRITE(6,108)(DATA(30,K),K=4,N3)
108 FORMAT(T11,'CRUSHING & SCREEN LOSS, (WTX) ....',F7.2,9F8.2)
WRITE(6,109)(DATA(32,K),K=4,N3)
109 FORMAT(/T11,'UNIT WORK, (JOULES/GRAM:)',.....',10F8.4)
WRITE(6,110)(DATA(31,K),K=4,N3)
110 FORMAT(T11,'UNIT WORK, (KWH/TONNE) .....',10F8.4)

```

CONTINUED.....

```

      WRITE(6,111)(DATA(33,K),K=4,N3)
111  FORMAT(/T11,'MEDIAN, (LOG. SIZE UNITS) .....',10F8.4)
      IF(IMOMEN.EQ.0)GO TO 117
      WRITE(6,112)(DATA(34,K),K=4,N3)
112  FORMAT(T11,'MEAN ..... ( " ) .....',10F8.4)
      WRITE(6,113)(DATA(35,K),K=4,N3)
113  FORMAT(T11,'STANDARD DEVIATION, ( " ) .....',10F8.4)
      WRITE(6,114)(DATA(36,K),K=4,N3)
114  FORMAT(T11,'SKEWNESS ..... ( " ) .....',10F8.4)
      WRITE(6,115)(DATA(37,K),K=4,N3)
115  FORMAT(T11,'KURTOSIS ..... ( " ) .....',10F8.4)
      WRITE(6,116)T,Y,P,E,VOLTS
116  FORMAT(/T16,'-----'//T30,'MATERIAL : '
X-----'//T30,'MATERIAL : '
X,4A4,T74,'APPLIED POTENTIAL : ',A4,' KV'/T27,'*****'
X*****')
117  IF(IMODES.EQ.0)GO TO 123
      WRITE(6,118)
118  FORMAT('1'/////T16,'-----'//T12,'SAMP
XAL ANALYSIS *-----'//T12,'SAMP
XLE UNIT WORK'/T12,'NUMBER JOULES/GRAM',T45,'X = LOCATION OF P
XEAKE : Y = PEAK HEIGHT, (WTX / SCREEN INTERVAL)',/)
      DO 121 I=1,NSAM
      J=ID(I,2)
119  WRITE(6,120)ID(I,1),DATA(32,I+3),(PEAKS(I,K),K=1,J)
120  FORMAT(/T14,I3,F12,3,T35,'X ',10F8.3)
121  WRITE(6,122)(PEAKS(I,K+10),K=1,J)
122  FORMAT(T35,'Y ',10F8.1)
      WRITE(6,116)T,Y,P,E,VOLTS
123  CONTINUE

```

C
C
C

PUNCH COMPUTED DATA FOR SUBSEQUENT USE

```

      WRITE(7,124)T,Y,P,E,VOLTS,NSAM
124  FORMAT(4A4,T20,A4,T30,I2)
      DO 125 I=4,N3
125  WRITE(7,126)ID(I-3,1),DATA(32,I),(DATA(J,I),J=33,37)
126  FORMAT(I5,6F10.4)
      GO TO 99
127  STOP
      END

```

C
C
C

MODAL ANALYSIS

```

      SUBROUTINE MODES(PEAKS,M,J,KOUNT)
      COMMON CALC(3500,11)
      DIMENSION PEAKS(10,20)
      DO 999 I=2,M
      DIFF1=CALC(I-1,KOUNT+1)-CALC(I,KOUNT+1)
      DIFF2=CALC(I,KOUNT+1)-CALC(I+1,KOUNT+1)
      IF(DIFF1*DIFF2)901,999,999
901  IF(DIFF1.GT.0.)GO TO 999
      J=J+1
      PEAKS(KOUNT,J)=CALC(I,1)

```

CONTINUED.....

```

PEAKS(KUUNT,J+10)=CALC(1,KUUNT+1)
IF(J.EQ.10)RETURN
999 CONTINUE
RETURN
END

```

```

C
C SIZE DISTRIBUTION PLOTTING
C

```

```

SUBROUTINE ACPLLOT(M,XARRAY,YARRAY,Q,W,WFACT,NSAM,T,Y,P,E,VOLTS,D,L
*ODP,NSET)

```

```

DIMENSION XARRAY(3500),YARRAY(3500),Q(3),W(10)

```

```

COMMON CALC(3500,11)

```

```

IF(LOOP.GT.1)GO TO 700

```

```

CALL PLUTON

```

```

CALL PLOT(0.0,1.0,-3)

```

```

700 XARRAY(M+1)=-1.0

```

```

XARRAY(M+2)=1.0

```

```

YARRAY(M+1)=0.0

```

```

YARRAY(M+2)=25.0

```

```

C
C DRAW & LABEL AXES
C

```

```

CALL PLOT(0.0,4.5,3)

```

```

CALL PLOT(0.0,0.0,2)

```

```

CALL PLOT(8.0,0.0,2)

```

```

CALL PLOT(8.0,4.5,2)

```

```

DO 701 I=1,9

```

```

A=I-1

```

```

B=A-1.

```

```

C=A-0.15

```

```

CALL NUMBER(C,-0.15,0.1,8.0,0.1)

```

```

701 CALL DASH(A,0.0,A,0.1,0.)

```

```

CALL SYMBOL(3.2,-0.4,0.15,11H-LOG (D/D ),0.0,11)

```

```

CALL SYMBOL(3.85,-0.5,0.1,114.0,0,-1)

```

```

CALL SYMBOL(4.55,-0.5,0.1,112.0,0,-1)

```

```

WFACT=WFACT/4.5

```

```

H=4.5

```

```

WD=-0.0

```

```

702 IF(H.LT.-0.0001)GO TO 703

```

```

HH=H-0.05

```

```

CALL NUMBER(-0.45,HH,0.1,-WD,0.0,2)

```

```

CALL DASH(0.0,H,0.1,H,0.0)

```

```

CALL DASH(8.0,H,7.9,H,0.0)

```

```

H=H-D/WFACT

```

```

WD=WD-D

```

```

GO TO 702

```

```

703 CALL SYMBOL(-0.60,0.6,0.15,22HUNIT WORK, JOULES/GRAM,90.0,22)

```

```

C
C PRINT CAPTIONS
C

```

```

CALL SYMBOL(3.6,5.5,0.2,T,0.0,4)

```

```

CALL SYMBOL(4.4,5.5,0.2,Y,0.0,4)

```

```

CALL SYMBOL(5.2,5.5,0.2,P,0.0,4)

```

```

CALL SYMBOL(6.0,5.5,0.2,E,0.0,4)

```

CONTINUED.....

```

CALL SYMBOL(4.4,5.0,0.2,VOLTS,0.0,4)
CALL SYMBOL(3.6,5.0,0.2,2HKV,0.0,2)
CALL PLOT(3.7,5.4,3)
CALL PLOT(6.0,5.4,2)
CALL PLOT(6.2,4.9,3)
CALL PLOT(4.0,4.9,2)
CALL SYMBOL(7.45,4.6,0.1,15HASSUMED MINIMUM,90.0,15)
CALL SYMBOL(7.65,4.7,0.1,13HPARTICLE SIZE,90.0,13)
CALL DASH(7.5,6.1,7.5,4.6,0.)
CALL DASHP(7.5,0.0,0.05)
CALL SYMBOL(2.35,4.6,0.1,15HFREQUENCY SCALE,90.0,15)
CALL SYMBOL(2.52,4.9,0.1,1H0,90.0,1)
CALL SYMBOL(2.52,5.27,0.1,6H10 20,90.0,6)
CALL DASH(2.63,5.75,2.58,5.75,0.0)
CALL DASH(2.63,5.75,2.63,4.95,0.0)
CALL DASH(2.63,5.35,2.58,5.35,0.0)
CALL DASH(2.63,4.95,2.58,4.95,0.0)
CALL SYMBOL(2.8,4.8,0.1,11HWEIGHTX PER,90.0,11)
CALL SYMBOL(2.95,4.6,0.1,15HSCREEN INTERVAL,90.0,15)
DO 801 I=1,M
801  XARRAY(I)=CALC(I,1)
    L=0
    CALL PLOT(0.0,4.5,-3)
    DO 804 J=1,NSAM
    L=L+1
    SHIFT=W(L)/WFACT
    DO 802 I=1,M
802  YARRAY(I)=CALC(I,L+1)-SHIFT*YARRAY(M+2)
C
C MARK EXPERIMENTAL POINTS
C
    DO 803 N=1,24
    II=(6.875-N*0.257/Q(2))
    X=(CALC(II,1)-Q(2)/2.)*1,
    Z=CALC(II,L+1)/25.-SHIFT
803  CALL SYMBOL(X,Z,0.05,4.0,0,-1)
    CALL SYMBOL(0.75,-SHIFT,0.05,4.0,0,-1)
    CALL SYMBOL(7.50,-SHIFT,0.05,4.0,0,-1)
C
C DRAW INTERPOLATED CURVE
C
    CALL LINE(XARRAY,YARRAY,M,1,0.4)
804  CONTINUE
    IF(LOOP.LT.NSET)GO TO 805
    CALL ENDPLT
    RETURN
805  CALL PLOT(11.0,-4.5,-3)
    RETURN
    END

```

C
C CALCULATION OF MEAN & STD. DEV. OF SCREENED PRODUCTS FROM OPTICALLY
C SIZED DATA
C

/LOAD FORTG
CALL XGCUN
DIMENSION Z(20,4)

C
C READ NO. OF INTERVALS, MAGNIFICATION, CENTRE OF UPPER INTERVAL,
C AND INTERVAL WIDTH.
C

1 READ(9,2)L,FACTOR,Z(1,1),STEP
2 FORMAT(4G80.0)
DO 100 I=2,L
J=1-1
100 Z(1,1)=Z(J,1)-STEP
DO 99 I=1,20
DO 99 J=2,4
99 Z(1,J)=0.0

C
C READ NO. OF PARTICLES IN EACH INTERVAL.
C

3 READ(9,3)(Z(1,2),I=1,L)
FORMAT(20G80.0)
NS=0
S3=0.0
S4=0.0
DO 98 I=1,L
Z(1,3)=Z(1,1)*Z(1,2)
NS=NS+Z(1,2)
98 S3=S3+Z(1,3)
AV=S3/NS
DO 97 I=1,L
Z(1,4)=(Z(1,2)*(Z(1,1)-AV)**2)
97 S4=S4+Z(1,4)
SDEV=(SQRT(S4/NS))/FACTOR
AV=AV/FACTOR
WRITE(6,4)AV,SDEV
4 FORMAT('MEAN=',1F10.3,'MM' STANDARD DEV.='1F10.3,'MM')
GO TO 1
END

C
 C DETERMINATION OF INTERCEPT BETWEEN TWO NORMAL CURVES BY ITERATION.
 C

/LOAD FORTG

CALL XGCUN

C=1./SQRT(2.*3.14159)

C
 C READ MEAN AND STD. DEV FOR EACH SAMPLE.
 C

```

1  READ(9,2)U1,SD1,U2,SD2
2  FORMAT(4G80.0)
   N=0
   XMAX=U2
   XMIN=U1
95  X=(XMAX+XMIN)/2.
   N=N+1
   IF(N.GT./20)GO TO 101
97  Y1=(C/SD1)*EXP((- (X-U1)**2)/(2.*SD1**2))
   Y2=(C/SD2)*EXP((- (X-U2)**2)/(2.*SD2**2))
   DIFF=Y2-Y1
   IF (ABS(DIFF).LT.0.0001)GO TO 100
   IF(DIFF)99,98,98
98  XMAX=X
   GO TO 95
99  XMIN=X
   GO TO 95
100 Y=(Y1+Y2)/2.
   WRITE(6,3)X,Y,N
3  FORMAT(/' INTERCEPT =',F10.5,' MM      Y =',F10.5,'      N =',
X12//)
4  FORMAT(/'N GREATER THAN 20')
   GO TO 1
101 WRITE(6,4)
   GO TO 1
   END

```

PLOTTING DISTRIBUTION PARAMETERS (KURTOSIS FOR AN EXAMPLE) VS. UNIT WORK.

```

DIMENSION X(12),Z(12),WT(10),COF(5),XF(1),YF(1)
CALL PLUTON
CALL PLOT(-5.0,4.0,-3)

```

READ NO. OF VOLTAGE CONDITIONS / GRAPH.

```

1 READ(5,2)NV
  IF(NV.EQ.99)GO TO 12
2 FORMAT(I2)
  DO 11 I=1,NV

```

READ MATERIAL NAME, APPLIED POTENTIAL, NO. OF POINTS.

```

  READ(5,3)T,Y,P,E,VOLTS,N
3 FORMAT(4A4,T20,A4,T30,I2)
  DO 4 J=1,N
    WT(J)=1.0

```

READ UNIT WORK & PARAMETER VALUE FOR EACH POINT.

```

4 READ(5,5)X(J),Z(J)
5 FORMAT(5X,F10.4,T50,F10.4)
  IF(I.GT.1)GO TO 7

```

DRAW GRAPH AND CAPTIONS.

```

CALL PLOT(12.0,0.0,-3)
CALL SYMBOL(0.5,-1.0,0.15,T,0.0,4)
CALL SYMBOL(1.1,-1.0,0.15,Y,0.0,4)
CALL SYMBOL(1.7,-1.0,0.15,P,0.0,4)
CALL SYMBOL(2.3,-1.0,0.15,E,0.0,4)
CALL SYMBOL(3.2,-1.0,0.15,11MKILOVOLTS :.0.0,11)
CALL RECT(0.0,0.0,5.0,8.0,0.0,3)
CALL SYMBOL(2.4,-0.4,0.15,22HUNIT WORK, JOULES/GRAM,0.0,22)
CALL SYMBOL(-0.6,1.8,0.15,8HKURTOSIS,90.0,8)

```

DETERMINE SUITABLE SCALE FACTORS (STANDARD ROUTINE).

```

CALL SCALE(Z,4.5,N,1)
CALL SCALE(X,7.5,N,1)
ZFACT=Z(N+2)
XFACT=X(N+2)
ZZERO=Z(N+1)

```

ZZERO=0.0: OPTIONAL SPECIFICATION OF ORIGIN.

```

ZZERO=0.0

```

CONTINUED.....

```

C
C LABEL AXES.
C
      POSN=-1.2
      DO 13 IX=1,9
        XNUM=(IX-1.0)*XFACT
        BLIP=IX-1.0
        POSN=POSN+1.0
        CALL NUMBER(POSN,-0.15,0.1,XNUM,0.0,2)
        CALL DASH(BLIP,5.0,BLIP,4.9,0.0)
13    CALL DASH(BLIP,0.1,BLIP,0.0,0.0)
      POSN=-1.05
      DO 14 IZ=1,6
        ZNUM=ZZERU+(IZ-1)*ZFACT
        IF(ZNUM.LT.1000.)NDEC=0
        IF(ZNUM.LT.100.)NDEC=1
        IF(ZNUM.LT.10.)NDEC=2
        POSN=POSN+1.0
        CALL NUMBER(-0.45,POSN,0.1,ZNUM,0.0,NDEC)
        BLIP=IZ-1.0
        CALL DASH(7.9,BLIP,8.0,BLIP,0.0)
14    CALL DASH(0.0,BLIP,0.1,BLIP,0.0)
C
C PRINT TITLE FOR DATA FROM BESTFT SUBROUTINE.
C
      7  WRITE(6,10)T,Y,P,E,VOLTS
C
C WRITE KEY.
C
      D=4.2+1*0.9
      DD=D+0.2
      CALL SYMBOL(DD,-1.0,0.1,VOLTS,0.0,4)
      CALL SYMBOL(D,-0.95,0.1,1.0,0,-1)
C
C FIT SUCCESSIVELY HIGHER POLYNOMIALS(1) (MAX. VALUE. J=4. HERE) AND
C PRINT OUT DATA (COEFFS., STD. DEV., ETC.)
C (*) 'BESTFT' IS MODIFIED FORM OF MCGILL SUBROUTINE 'CURVFT'.
C
      DO 16 J=1,4
        XF(1)=0.0
        YF(1)=0.0
16    CALL BESTFT(X,Z,WT,N,1,J,COF,NCOF,1,1,XF,YF)
C
C PLOT POINTS. DIFF. SYMBOL FOR EACH VOLTAGE.
C
      DO 15 NN=1,N
        XX=X(NN)/XFACT
        ZZ=(Z(NN)-ZZERU)/ZFACT
15    CALL SYMBOL(XX,ZZ,0.07,1.0,0,-1)
C
C DRAW BEST-FIT POLYNOMIAL. (IF NOT REQD. GO TO 10).
C
      FEED=YF(1)/ZFACT
      CALL PLUT(0,FEED,3)

```

CONTINUED.....


```
DO 9 K=1.800
UP=0.0
XK=0.01*K
XCALC=XK*XFACT
DO 8 L=1,NCOF
8  UP=(UP+COF(L)*(XCALC)**(L-1))
   UP=UP/ZFACT
   IF(UP.GT.5.0)GO TO 11
9  CALL PLOT(XK,UP,2)
10 FORMAT('1',T10,4A4,T50,A4//)
11 CONTINUE
   GO TO 1
12 CALL ENDPLT
   STOP
   END
```

A.VI. TABLES

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3.	Screen Analyses and Frequency Distribution Parameters	256-275
4.	Modal Analyses	276-295
5.	Float and Sink Analysis	296

Sample	Init. Weight (g)	Work Done (in-lb)	Unit Work (W.D./g)	*	MESH NUMBER													Total Weight (g)	K (mm)
					12	16	20	30	40	50	70	100	140	200	270	325	-325		
A	1.75	4.0	2.28	a	1.58	0.09	0.03	0.01	0.01	0.00	0.01							1.73	18.0
				b	8.68	3.47	1.73	1.15	0.58									1.77	9.30
B	1.78	3.2	1.80	a	1.41	0.21	0.06	0.03	0.02	0.01	0.01	0.01						1.79	6.00
				b	20.3	8.48	5.08	3.39	1.70	1.13	0.57							1.74	5.10
C	1.79	5.6	3.13	a	1.18	0.31	0.15	0.05	0.04	0.02	0.01	0.03						1.76	3.10
				b	34.1	16.7	8.38	5.59	3.35	2.24	1.68							1.76	2.50
D	1.75	5.3	3.03	a	1.09	0.31	0.15	0.08	0.04	0.02	0.02	0.03						1.76	2.28
				b	37.4	19.5	10.9	6.33	4.02	2.87	1.72							1.70	2.00
E	1.78	10.0	5.62	a	0.60	0.40	0.39	0.15	0.08	0.05	0.03	0.02	0.04					1.78	1.59
				b	67.0	43.2	21.0	12.5	7.96	5.11	3.41	2.27						1.73	1.39
F	1.76	10.2	5.80	a	0.45	0.34	0.44	0.21	0.11	0.06	0.04	0.03	0.02	0.04				1.71	1.14
				b	74.1	54.6	29.3	17.2	10.9	7.47	5.18	3.45	2.30					1.72	1.14
G	1.77	12.8	7.23	a	0.56	0.32	0.40	0.20	0.10	0.06	0.04	0.03	0.02	0.03				1.74	0.98
				b	62.2	50.0	27.3	15.9	10.2	6.82	4.55	2.84	1.70					1.67	0.86
H	1.74	14.2	8.17	a	0.38	0.26	0.45	0.25	0.14	0.08	0.04	0.10							
				b	77.6	62.3	35.9	21.2	12.9	8.23	5.82								
I	1.78	14.9	8.38	a			0.99	0.32	0.16	0.10	0.06	0.05	0.04	0.03	0.01	0.02		1.78	
				b			44.4	26.4	17.4	11.8	8.42	5.62	3.37	1.69	1.12			1.73	
J	1.75	21.4	12.2	a			0.68	0.43	0.24	0.14	0.08	0.06	0.04	0.06				1.71	
				b			60.7	35.8	22.0	13.9	9.25	5.78	3.47					1.72	
K	1.74	26.4	15.2	a			0.53	0.44	0.26	0.17	0.09	0.08	0.06	0.08				1.74	
				b			69.0	43.3	28.1	18.1	12.9	8.19	4.68					1.67	
L	1.74	29.8	17.1	a			0.49	0.45	0.29	0.17	0.10	0.09	0.05	0.03	0.05			1.74	
				b			71.5	45.4	28.5	18.6	12.8	7.56	4.65	2.91				1.67	
M	1.76	34.7	19.7	a			0.30	0.49	0.36	0.21	0.12	0.09	0.07	0.05	0.05			1.67	
				b			82.7	54.6	33.9	21.8	14.9	9.77	5.25	2.87				1.67	
N	1.71	46.5	29.9	a			0.60	0.41	0.24	0.13	0.11	0.07	0.05	0.06				1.67	
				b			64.1	39.5	25.1	17.4	10.8	6.59	3.59					1.67	

* a) Weight retained;
b) Cumulative weight % passing.

Applied potential: 0 kv
Material: Quartzite

Sample	Init. Weight (g)	Work Done (in-lb)	Unit Work (W.D./g)	*	MESH NUMBER													Total Weight (g)	K (mm)
					12	16	20	30	40	50	70	100	140	200	270	325	-325		
A	1.76	2.83	1.61	a	1.50	0.14	0.04	0.02	0.01	0.01	0.01	0.01						1.74	
				b	13.7	5.65	3.35	2.20	1.72	1.15	0.57								
B	1.74	7.30	4.19	a	1.19	0.26	0.12	0.05	0.03	0.02	0.01	0.03						1.71	
				b	30.4	15.2	8.19	5.26	3.51	2.34	1.75								
C	1.74	9.73	5.59	a	0.71	0.38	0.29	0.13	0.07	0.05	0.02	0.05						1.70	
				b	58.3	36.9	18.8	11.2	7.06	4.12	2.94								
D	1.72	14.4	8.38	a	0.57	0.41	0.34	0.16	0.08	0.04	0.02	0.05						1.67	
				b	65.9	41.3	20.9	11.4	6.59	4.09	2.99								
E	1.76	12.3	7.00	a	0.53	0.54	0.35	0.11	0.07	0.05	0.03	0.02	0.04					1.74	
				b	69.5	38.5	20.1	12.1	8.05	5.18	3.45	2.30							
F	1.79	13.3	7.43	a		0.92	0.40	0.18	0.11	0.06	0.03	0.03	0.02	0.03				1.78	
				b		48.3	25.8	15.7	9.55	6.18	4.49	2.81	1.69						
G	1.73	17.2	10.1	a		0.78	0.39	0.22	0.11	0.06	0.03	0.03	0.02	0.03				1.67	
				b		53.3	29.9	16.8	10.2	6.58	4.79	2.99	1.79						
H	1.75	19.4	11.1	a		0.48	0.49	0.30	0.18	0.10	0.05	0.05	0.07					1.72	
				b		72.1	43.8	26.2	15.7	9.88	6.97	4.07							
I	1.75	18.0	10.3	a			0.91	0.34	0.18	0.11	0.06	0.05	0.03	0.05				1.73	
				b			47.4	28.3	17.4	11.0	7.52	4.62	2.89						
J	1.7	23.6	13.3	a			0.83	0.36	0.21	0.12	0.07	0.06	0.04	0.02	0.04			1.75	
				b			52.6	32.0	20.0	13.1	9.15	5.71	3.43	2.29					
K	1.7	25.7	14.5	a			0.64	0.40	0.28	0.15	0.09	0.07	0.04	0.08				1.75	
				b			74.9	40.6	24.6	16.0	10.9	6.86	4.57						
L	1.78	28.3	15.9	a			0.56	0.43	0.29	0.17	0.09	0.08	0.04	0.03	0.07			1.76	
				b			68.2	43.7	27.3	17.6	12.5	7.96	5.68	3.98					
M	1.79	34.4	19.2	a			0.40	0.49	0.33	0.20	0.10	0.09	0.05	0.04	0.03	0.04		1.77	
				b			77.4	49.7	31.1	19.8	14.1	9.04	6.21	3.95	2.28				
N	1.73	53.5	30.9	a				0.57	0.39	0.25	0.14	0.11	0.07	0.06	0.04	0.02	0.01	1.66	
				b				65.7	42.2	27.1	18.7	12.0	7.83	4.22	1.81	0.60			

a) Weight retained;
b) Cumulative weight % passing.

Applied potential: 15.0 kV
Material: Quartzite

Sample	Init. Weight (g)	Work Done (in-lb)	Unit Work (W.D./g)	*	MESH NUMBER													Total Weight (g)	K (mm)
					12	16	20	30	40	50	70	100	140	200	270	325	-325		
A	2.66	1.99	0.75	a	1.76	0.44	0.19	0.10	0.07	0.03	0.06							2.65	
				b	33.6	17.0	9.80	6.04	3.41	2.26									5.30
B	2.65	4.64	1.75	a	1.10	0.60	0.36	0.23	0.12	0.08	0.13							2.62	
				b	58.0	35.1	21.4	12.6	8.00	4.96									2.95
C	2.66	3.99	1.50	a		1.61	0.37	0.24	0.16	0.09	0.06	0.04	0.07					2.64	
				b		39.0	25.0	15.9	9.85	6.44	4.17	2.65							2.50
D	2.65	7.82	2.95	a		1.13	0.53	0.32	0.28	0.12	0.09	0.05	0.12					2.64	
				b		57.2	37.1	25.0	14.4	9.85	6.44	4.55							1.85
E	2.63	12.7	4.83	a			1.09	0.47	0.36	0.29	0.08	0.12	0.08	0.04	0.06			2.59	
				b			58.0	39.8	25.9	14.7	11.6	6.95	3.86	2.32					1.20
F	2.65	16.9	6.37	a				1.47	0.40	0.26	0.16	0.13	0.07	0.06	0.08			2.63	
				b				44.1	28.9	19.0	12.9	8.00	5.32	3.04					1.08
G	2.68	21.0	7.85	a				1.37	0.37	0.31	0.18	0.16	0.09	0.06	0.05	0.06		2.65	
				b				48.2	34.3	22.6	15.8	9.81	6.41	4.15	2.26				0.90
H	2.65	23.8	9.00	a				1.46	0.37	0.26	0.17	0.13	0.08	0.06	0.02	0.06		2.61	
				b				44.1	29.9	19.9	13.4	8.43	5.36	3.07	2.30				0.73
I	2.64	29.6	11.2	a				1.51	0.34	0.22	0.18	0.10	0.09	0.05	0.03	0.06		2.58	
				b				41.4	28.3	19.8	12.8	8.91	5.42	3.49	2.33				0.73
J	2.65	35.3	13.3	a				1.39	0.37	0.26	0.21	0.15	0.09	0.05	0.03	0.06		2.61	
				b				46.7	32.6	22.6	14.6	8.81	5.36	3.45	2.30				0.67
K	2.66	39.9	15.0	a				1.30	0.29	0.31	0.23	0.18	0.11	0.07	0.04	0.08		2.61	
				b				50.0	39.1	27.2	18.4	11.5	7.28	4.60	3.06				0.59

a) Weight retained;
b) Cumulative weight % passing.

Applied potential: 0 kv
Material: Mono-Sphalerite

Sample	Init. Weight (g)	Work Done (in-lb)	Unit Work (W.D./g)	*	MESH NUMBER													Total Weight (g)	K (mm)
					12	16	20	30	40	50	70	100	140	200	270	325	-325		
A	2.65	1.85	0.70	a	1.31	0.83	0.23	0.09	0.06	0.04	0.02	0.04						2.62	
				b	50.0	18.3	9.55	6.11	3.81	2.29	1.53								
B	2.65	3.18	1.20	a	0.74	1.10	0.34	0.18	0.10	0.04	0.04	0.02	0.02	0.03				2.61	
				b	71.6	29.5	16.5	9.58	5.75	4.22	2.69	1.92	1.15						
C	2.66	5.19	1.95	a		1.31	0.58	0.27	0.15	0.13	0.07	0.03	0.03	0.06				2.63	
				b		50.2	28.1	17.9	12.2	7.22	4.56	3.42	2.28						
D	2.65	9.39	3.54	a		0.92	0.71	0.35	0.16	0.19	0.11	0.06	0.03	0.09				2.62	
				b		64.9	37.8	24.4	18.3	11.0	6.87	4.58	3.44						
E	2.64	12.5	4.75	a			1.37	0.42	0.28	0.18	0.11	0.08	0.06	0.04	0.07			2.61	
				b			47.5	31.4	20.7	13.8	9.58	6.51	4.21	2.68					
F	2.67	15.9	5.95	a			1.17	0.44	0.27	0.22	0.18	0.12	0.06	0.05	0.04	0.05		2.60	
				b			55.0	38.1	27.7	19.2	12.3	7.70	5.38	3.46	1.92				
G	2.65	18.5	7.00	a			1.11	0.40	0.35	0.21	0.24	0.08	0.08	0.05	0.04	0.06		2.62	
				b			57.6	42.4	29.0	21.0	11.8	8.78	5.22	3.32	2.29				
H	2.65	21.5	8.12	a			0.93	0.41	0.42	0.21	0.23	0.13	0.09	0.07	0.05	0.07		2.61	
				b			64.4	48.7	32.5	24.5	15.7	10.7	7.28	4.60	2.68				
I	2.66	28.6	10.8	a					1.52	0.33	0.24	0.19	0.11	0.09	0.07	0.02	0.06	2.63	
				b					42.2	29.6	20.5	13.3	9.13	5.71	3.04	2.28			
J	2.66	36.2	14.0	a					1.40	0.36	0.27	0.18	0.16	0.07	0.07	0.03	0.06	2.60	
				b					47.2	32.3	21.9	15.0	8.85	6.15	3.46	2.31			
K	2.65	44.0	16.6	a					1.27	0.40	0.29	0.17	0.16	0.12	0.07	0.03	0.08	2.59	
				b					51.0	35.5	24.3	17.7	11.6	6.95	4.25	3.09			

* a) Weight retained;
b) Cumulative weight % passing.

Applied potential: 15.0 kV
Material: Mono-Sphalerite

(a)	SAMPLE NO.	145	146	147	148	149	150	151	152	153	154
(b)	INTENDED UNIT WORK, in-lb/gm	2.5	5	7.5	10	12.5	15	17.5	20	25	6500lb
(c)	EXPECTED RATIO *	3.5	3.3	3.2	3.2	3.3	3.4	3.4	3.8	4.0	limit
(d)	EXPECTED W_{total} , (b)×(c)	8.75	16.5	24	32	41	51	59.5	76	100	
(e)	LOAD SCALE, lbs/F.S.D. **	500	1000	2000	2000	5000	5000	5000	5000	10,000	10,000
(f)	SCALE FACTOR, counts/in-lb	100	50	25	25	10	10	10	10	5	5
(g)	INTENDED COUNT, (d)×(f)	875	830	600	800	410	510	595	760	500	-
(h)	ACTUAL... { DOWN ($\equiv W_{total}$)	620	829	579	807	413	515	592	730	508	689
(i)	...COUNT { UP ($\equiv W_{Instron}$)	112	129	101	143	89	116	172	245	228	362
(j)	DIFFERENCE, (h)-(i)	508	700	478	664	324	399	420	485	280	327
(k)	% F.S.D. (i.e. PEAK HEIGHT)	97	86	55	77	38	45	57	70	50	65
(l)	CORRECTED DIFFERENCE, (j)+0.2(k)	527	717	489	679	332	408	431	499	290	340
(m)	UNIT WORK, (l)/(f)	5.27	14.34	19.50	27.18	33.16	40.80	43.14	49.90	58.00	68.00

APPLIED POTENTIAL 0 kv

MATERIAL Quartzite

(a)	SAMPLE NO.	186	187	188	189	190	191	192	193	194	195
(b)	INTENDED UNIT WORK, in-lb/gm	2.5	5	7.5	10	12.5	15	17.5	20	25	6500lb
(c)	EXPECTED RATIO *	3	3	3.1	3.2	3.2	3.3	3.5	3.8	4.5	limit
(d)	EXPECTED W_{total} , (b)×(c)	7.5	15	23	32	40	49.5	61	76	112	
(e)	LOAD SCALE, lbs/F.S.D. **	500	1000	2000	2000	2000	5000	5000	5000	10,000	10,000
(f)	SCALE FACTOR, counts/in-lb	100	50	25	25	25	10	10	10	5	5
(g)	INTENDED COUNT (d)×(f)	750	750	580	800	1000	495	610	760	560	-
(h)	ACTUAL... { DOWN ($\equiv W_{total}$)	766	760	575	754	1001	491	619	774	563	713
(i)	...COUNT { UP ($\equiv W_{Instron}$)	128	152	92	141	205	108	159	228	244	357
(j)	DIFFERENCE, (h)-(i)	638	608	483	613	796	383	460	546	317	356
(k)	% F.S.D. (i.e. PEAK HEIGHT)	110	94	55	60	93	44	55	69	53	65
(l)	CORRECTED DIFFERENCE, (j)+0.2(k)	660	627	494	625	815	392	471	560	328	369
(m)	UNIT WORK, (l)/(f)	6.60	12.54	19.76	25.00	32.58	39.18	47.10	55.98	65.52	73.80

APPLIED POTENTIAL 7.5 kv

MATERIAL Quartzite

* W_{total} /UNIT WORK - estimate based on previous tests

** Chosen to give highest on-scale deflection

(a)	SAMPLE NO.	165	166	167	175	169	170	171	172	173	174
(b)	INTENDED UNIT WORK, in-lb/gm	2.5	5	7.5	10	12.5	15	17.5	20	25	6500lb
(c)	EXPECTED RATIO *	3.0	3.1	3.0	3.2	3.2	3.2	3.5	4.0	4.7	limit
(d)	EXPECTED W_{total} , (b)x(c)	7.5	15.5	22.5	32	40	48	61	80	117	
(e)	LOAD SCALE, lbs/F.S.D. **	500	1000	2000	2000	5000	5000	5000	5000	10,000	10,000
(f)	SCALE FACTOR, counts/in-lb	100	50	25	25	10	10	10	10	5	5
(g)	INTENDED COUNT, (d)x(f)	750	775	562	800	400	480	610	800	590	-
(h)	ACTUAL... { DOWN ($\approx W_{total}$)	964	744	553	792	401	487	623	784	598	700
(i)	...COUNT { UP ($\approx W_{Instron}$)	120	68	95	132	61	110	156	267	299	361
(j)	DIFFERENCE, (h)-(i)	744	676	458	660	340	377	467	517	299	339
(k)	% F.S.D. (i.e. PEAK HEIGHT)	105	52	52	64	30	45	55	74	59	66
(l)	CORRECTED DIFFERENCE, (j)+0.2(k)	765	686	468	673	346	386	478	532	311	352
(m)	UNIT WORK, (l)/(f)	7.65	13.73	18.74	26.91	34.6	38.6	47.8	53.18	62.16	70.44

		APPLIED POTENTIAL 15 kV									
		MATERIAL Quartzite									
(a)	SAMPLE NO.	176	177	178	179	180	181	182	183	184	185
(b)	INTENDED UNIT WORK, in-lb/gm	2.5	5	7.5	10	12.5	15	17.5	20	25	6500lb
(c)	EXPECTED RATIO *	3.0	3.0	3.1	3.2	3.2	3.3	3.4	4.0	4.5	limit
(d)	EXPECTED W_{total} , (b)x(c)	7.5	15	23.2	32	40	49.5	60	80	112	
(e)	LOAD SCALE, lbs/F.S.D. **	500	1000	2000	2000	2000	5000	5000	5000	10,000	10,000
(f)	SCALE FACTOR, counts/in-lb	100	50	25	25	25	10	10	10	5	5
(g)	INTENDED COUNT (d)x(f)	750	750	580	800	1000	495	600	800	560	-
(h)	ACTUAL... { DOWN ($\approx W_{total}$)	750	751	576	852	1037	493	611	795	564	668
(i)	...COUNT { UP ($\approx W_{Instron}$)	69	87	90	123	173	102	161	237	258	361
(j)	DIFFERENCE, (h)-(i)	681	644	486	739	864	391	450	558	306	307
(k)	% F.S.D. (i.e. PEAK HEIGHT)	72	66	55	75	91	44	52	69	55	66
(l)	CORRECTED DIFFERENCE, (j)+0.2(k)	695	657	497	754	882	400	460	572	317	320
(m)	UNIT WORK, (l)/(f)	6.95	13.14	19.88	30.16	35.28	39.98	46.04	57.18	63.40	64.04

APPLIED POTENTIAL 22.5 kV

MATERIAL Quartzite

* W_{total} /UNIT WORK - estimate based on previous tests

** Chosen to give highest on-scale deflection

(a)	SAMPLE NO.	155	156	157	158	159	160	161	162	163	164
(b)	INTENDED UNIT WORK, in-lb/gm	2.5	5	7.5	10	12.5	15	17.5	20	25	6500lb
(c)	EXPECTED RATIO *	3.2	3.2	3.2	3.2	3.2	3.2	3.5	4.0	4.5	limit
(d)	EXPECTED W_{total} , (b)x(c)	8	16	24	32	40	48	61	80	112.5	
(e)	LOAD SCALE, lbs/F.S.D. **	500	1000	2000	2000	5000	5000	5000	5000	10,000	10,000
(f)	SCALE FACTOR, counts/in-lb	100	50	25	25	10	10	10	10	5	5
(g)	INTENDED COUNT, (d)x(f)	800	800	600	800	400	480	610	800	560	-
(h)	ACTUAL... { DOWN ($=W_{total}$)	804	795	611	802	393	529	628	806	560	686
(i)	...COUNT { UP ($=W_{Instron}$)	95	105	78	109	52	113	183	283	256	365
(j)	DIFFERENCE, (h)-(i)	709	690	533	693	341	416	445	523	304	321
(k)	% F.S.D. (i.e. PEAK HEIGHT)	84	69	45	64	27	52	64	77	54	66
(l)	CORRECTED DIFFERENCE, (j)+0.2(k)	726	704	542	706	346	426	458	538	315	334
(m)	UNIT WORK, (l)/(f)	7.26	14.08	21.68	28.23	34.64	42.64	45.78	53.84	62.96	66.84

APPLIED POTENTIAL 30 kv
MATERIAL Quartzite

(a)	SAMPLE NO.	223	224	225	226	227	228	229	230	231	222
(b)	INTENDED UNIT WORK, in-lb/gm	2.5	5	7.5	10	12.5	15	17.5	20	25	30
(c)	EXPECTED RATIO *	3.0	3.0	3.0	3.1	3.4	3.3	3.5	3.8	4.5	5.0
(d)	EXPECTED W_{total} , (b)x(c)	7.5	15	22.5	31	42.6	49.5	61.3	76	112.5	150
(e)	LOAD SCALE, lbs/F.S.D. **	500	1000	2000	2000	5000	5000	5000	5000	10,000	10,000
(f)	SCALE FACTOR, counts/in-lb	100	50	25	25	10	10	10	10	5	5
(g)	INTENDED COUNT (d)x(f)	750	750	563	775	426	495	613	760	563	750
(h)	ACTUAL... { DOWN ($=W_{total}$)	767	751	566	760	430	499	621	767	595	627
(i)	...COUNT { UP ($=W_{Instron}$)	117	96	82	157	80	150	183	314	295	322
(j)	DIFFERENCE, (h)-(i)	650	655	484	603	350	349	438	453	300	305
(k)	% F.S.D. (i.e. PEAK HEIGHT)	102	75	50	75	36	51	59	80	58	60
(l)	CORRECTED DIFFERENCE, (j)+0.2(k)	670	670	494	618	357	359	450	469	312	317
(m)	UNIT WORK, (l)/(f)	6.7	13.4	19.76	24.72	35.7	35.9	45.0	46.9	62.4	63.4

APPLIED POTENTIAL 0 kv
MATERIAL Mono-Quartz

* W_{total} /UNIT WORK - estimate based on previous tests

** Chosen to give highest on-scale deflection

(a)	SAMPLE NO.	232	233	234	235	236	237	238	239	240	241
(b)	INTENDED UNIT WORK, in-lb/gm	2.5	5	7.5	10	12.5	15	17.5	20	5000lb	16.5
(c)	EXPECTED RATIO *	3.0	3.1	3.1	3.1	3.1	3.5	4.0	4.0	limit	3.7
(d)	EXPECTED W_{total} , (b) x (c)	7.5	15.5	23.3	31	38.8	52.5	70	80	61	61
(e)	LOAD SCALE, lbs/F.S.D. **	500	1000	2000	2000	5000	5000	5000	5000	5000	5000
(f)	SCALE FACTOR, counts/in-lb	100	50	25	25	10	10	10	10	10	10
(g)	INTENDED COUNT, (d) x (f)	750	775	583	775	388	525	700	800	-	610
(h)	ACTUAL... { DOWN ($\approx W_{total}$)	754	781	578	779	385	530	698	804	1009	617
(i)	...COUNT { UP ($\approx W_{Instron}$)	129	95	67	104	80	148	218	308	483	183
(j)	DIFFERENCE, (h) - (i)	625	686	511	675	305	382	480	496	526	434
(k)	% F.S.D. (i.e. PEAK HEIGHT)	105	69	46	58	37	52	65	79	102	59
(l)	CORRECTED DIFFERENCE, (j) + 0.2(k)	646	700	520	687	312	392	493	512	546	446
(m)	UNIT WORK, (l)/(f)	6.46	14.0	20.8	27.48	31.2	39.2	49.3	51.2	54.6	44.6

APPLIED POTENTIAL 15 kV

MATERIAL Mono-Quartz

(a)	SAMPLE NO.	242	243	244	245	246	247	248	249	250	251
(b)	INTENDED UNIT WORK, in-lb/gm	2.5	5	7.5	10	12.5	15	17.5	20	6000lb	10.5
(c)	EXPECTED RATIO *	3.0	3.0	3.0	3.1	3.3	3.5	3.7	4.5	limit	3.2
(d)	EXPECTED W_{total} , (b) x (c)	7.5	15	22.5	31	41.3	52.5	64.8	90	33.6	33.6
(e)	LOAD SCALE, lbs/F.S.D. **	500	1000	2000	2000	5000	5000	5000	10,000	10,000	10,000
(f)	SCALE FACTOR, counts/in-lb	100	50	25	25	10	10	10	5	5	25
(g)	INTENDED COUNT (d) x (f)	750	750	563	625	413	525	648	450	-	840
(h)	ACTUAL... { DOWN ($\approx W_{total}$)	743	744	572	627	422	534	642	451	604	842
(i)	...COUNT { UP ($\approx W_{Instron}$)	111	89	93	97	81	126	234	194	343	125
(j)	DIFFERENCE, (h) - (i)	632	655	479	530	341	408	408	257	261	717
(k)	% F.S.D. (i.e. PEAK HEIGHT)	93	66	54	55	35	49	66	45	60	69
(l)	CORRECTED DIFFERENCE, (j) + 0.2(k)	651	668	490	541	348	418	421	266	273	731
(m)	UNIT WORK, (l)/(f)	6.51	13.36	19.6	21.64	34.8	41.8	42.1	53.2	54.6	29.24

APPLIED POTENTIAL 30 kV

MATERIAL Mono-Quartz

* W_{total} /UNIT WORK - estimate based on previous tests

** Chosen to give highest on-scale deflection

(a)	SAMPLE NO.	311	312	313	314	315	316	318	319	320	321
(b)	INTENDED UNIT WORK, in-lb/gm	Preliminary		6	1	2	3	4	5	6.5	7
(c)	EXPECTED RATIO *	-	-	5.0	4.5	4.7	4.8	4.9	5.0	5.1	5.5
(d)	EXPECTED W_{total} , (b)×(c)	-	-	30	4.5	9.4	14.4	19.6	25.0	33.1	38.5
(e)	LOAD SCALE, lbs/F.S.D. **	5000	5000	5000	500	1000	1000	2000	2000	5000	5000
(f)	SCALE FACTOR, counts/in-lb	10	10	10	100	50	50	25	25	10	10
(g)	INTENDED COUNT, (d)×(f)	-	-	300	450	470	720	490	625	331	385
(h)	ACTUAL... { DOWN ($=W_{total}$)	526	662	303	461	475	727	501	613	333	405
(i)	...COUNT { UP ($=W_{Instron}$)	230	325	93	83	90	145	100	151	107	149
(j)	DIFFERENCE, (h)-(i)	296	337	210	378	385	582	401	462	226	256
(k)	% F.S.D. (i.e. PEAK HEIGHT)	63	80	38	73	64	91	58	70	40	51
(l)	CORRECTED DIFFERENCE, (j)+0.2(k)	309	353	218	393	398	600	413	476	234	266
(m)	UNIT WORK, (l)/(f)	30.9	35.3	21.8	3.93	7.96	12.0	16.5	19.0	23.4	26.6

APPLIED POTENTIAL 0 kv

MATERIAL Poly-Sphalerite

(a)	SAMPLE NO.	335	336	337	338	339	340	341	342	343	344
(b)	INTENDED UNIT WORK, in-lb/gm	1	2	3	4	5	6	2500lb	4.2	5.5	3500lb
(c)	EXPECTED RATIO *	4.6	4.7	4.8	5.0	5.2	5.5	limit	5.2	5.4	limit
(d)	EXPECTED W_{total} , (b)×(c)	4.6	9.4	14.4	20	26	33	limit	21.8	29.7	limit
(e)	LOAD SCALE, lbs/F.S.D. **	500	1000	1000	2000	2000	5000	5000	2000	2000	5000
(f)	SCALE FACTOR, counts/in-lb	100	50	50	25	25	10	10	25	25	10
(g)	INTENDED COUNT (d)×(f)	460	470	720	500	650	330	-	546	743	-
(h)	ACTUAL... { DOWN ($=W_{total}$)	450	472	730	498	637	332	445	556	759	525
(i)	...COUNT { UP ($=W_{Instron}$)	86	79	152	136	171	88	158	137	208	205
(j)	DIFFERENCE, (h)-(i)	364	393	578	362	466	244	287	419	551	320
(k)	% F.S.D. (i.e. PEAK HEIGHT)	70	55	83	61	75	36	51	75	85	70
(l)	CORRECTED DIFFERENCE, (j)+0.2(k)	378	404	594	374	481	251	297	434	568	334
(m)	UNIT WORK, (l)/(f)	3.78	8.08	11.88	14.94	19.24	25.1	29.7	17.32	22.72	33.4

APPLIED POTENTIAL 15 kv

MATERIAL Poly-Sphalerite

* W_{total} /UNIT WORK - estimate based on previous tests

** Chosen to give highest on-scale deflection

(a)	SAMPLE NO.	324	325	326	327	328	329	331	332	333	334
(b)	INTENDED UNIT WORK, in-lb/gm	1	8	2	3	4	5	6	7	3.2	
(c)	EXPECTED RATIO *	4.6	6.0	4.7	4.7	4.9	5.0	5.2	3000lb	6.0	4.8
(d)	EXPECTED W_{total} , (b)x(c)	4.6	48.0	9.4	14.1	19.6	25.0	31.2	limit	42.0	15.4
(e)	LOAD SCALE, lbs/F.S.D. **	500	5000	1000	1000	2000	2000	5000	5000	5000	2000
(f)	SCALE FACTOR, counts/in-lb	100	10	50	50	25	25	10	10	10	25
(g)	INTENDED COUNT, (d)x(f)	460	480	470	705	490	625	312	-	420	384
(h)	ACTUAL... { DOWN ($\equiv W_{total}$)	461	510	477	700	510	630	312	559	451	381
(i)	...COUNT { UP ($\equiv W_{Instron}$)	63	201	81	141	135	142	96	218	180	86
(j)	DIFFERENCE, (h)-(i)	398	309	396	559	375	488	216	341	271	295
(k)	% F.S.D. (i.e. PEAK HEIGHT)	59	55	59	88	64	67	37	61	55	45
(l)	CORRECTED DIFFERENCE, (j)+0.2(k)	410	320	408	577	388	501	223	353	282	304
(m)	UNIT WORK, (l)/(f)	4.10	32.0	8.16	11.54	15.52	20.04	22.3	35.3	28.2	12.16

APPLIED POTENTIAL 30 kv

MATERIAL Poly-Sphalerite

(a)	SAMPLE NO.	253	255	256	257	258	259	260	261	262
(b)	INTENDED UNIT WORK, in-lb/gm	1	2	3	4	5	6	1.5	2.5	
(c)	EXPECTED RATIO *	2500lb	4.0	4.5	4.4	4.5	4.6	5.0	4.3	4.5
(d)	EXPECTED W_{total} , (b)x(c)	limit	4.0	9.0	13.2	18	23	30	6.45	11.25
(e)	LOAD SCALE, lbs/F.S.D. **	5000	500	500	1000	2000	2000	5000	500	1000
(f)	SCALE FACTOR, counts/in-lb	10	100	100	50	25	25	10	100	50
(g)	INTENDED COUNT (d)x(f)	2	400	900	660	450	575	300	645	562
(h)	ACTUAL... { DOWN ($\equiv W_{total}$)	418	399	944	654	455	588	307	633	576
(i)	...COUNT { UP ($\equiv W_{Instron}$)	143	49	126	100	73	144	102	78	82
(j)	DIFFERENCE, (h)-(i)	275	350	818	554	382	444	205	555	494
(k)	% F.S.D. (i.e. PEAK HEIGHT)	50	57	110	73	48	72	38	75	65
(l)	CORRECTED DIFFERENCE, (j)+0.2(k)	285	361	840	569	392	458	213	570	507
(m)	UNIT WORK, (l)/(f)	28.5	3.61	8.4	11.38	15.68	18.32	21.3	5.7	10.14

APPLIED POTENTIAL 0 kv

MATERIAL Mono-Sphalerite

* W_{total} /UNIT WORK - estimate based on previous tests

** Chosen to give highest on-scale deflection

(a)	SAMPLE NO.	263	264	265	266	267	268	269	270	271	272
(b)	INTENDED UNIT WORK, in-lb/gm	1	2	3	4	5	6	7	2.5	3.5	4.5
(c)	EXPECTED RATIO *	4.3	4.5	4.6	4.6	5.0	5.5	6.0	4.6	4.6	4.8
(d)	EXPECTED W_{total} , (b)x(c)	4.3	9.0	13.8	18.4	25	33	42	11.5	16.0	21.6
(e)	LOAD SCALE, lbs/F.S.D. **	500	1000	1000	2000	2000	5000	5000	1000	2000	2000
(f)	SCALE FACTOR, counts/in-lb	100	50	50	25	25	10	10	50	25	25
(g)	INTENDED COUNT, (d)x(f)	430	450	690	460	625	330	420	575	400	540
(h)	ACTUAL... { DOWN ($=W_{total}$)	433	458	682	462	631	332	419	589	409	546
(i)	...COUNT { UP ($=W_{Instron}$)	62	71	92	80	137	94	158	123	54	113
(j)	DIFFERENCE, (h)-(i)	371	387	590	382	494	238	261	466	355	433
(k)	% F.S.D. (i.e. PEAK HEIGHT)	64	56	70	49	70	40	54	83	40	61
(l)	CORRECTED DIFFERENCE, (j)+0.2(k)	384	398	604	392	508	246	272	483	363	445
(m)	UNIT WORK, (l)/(f)	3.84	7.96	12.08	15.68	20.32	24.6	27.2	9.66	14.52	17.80

APPLIED POTENTIAL 15 kv

MATERIAL Mono-Sphalerite

(a)	SAMPLE NO.	273	274	275	276	277	278	279	280	281	282
(b)	INTENDED UNIT WORK, in-lb/gm	1	2	3	4	5	6	6	7	2.5	3.5
(c)	EXPECTED RATIO *	4.4	4.5	4.6	4.8	4.9	5.4	5.4	6.0	4.6	4.7
(d)	EXPECTED W_{total} , (b)x(c)	4.4	9.0	13.8	19.2	24.5	32.4	32.4	42	11.5	16.5
(e)	LOAD SCALE, lbs/F.S.D. **	500	500	1000	2000	2000	500	5000	5000	1000	1000
(f)	SCALE FACTOR, counts/in-lb	100	100	50	25	25	100	10	10	50	25
(g)	INTENDED COUNT (d)x(f)	440	900	690	480	612	324	324	420	575	412
(h)	ACTUAL... { DOWN ($=W_{total}$)	433	826	694	484	626	329	329	421	575	420
(i)	...COUNT { UP ($=W_{Instron}$)	53	120	115	86	126	40	85	137	66	65
(j)	DIFFERENCE, (h)-(i)	380	706	579	398	500	289	244	284	509	355
(k)	% F.S.D. (i.e. PEAK HEIGHT)	59	103	80	54	67	49	36	49	61	44
(l)	CORRECTED DIFFERENCE, (j)+0.2(k)	392	727	595	409	513	299	251	294	521	364
(m)	UNIT WORK, (l)/(f)	3.92	7.27	11.9	16.36	20.52	2.99	25.1	29.4	10.42	14.56

APPLIED POTENTIAL 30 kv

MATERIAL Mono-Sphalerite

* W_{total} /UNIT WORK - estimate based on previous tests

** Chosen to give highest on-scale deflection

(a)	SAMPLE NO.	196	197	201	198	202	199	203	200	204
(b)	INTENDED UNIT WORK, in-lb/gm	1	1	1.5	2	2.5	3	3.5	4	0.5
(c)	EXPECTED RATIO *	3.0	3.3	3.3	3.3	3.3	3.3	3.3	3.3	3.2
(d)	EXPECTED W_{total} , (b)x(c)	3.0	3.3	4.95	6.6	8.25	9.9	11.5	13.2	1.6
(e)	LOAD SCALE, lbs/F.S.D. **	500	500	500	500	500	500	500	1000	500
(f)	SCALE FACTOR, counts/in-lb	100	100	100	100	100	100	100	50	100
(g)	INTENDED COUNT, (d)x(f)	300	330	495	660	825	990	1150	660	160
(h)	ACTUAL... { DOWN ($=W_{total}$)	294	336	452	664	808	940	1093	661	159
(i)	...COUNT { UP ($=W_{Instron}$)	23	29	32	41	67	100	199	141	21
(j)	DIFFERENCE, (h)-(i)	271	307	420	623	741	840	894	520	138
(k)	% F.S.D. (i.e. PEAK HEIGHT)	31	35	41	46	62	82	110	84	27
(l)	CORRECTED DIFFERENCE, (j)+0.2(k)	277	314	428	632	753	856	1016	537	143
(m)	UNIT WORK, (l)/(f)	2.77	3.14	4.28	6.32	7.53	8.56	10.16	10.74	1.43

APPLIED POTENTIAL 0 kv
MATERIAL Iron Ore

(a)	SAMPLE NO.	205	206	207	208	209	210	211	212
(b)	INTENDED UNIT WORK, in-lb/gm	0.5	1	1.5	2	2.5	3	3.5	0.8
(c)	EXPECTED RATIO *	3.3	3.3	3.3	3.3	3.3	3.3	3.7	3.3
(d)	EXPECTED W_{total} , (b)x(c)	1.65	3.3	4.95	6.6	8.25	9.9	13	2.64
(e)	LOAD SCALE, lbs/F.S.D. **	500	500	500	500	500	500	1000	500
(f)	SCALE FACTOR, counts/in-lb	100	100	100	100	100	100	50	100
(g)	INTENDED COUNT (d)x(f)	165	330	495	660	825	990	650	264
(h)	ACTUAL... { DOWN ($=W_{total}$)	167	331	497	667	832	988	632	222
(i)	...COUNT { UP ($=W_{Instron}$)	25	14	31	28	45	141	141	19
(j)	DIFFERENCE, (h)-(i)	142	317	466	639	787	847	491	203
(k)	% F.S.D. (i.e. PEAK HEIGHT)	29	27	35	41	56	102	85	25
(l)	CORRECTED DIFFERENCE, (j)+0.2(k)	148	322	473	647	798	867	508	208
(m)	UNIT WORK, (l)/(f)	1.48	3.22	4.73	6.47	7.98	8.67	10.16	2.08

APPLIED POTENTIAL 15 kv
MATERIAL Iron Ore

* W_{total} /UNIT WORK - estimate based on previous tests

** Chosen to give highest on-scale deflection

(a)	SAMPLE NO.	212	213	214	215	216	217	218	219	220	221
(b)	INTENDED UNIT WORK, in-lb/gm	0.5	1	1.5	2	2.5	3	3.5	0.3	0.8	1.8
(c)	EXPECTED RATIO *	3.3	3.3	3.3	3.3	3.3	3.3	3.7	3.3	3.3	3.3
(d)	EXPECTED W_{total} , (b)x(c)	1.65	3.3	4.95	6.6	8.25	9.9	13	1.0	2.64	6.0
(e)	LOAD SCALE, lbs/F.S.D. **	500	500	500	500	500	500	1000	500	500	500
(f)	SCALE FACTOR, counts/in-lb	100	100	100	100	100	100	50	100	100	100
(g)	INTENDED COUNT, (d)x(f)	165	330	495	660	825	990	650	100	264	600
(h)	ACTUAL... { DOWN ($\equiv W_{total}$)	183	334	495	661	832	990	653	107	255	572
(i)	...COUNT { UP ($\equiv W_{Instron}$)	17	35	40	38	62	153	133	11	29	40
(j)	DIFFERENCE, (h)-(i)	166	299	455	623	770	837	520	96	226	532
(k)	% F.S.D. (i.e. PEAK HEIGHT)	22	36	38	45	57	105	79	12	30	41
(l)	CORRECTED DIFFERENCE, (j)+0.2(k)	162	306	463	632	781	858	536	94	232	540
(m)	UNIT WORK, (l)/(f)	1.62	3.06	4.63	6.32	7.81	8.58	10.72	0.94	2.32	5.40

						APPLIED POTENTIAL			30	kV
						MATERIAL		Iron Ore		
(a)	SAMPLE NO.	377	378	379	380	381	382	383	384	385
(b)	INTENDED UNIT WORK, in-lb/gm	1	1.5	2.5	3.5	4.5	5.5	6.5	8.0	4.5
(c)	EXPECTED RATIO *	6.0	6.2	6.5	6.8	7.0	7.2	7.5	7.7	7.0
(d)	EXPECTED W_{total} , (b)x(c)	6.0	9.3	16.25	23.8	31.5	39.6	48.7	61.6	31.5
(e)	LOAD SCALE, lbs/F.S.D. **	500	1000	2000	2000	2000	5000	5000	5000	2000
(f)	SCALE FACTOR, counts/in-lb	100	50	25	25	25	10	10	10	25
(g)	INTENDED COUNT (d)x(f)	600	465	406	595	787	396	487	616	787
(h)	ACTUAL... { DOWN ($\equiv W_{total}$)	410	476	392	601	687	390	487	624	781
(i)	...COUNT { UP ($\equiv W_{Instron}$)	79	121	105	141	186	102	148	213	211
(j)	DIFFERENCE, (h)-(i)	331	355	287	460	501	288	339	411	570
(k)	% F.S.D. (i.e. PEAK HEIGHT)	72	79	57	70	84	41	51	64	91
(l)	CORRECTED DIFFERENCE, (j)+0.2(k)	345	371	298	474	518	296	349	424	588
(m)	UNIT WORK, (l)/(f)	3.45	7.42	11.92	18.96	20.72	29.6	34.9	42.4	23.52

APPLIED POTENTIAL 0 kV

MATERIAL Poly-Hematite

* W_{total} /UNIT WORK - estimate based on previous tests

** Chosen to give highest on-scale deflection

(a)	SAMPLE NO.	369	370	371	372	373	374	375	376
(b)	INTENDED UNIT WORK, in-lb/gm	1	2	3	4	5	6	5.3	7.5
(c)	EXPECTED RATIO *	6.0	6.0	6.3	6.5	6.7	7.4	7.1	7.5
(d)	EXPECTED W_{total} , (b)x(c)	6.0	12.0	18.9	26.0	33.5	44.4	37.6	56.3
(e)	LOAD SCALE, lbs/F.S.D. **	500	1000	2000	2000	2000	5000	5000	5000
(f)	SCALE FACTOR, counts/in-lb	100	50	25	25	25	10	10	10
(g)	INTENDED COUNT, (d)x(f)	600	600	472	650	755	444	376	563
(h)	ACTUAL... { DOWN ($\#W_{total}$)	573	581	479	653	774	447	380	561
(i)	...COUNT { UP ($\#W_{Instron}$)	101	107	96	145	202	132	109	179
(j)	DIFFERENCE, (h)-(i)	472	474	383	508	572	315	271	382
(k)	% F.S.D. (i.e. PEAK HEIGHT)	83	73	54	70	87	46	41	56
(l)	CORRECTED DIFFERENCE, (j)+0.2(k)	489	489	394	522	589	324	279	393
(m)	UNIT WORK, (l)/(f)	4.89	9.78	15.76	20.88	23.56	32.4	27.9	39.3

APPLIED POTENTIAL 15 kV
MATERIAL Poly-Hematite

(a)	SAMPLE NO.	360	361	362	363	364	365	366	367	368
(b)	INTENDED UNIT WORK, in-lb/gm	3000lb	3500lb	2500lb	7	5	4	3	2	1
(c)	EXPECTED RATIO *	limit	limit	limit	7.7	7.3	7.2	6.9	6.5	6.0
(d)	EXPECTED W_{total} , (b)x(c)				53.9	36.5	28.8	20.7	13.0	6.0
(e)	LOAD SCALE, lbs/F.S.D. **	5000	5000	5000	5000	2000	2000	2000	1000	500
(f)	SCALE FACTOR, counts/in-lb	10	10	10	10	25	25	25	50	100
(g)	INTENDED COUNT (d)x(f)	-	-	-	539	913	720	518	650	600
(h)	ACTUAL... { DOWN ($\#W_{total}$)	600	701	451	540	909	725	518	647	617
(i)	...COUNT { UP ($\#W_{Instron}$)	215	262	142	174	271	187	115	143	132
(j)	DIFFERENCE, (h)-(i)	385	439	309	366	638	538	403	504	485
(k)	% F.S.D. (i.e. PEAK HEIGHT)	62	70	49	51	102	81	59	86	101
(l)	CORRECTED DIFFERENCE, (j)+0.2(k)	397	453	319	356	658	554	415	521	505
(m)	UNIT WORK, (l)/(f)	39.7	45.3	31.9	35.6	26.32	22.16	16.60	10.42	5.05

APPLIED POTENTIAL 30 kV
MATERIAL Poly-Hematite

* W_{total} /UNIT WORK - estimate based on previous tests

** Chosen to give highest on-scale deflection

----- EXPERIMENTAL DATA -----

SAMPLE NUMBER	145	146	147	148	149	150	151	152	153	154
WEIGHT RESOLVE (GMS/CM.)	2.6648	2.6612	2.6607	2.6596	2.6444	2.6403	2.6485	2.6405	2.6519	2.6489
WOM DCME. (INCH-PUNOS)	5.27	10.14	19.50	27.18	33.16	40.60	43.14	49.90	58.00	68.00

----- SCREEN ANALYSES -----

WCSH NUMBER	APERTURE (MM)	SAMPLE WEIGHTS, GM.
10	2.000	0.0900 0.0097 0.0083 0.0179 0.0106 0.0763 0.0366 0.0905 0.0754 0.0189
12	1.750	1.1549 0.7691 0.5035 0.3866 0.2163 0.1215 0.1451 0.0455 0.0840 0.0447
14	1.500	0.2432 0.4429 0.3294 0.2183 0.1527 0.1109 0.0793 0.0600 0.1325 0.0713
16	1.250	0.0886 0.3139 0.3520 0.2223 0.2158 0.2430 0.1241 0.1095 0.0524 0.0624
18	1.000	0.0649 0.2795 0.3630 0.3912 0.3737 0.3400 0.3244 0.2258 0.1924 0.2078
20	0.800	0.0266 0.1168 0.1489 0.2665 0.2594 0.2818 0.2400 0.2330 0.2064 0.1947
25	0.710	0.0204 0.0645 0.1116 0.1838 0.2509 0.2503 0.2678 0.2263 0.2369 0.2397
30	0.630	0.0213 0.0074 0.0074 0.2034 0.2374 0.2717 0.2697 0.2554 0.2509 0.2644
35	0.560	0.0110 0.0310 0.0624 0.1145 0.1531 0.1901 0.2198 0.2076 0.2337 0.2410
40	0.525	0.0120 0.0334 0.0440 0.0466 0.1210 0.1439 0.1411 0.1447 0.1584 0.2255
45	0.475	0.0079 0.0193 0.0201 0.0586 0.0722 0.0835 0.0884 0.1263 0.1325 0.1450
50	0.430	0.0046 0.0128 0.0297 0.0662 0.0833 0.0975 0.1206 0.1440 0.1552 0.1746
60	0.350	0.0051 0.0155 0.0209 0.0390 0.0493 0.0532 0.0713 0.0842 0.0814 0.0994
70	0.280	0.0041 0.0141 0.0461 0.0360 0.0333 0.0464 0.0522 0.0557 0.0589 0.0824
80	0.250	0.0035 0.0119 0.0191 0.0278 0.0324 0.0411 0.0498 0.0609 0.0597 0.0731
100	0.200	0.0037 0.0130 0.0132 0.0236 0.0330 0.0430 0.0528 0.0676 0.0568 0.0829
120	0.175	0.0019 0.0160 0.0160 0.0159 0.0245 0.0237 0.0279 0.0349 0.0347 0.0450
140	0.150	0.0011 0.0142 0.0141 0.0163 0.0256 0.0250 0.0320 0.0433 0.0438 0.0513
160	0.130	0.0006 0.0046 0.0046 0.0054 0.0162 0.0188 0.0210 0.0260 0.0260 0.0300
200	0.100	0.0008 0.0037 0.0031 0.0080 0.0136 0.0187 0.0180 0.0217 0.0245 0.0290
250	0.080	0.0008 0.0028 0.0016 0.0054 0.0095 0.0123 0.0140 0.0142 0.0203 0.0201
270	0.075	0.0006 0.0022 0.0018 0.0050 0.0102 0.0147 0.0152 0.0262 0.0268 0.0266
325	0.060	0.0011 0.0013 0.0010 0.0039 0.0081 0.0105 0.0125 0.0173 0.0204 0.0220
400	0.045	0.0009 0.0011 0.0007 0.0008 0.0034 0.0053 0.0089 0.0121 0.0164 0.0158
450	0.038	0.0000 0.0000 0.0000 0.0000 0.0009 0.0025 0.0055 0.0089 0.0136 0.0150
500	0.030	0.0000 0.0000 0.0000 0.0000 0.0009 0.0025 0.0055 0.0089 0.0136 0.0150

----- COMPUTED DATA -----

WCSH NUMBER	APERTURE (MM)	SAMPLE WEIGHTS, GM.
10	2.000	0.0900 0.0097 0.0083 0.0179 0.0106 0.0763 0.0366 0.0905 0.0754 0.0189
12	1.750	1.1549 0.7691 0.5035 0.3866 0.2163 0.1215 0.1451 0.0455 0.0840 0.0447
14	1.500	0.2432 0.4429 0.3294 0.2183 0.1527 0.1109 0.0793 0.0600 0.1325 0.0713
16	1.250	0.0886 0.3139 0.3520 0.2223 0.2158 0.2430 0.1241 0.1095 0.0524 0.0624
18	1.000	0.0649 0.2795 0.3630 0.3912 0.3737 0.3400 0.3244 0.2258 0.1924 0.2078
20	0.800	0.0266 0.1168 0.1489 0.2665 0.2594 0.2818 0.2400 0.2330 0.2064 0.1947
25	0.710	0.0204 0.0645 0.1116 0.1838 0.2509 0.2503 0.2678 0.2263 0.2369 0.2397
30	0.630	0.0213 0.0074 0.0074 0.2034 0.2374 0.2717 0.2697 0.2554 0.2509 0.2644
35	0.560	0.0110 0.0310 0.0624 0.1145 0.1531 0.1901 0.2198 0.2076 0.2337 0.2410
40	0.525	0.0120 0.0334 0.0440 0.0466 0.1210 0.1439 0.1411 0.1447 0.1584 0.2255
45	0.475	0.0079 0.0193 0.0201 0.0586 0.0722 0.0835 0.0884 0.1263 0.1325 0.1450
50	0.430	0.0046 0.0128 0.0297 0.0662 0.0833 0.0975 0.1206 0.1440 0.1552 0.1746
60	0.350	0.0051 0.0155 0.0209 0.0390 0.0493 0.0532 0.0713 0.0842 0.0814 0.0994
70	0.280	0.0041 0.0141 0.0461 0.0360 0.0333 0.0464 0.0522 0.0557 0.0589 0.0824
80	0.250	0.0035 0.0119 0.0191 0.0278 0.0324 0.0411 0.0498 0.0609 0.0597 0.0731
100	0.200	0.0037 0.0130 0.0132 0.0236 0.0330 0.0430 0.0528 0.0676 0.0568 0.0829
120	0.175	0.0019 0.0160 0.0160 0.0159 0.0245 0.0237 0.0279 0.0349 0.0347 0.0450
140	0.150	0.0011 0.0142 0.0141 0.0163 0.0256 0.0250 0.0320 0.0433 0.0438 0.0513
160	0.130	0.0006 0.0046 0.0046 0.0054 0.0162 0.0188 0.0210 0.0260 0.0260 0.0300
200	0.100	0.0008 0.0037 0.0031 0.0080 0.0136 0.0187 0.0180 0.0217 0.0245 0.0290
250	0.080	0.0008 0.0028 0.0016 0.0054 0.0095 0.0123 0.0140 0.0142 0.0203 0.0201
270	0.075	0.0006 0.0022 0.0018 0.0050 0.0102 0.0147 0.0152 0.0262 0.0268 0.0266
325	0.060	0.0011 0.0013 0.0010 0.0039 0.0081 0.0105 0.0125 0.0173 0.0204 0.0220
400	0.045	0.0009 0.0011 0.0007 0.0008 0.0034 0.0053 0.0089 0.0121 0.0164 0.0158
450	0.038	0.0000 0.0000 0.0000 0.0000 0.0009 0.0025 0.0055 0.0089 0.0136 0.0150
500	0.030	0.0000 0.0000 0.0000 0.0000 0.0009 0.0025 0.0055 0.0089 0.0136 0.0150

APPLIED POTENTIAL : 2000 KV

* EXPERIMENTAL DATA *									
SAMPLE NUMBER	176	177	178	179	180	181	182	183	185
WEIGHT BEFORE CRUSHING. (GM.) ...	2.6563	2.6572	2.6519	2.6628	2.6524	2.6562	2.6507	2.6504	2.6520
WCHN DONE. (INCH-POUNDS)	6.95	13.14	19.68	30.16	35.28	39.98	46.04	57.18	64.04

* SCREEN ANALYSES *									
WESH NUMBER	NOMINAL APERTURE (MM)	SAMPLE WEIGHTS, GM.							
10	2.000	0.8763	0.8475	0.5371	0.2338	0.1406	0.1112	0.0680	0.0720
12	1.700	1.1041	0.8424	0.4294	0.3321	0.2326	0.2341	0.1382	0.0664
14	1.400	0.2775	0.3618	0.3812	0.3264	0.2590	0.1823	0.1146	0.0499
16	1.180	0.1310	0.1356	0.2859	0.3272	0.2655	0.2085	0.1725	0.1484
18	1.000	0.1060	0.1217	0.2575	0.3720	0.3973	0.4064	0.3051	0.2864
20	0.850	0.0263	0.0534	0.1674	0.2313	0.2081	0.2416	0.2916	0.2651
25	0.710	0.0332	0.0445	0.0924	0.1617	0.2233	0.2132	0.2472	0.2594
30	0.600	0.0257	0.0497	0.1063	0.1671	0.2011	0.2171	0.2780	0.3279
35	0.500	0.0187	0.0178	0.0599	0.0842	0.1246	0.1448	0.2000	0.2020
40	0.425	0.0104	0.0163	0.0447	0.0714	0.0940	0.1164	0.1532	0.1762
45	0.355	0.0085	0.0122	0.0295	0.0433	0.0588	0.0700	0.0992	0.1011
50	0.300	0.0066	0.0154	0.0340	0.0512	0.0670	0.0657	0.1159	0.1257
60	0.250	0.0051	0.0049	0.0225	0.0350	0.0409	0.0501	0.0670	0.0747
70	0.212	0.0048	0.0068	0.0171	0.0249	0.0306	0.0385	0.0495	0.0570
80	0.180	0.0046	0.0066	0.0149	0.0233	0.0240	0.0377	0.0462	0.0537
100	0.150	0.0046	0.0080	0.0167	0.0261	0.0315	0.0407	0.0497	0.0594
120	0.125	0.0034	0.0053	0.0103	0.0160	0.0224	0.0268	0.0318	0.0366
140	0.106	0.0028	0.0054	0.0087	0.0160	0.0191	0.0255	0.0317	0.0378
170	0.090	0.0023	0.0038	0.0086	0.0119	0.0139	0.0181	0.0218	0.0255
200	0.075	0.0021	0.0028	0.0035	0.0086	0.0093	0.0121	0.0143	0.0187
230	0.063	0.0027	0.0016	0.0021	0.0060	0.0065	0.0089	0.0100	0.0123
270	0.053	0.0023	0.0023	0.0020	0.0074	0.0081	0.0105	0.0155	0.0165
325	0.045	0.0030	0.0017	0.0014	0.0061	0.0063	0.0079	0.0111	0.0143
400	0.038	0.0011	0.0010	0.0009	0.0043	0.0035	0.0035	0.0080	0.0097
-400		0.0	0.0006	0.0010	0.0027	0.0019	0.0016	0.0021	0.0060

* COMPUTED DATA *									
TOTAL SCREENED WEIGHT. (GM.)	2.6651	2.6300	2.5710	2.5965	2.5749	2.5652	2.5622	2.5495	2.5565
CRUSHING & SCREEN LOSS. (WT%) ...	-0.34	1.02	2.98	2.53	2.92	3.43	3.34	3.81	3.60
WCHN WORK. (JOULES/GRAM.)	0.2906	0.5587	0.8470	1.2797	1.5028	1.7006	1.9624	2.4376	2.7223
UNIT WORK. (KWH/TONNE)	0.0821	0.1552	0.2353	0.3555	0.4175	0.4724	0.5452	0.6772	0.7579
MEDIAN. (LOG. SIZE UNITS)	0.1023	0.1239	0.4599	0.8026	0.6952	1.1193	1.4230	1.5661	1.6974
MEAN. (")	0.2435	0.3672	0.7376	1.0561	1.2440	1.3801	1.6350	1.7869	1.9347
STANDARD DEVIATION. (")	0.6134	0.7277	0.9523	1.0389	1.0380	1.0911	1.1406	1.1522	1.2057
SKENNESS. (")	17.3734	10.7599	3.4596	2.8731	2.0229	1.4910	1.1568	1.1152	0.8734
KURTOSIS. (")	25.5020	16.5742	7.2728	6.4710	5.4346	4.5564	4.3744	4.1851	3.7509

MATERIAL : QUARTZITE APPLIED POTENTIAL : 22.5 KV

----- EXPERIMENTAL DATA -----

SAMPLE ALVOER 155 156 157 158 159 160 161 162 163 164

BEIGHT BEFORE CRUSHING, (GM.) ... 2.6442 2.6522 2.6510 2.6416 2.6455 2.6453 2.6474 2.6523 2.6595 2.6585

WORK DONE, (INCH-POUNDS) 7.26 18.08 21.68 28.23 34.64 42.04 49.76 53.84 62.96 66.84

----- SCREEN ANALYSES -----

WEST MILLER	NOMINAL APERTURE (MM)	SAMPLE WEIGHTS, GM.									
10	4.000	1.1235	0.8410	0.4164	0.3651	0.2141	0.0891	0.0451	0.0633	0.0129	0.0536
12	1.700	0.9008	1.0030	0.5664	0.4228	0.2308	0.1256	0.1472	0.1373	0.1020	0.0520
14	1.400	0.2057	0.2654	0.3478	0.2502	0.1858	0.1489	0.1226	0.0913	0.0987	0.0422
16	1.180	0.1566	0.1146	0.1306	0.2390	0.2787	0.2350	0.1638	0.1567	0.0915	0.0442
18	1.000	0.0546	0.0376	0.4236	0.3712	0.3903	0.4248	0.3522	0.3033	0.2038	0.2217
20	0.850	0.0425	0.0530	0.1399	0.1690	0.2775	0.3261	0.2710	0.2493	0.2275	0.2404
25	0.710	0.0248	0.0484	0.0557	0.1487	0.1597	0.2153	0.2580	0.2451	0.2500	0.2347
30	0.600	0.0215	0.0272	0.0504	0.1521	0.1910	0.2563	0.2521	0.2066	0.3516	0.3552
35	0.500	0.0060	0.0245	0.0553	0.0865	0.1200	0.1587	0.1642	0.1797	0.2244	0.2147
40	0.425	0.0058	0.0163	0.0386	0.0707	0.0851	0.1270	0.1531	0.1527	0.1975	0.2578
45	0.355	0.0046	0.0133	0.0246	0.0410	0.0551	0.0819	0.0694	0.1029	0.1319	0.1343
50	0.300	0.0063	0.0144	0.0289	0.0476	0.0689	0.0957	0.1060	0.1197	0.1471	0.1531
60	0.250	0.0038	0.0064	0.0165	0.0265	0.0400	0.0512	0.0592	0.0716	0.0817	0.0505
70	0.212	0.0026	0.0070	0.0121	0.0157	0.0325	0.0405	0.0465	0.0563	0.0662	0.0734
80	0.180	0.0023	0.0075	0.0124	0.0177	0.0264	0.0386	0.0429	0.0544	0.0590	0.0694
100	0.150	0.0025	0.0076	0.0125	0.0178	0.0304	0.0399	0.0455	0.0565	0.0620	0.0735
120	0.125	0.0017	0.0050	0.0081	0.0117	0.0205	0.0249	0.0321	0.0349	0.0399	0.0471
140	0.106	0.0016	0.0040	0.0068	0.0075	0.0160	0.0241	0.0245	0.0305	0.0380	0.0465
170	0.090	0.0010	0.0024	0.0042	0.0053	0.0101	0.0124	0.0147	0.0225	0.0243	0.0299
200	0.075	0.0007	0.0028	0.0042	0.0055	0.0109	0.0147	0.0140	0.0200	0.0250	0.0242
230	0.063	0.0005	0.0017	0.0029	0.0041	0.0068	0.0088	0.0093	0.0163	0.0153	0.0197
270	0.053	0.0007	0.0008	0.0034	0.0047	0.0090	0.0126	0.0089	0.0147	0.0147	0.0237
320	0.044	0.0006	0.0027	0.0029	0.0043	0.0080	0.0112	0.0077	0.0154	0.0126	0.0199
400	0.035	0.0005	0.0014	0.0012	0.0012	0.0027	0.0047	0.0036	0.0087	0.0045	0.0111
420	0.030	0.0003	0.0005	0.0004	0.0006	0.0013	0.0026	0.0018	0.0040	0.0023	0.0032

----- COMPUTED DATA -----

TOTAL SCREENED WEIGHT, (GM.) 2.6367 2.6472 2.5728 2.5013 2.5759 2.5606 2.5470 2.5674 2.4924 2.5367

CRUSHING & SCREEN LOSS, (WT) ... 0.028 0.19 2.51 5.31 2.63 3.20 4.15 3.20 6.66 4.58

UNIT WORK, (JULLES/GRAM) 0.3162 0.5558 0.9240 1.2078 1.4798 1.8212 1.9404 2.2925 2.6708 2.8407

UNIT WORK, (KWH/TONNE) 0.0862 0.1666 0.2567 0.3354 0.4110 0.5059 0.5407 0.6371 0.7431 0.7871

MECHAN. (LUG. SIZE UNITS) 0.0507 0.1136 0.3581 0.7112 0.9286 1.1969 1.3477 1.4476 1.6782 1.7356

PLAY 0.1977 0.3361 0.6705 0.9123 1.1709 1.4640 1.5361 1.7108 1.8605 2.0050

STANDARD DEVIATION, (") 0.4982 0.7126 0.8494 0.9543 1.0543 1.0636 1.0636 1.0636 1.0636 1.1724

SKIDNESS 20.544 12.7020 4.7641 2.3705 1.9112 1.5591 1.1508 1.1163 0.7017 0.7989

KINETICS 33.3063 18.8380 9.1706 6.0110 5.1944 4.9131 4.2692 4.1943 3.6936 3.7028

MATERIAL : CLAYZITE

APPLIED POTENTIAL : 30.0 KV

----- * EXPERIMENTAL DATA * -----

SAMPLE NUMBER	222	223	224	225	226	227	228	229	230	231
WEIGHT BEFORE CRUSHING, (GM.) ...	2.6464	2.6457	2.6422	2.6515	2.6502	2.6488	2.6496	2.6609	2.6599	2.6453
WORK DONE, (INCH-POUNDS)	63.40	6.70	13.40	19.76	24.72	31.20	35.50	45.00	46.90	62.40

----- * SCREEN ANALYSES * -----

MESH NUMBER	NOMINAL APERTURE (MM)	SAMPLE WEIGHTS, GM.									
10	2.000	0.0842	1.2350	0.3549	0.4088	0.3397	0.2161	0.1737	0.1794	0.2941	0.0502
12	1.700	0.1234	0.7763	0.0593	0.5768	0.3999	0.2978	0.2408	0.1874	0.2237	0.1517
14	1.400	0.0608	0.2634	0.2695	0.2534	0.2558	0.2200	0.1532	0.0779	0.1400	0.0580
16	1.180	0.1027	0.1143	0.2462	0.2439	0.2197	0.2627	0.2453	0.1573	0.1822	0.0840
18	1.000	0.2076	0.0577	0.1700	0.3374	0.2940	0.3455	0.3134	0.2453	0.1909	0.2221
20	0.850	0.1714	0.0540	0.0729	0.1942	0.2522	0.2817	0.2765	0.2557	0.2167	0.1560
25	0.710	0.1940	0.0248	0.0660	0.1273	0.1678	0.1999	0.2281	0.2282	0.1958	0.2019
30	0.600	0.3590	0.0228	0.0542	0.1200	0.1722	0.1873	0.2373	0.3283	0.2669	0.2825
35	0.500	0.2623	0.0200	0.0364	0.0834	0.0767	0.1231	0.1260	0.1891	0.2004	0.2051
40	0.425	0.2104	0.0129	0.0247	0.0532	0.0821	0.1081	0.1135	0.1528	0.1540	0.2248
45	0.355	0.1368	0.0054	0.0212	0.0362	0.0538	0.0608	0.0755	0.1045	0.0958	0.1479
50	0.300	0.1450	0.0112	0.0239	0.0475	0.0708	0.0674	0.0914	0.1183	0.1179	0.1700
60	0.250	0.0927	0.0082	0.0143	0.0270	0.0344	0.0393	0.0620	0.0750	0.0779	0.1030
70	0.212	0.0706	0.0013	0.0113	0.0169	0.0214	0.0312	0.0306	0.0515	0.0519	0.0778
80	0.180	0.0642	0.0043	0.0098	0.0149	0.0192	0.0283	0.0304	0.0409	0.0479	0.0705
100	0.150	0.0602	0.0053	0.0084	0.0159	0.0181	0.0274	0.0248	0.0469	0.0507	0.0695
120	0.125	0.0468	0.0046	0.0053	0.0117	0.0107	0.0185	0.0243	0.0257	0.0348	0.0455
140	0.106	0.0365	0.0037	0.0042	0.0065	0.0094	0.0082	0.0149	0.0190	0.0210	0.0373
170	0.090	0.0203	0.0018	0.0019	0.0021	0.0027	0.0087	0.0065	0.0103	0.0132	0.0206
200	0.075	0.0234	0.0016	0.0030	0.0026	0.0039	0.0087	0.0106	0.0103	0.0130	0.0193
230	0.063	0.0123	0.0017	0.0016	0.0035	0.0042	0.0045	0.0084	0.0085	0.0091	0.0114
270	0.053	0.0177	0.0018	0.0020	0.0021	0.0028	0.0081	0.0051	0.0065	0.0117	0.0164
325	0.045	0.0131	0.0007	0.0008	0.0010	0.0024	0.0066	0.0067	0.0075	0.0097	0.0121
400	0.038	0.0113	0.0006	0.0009	0.0005	0.0008	0.0056	0.0032	0.0047	0.0056	0.0082
-400		0.0100	0.0002	0.0003	0.0006	0.0007	0.0040	0.0025	0.0030	0.0040	0.0081

----- * COMPUTED DATA * -----

TOTAL SCREENED WEIGHT, (GM.)	2.6452	2.6404	2.6123	2.5976	2.5556	2.5689	2.5647	2.5420	2.5558	2.5129
CRUSHING & SCREEN LOSS, (WT%) ...	3.62	-0.03	1.13	2.03	3.57	3.02	3.20	4.47	3.91	5.01
UNIT WORK, (FOOT-POUNDS/GRAM)	2.7124	0.2861	0.5730	0.8420	1.0539	1.3308	1.5309	1.9108	1.9922	2.6652
UNIT WORK, (KWH/TONNE)	0.7535	0.0755	0.1592	0.2339	0.2928	0.3697	0.4253	0.5308	0.5534	0.7404
MEDIAN, (LOG. SIZE UNITS)	1.7288	0.0283	0.1556	0.5510	0.7863	0.9583	1.1048	1.4340	1.3930	1.7972
PEAK, (LOG. SIZE UNITS)	1.8560	0.0561	0.4711	0.7981	0.9787	1.1819	1.3057	1.5416	1.5225	1.9186
STANDARD DEVIATION, (")	1.1813	0.0400	0.7533	0.8858	0.9473	1.0470	1.0487	1.0959	1.1725	1.1540
SKEWNESS, (")	0.6572	14.0089	6.2503	2.4823	1.5873	2.0357	1.3125	0.7407	0.7224	0.4578
KURTOSIS, (")	2.8725	21.5783	10.9627	6.0241	4.9050	5.7334	4.6685	4.0828	3.7274	3.5862

MATERIAL : MONO-QUARTZ APPLIED POTENTIAL : ZERO KV

----- * EXPERIMENTAL DATA *										
SAMPLE NUMBER	432	233	234	235	236	237	238	239	240	241
HEIGHT BEFORE CRUSHING, (GM.) ...	2.6500	2.6503	2.6526	2.6430	2.6474	2.6410	2.6487	2.6541	2.6514	2.6557
WORK DONE, (INCH-POUNDS)	6.46	14.00	20.80	27.46	35.70	39.20	49.30	51.20	54.60	44.60
----- * SCREEN ANALYSES *										
		SAMPLE WEIGHTS, GM.								
WLS#	APERTURE (MM)	10	12	14	16	18	20	25	30	40
10	2.000	1.1699	0.7924	0.6302	0.3167	0.1541	0.1562	0.1300	0.1234	0.1179
12	1.700	0.9100	0.7144	0.6161	0.4944	0.3158	0.2872	0.2422	0.1785	0.1525
14	1.400	0.2451	0.3871	0.2545	0.2955	0.1552	0.1405	0.1473	0.0962	0.1174
16	1.180	0.1020	0.2073	0.2888	0.3168	0.2056	0.2300	0.1269	0.1440	0.0931
18	1.000	0.0708	0.1615	0.2675	0.3969	0.3615	0.3262	0.2440	0.2355	0.2309
20	0.850	0.0242	0.0456	0.1294	0.1521	0.2500	0.2756	0.2318	0.2285	0.2024
25	0.710	0.0260	0.0522	0.0840	0.1240	0.2268	0.2017	0.2286	0.2395	0.2077
30	0.600	0.0217	0.0572	0.0509	0.1093	0.2313	0.2364	0.2613	0.4913	0.3126
35	0.500	0.0139	0.0411	0.0355	0.0755	0.1358	0.1438	0.2110	0.1990	0.2231
40	0.425	0.0145	0.0272	0.0297	0.0616	0.1129	0.1306	0.1567	0.1653	0.2003
45	0.355	0.0068	0.0173	0.0204	0.0347	0.0768	0.0700	0.0865	0.1055	0.1241
50	0.300	0.0104	0.0180	0.0319	0.0415	0.0949	0.0876	0.1167	0.1195	0.1468
60	0.250	0.0060	0.0110	0.0182	0.0250	0.0456	0.0435	0.0632	0.0728	0.0936
70	0.212	0.0048	0.0065	0.0148	0.0180	0.0264	0.0356	0.0435	0.0472	0.0538
80	0.180	0.0044	0.0069	0.0129	0.0174	0.0237	0.0350	0.0426	0.0448	0.0521
100	0.150	0.0049	0.0060	0.0129	0.0167	0.0259	0.0331	0.0366	0.0428	0.0520
120	0.125	0.0032	0.0052	0.0078	0.0085	0.0175	0.0191	0.0210	0.0371	0.0456
140	0.100	0.0037	0.0039	0.0079	0.0080	0.0080	0.0091	0.0170	0.0237	0.0364
160	0.090	0.0022	0.0028	0.0043	0.0059	0.0031	0.0070	0.0102	0.0110	0.0139
170	0.090	0.0018	0.0026	0.0043	0.0052	0.0066	0.0097	0.0114	0.0138	0.0149
200	0.075	0.0015	0.0014	0.0027	0.0031	0.0062	0.0052	0.0058	0.0077	0.0091
230	0.063	0.0017	0.0015	0.0025	0.0035	0.0036	0.0036	0.0045	0.0114	0.0142
270	0.053	0.0012	0.0018	0.0030	0.0040	0.0034	0.0055	0.0050	0.0102	0.0110
325	0.045	0.0012	0.0012	0.0021	0.0022	0.0006	0.0039	0.0060	0.0071	0.0063
400	0.038	0.0006	0.0005	0.0005	0.0005	0.0013	0.0043	0.0080	0.0097	0.0150
-400										

----- * COMPUTED DATA *												
TOTAL SCREENED WEIGHT, (GM.)	2.6624	2.6298	2.6138	2.5845	2.5366	2.5043	2.5116	2.5262	2.5379	2.5374		
CRUSHING & SCREEN LOSS, (WT%) ...	-0.47	1.07	1.46	2.20	4.19	5.21	5.18	4.82	4.28	4.45		
UNIT WORK, (JOULES/GRAM.)	0.2754	0.5450	0.8560	1.1747	1.5226	1.6764	2.1030	2.1796	2.3267	1.8975		
UNIT WORK, (KWH/TONNE)	0.0715	0.1653	0.2461	0.3263	0.4233	0.4657	0.5482	0.6055	0.6464	0.5271		
PELIAN, (LCU, SIZE UNITS)	0.0443	0.1828	0.3055	0.6407	1.0622	1.1016	1.3734	1.4508	1.6078	1.3178		
PLAN, (LCU, SIZE UNITS)	0.2381	0.4613	0.6546	0.8611	1.2242	1.2988	1.4581	1.5767	1.7175	1.4448		
STANDARD DEVIATION, (M)	0.6308	0.7637	0.8588	0.9278	0.9612	1.0435	1.1107	1.1514	1.1501	1.1047		
SKINNESS, (M)	18.6612	7.4179	4.6224	3.3734	1.6633	1.3740	0.9790	0.8522	0.5968	1.0052		
KURTOSIS, (M)	26.9509	12.8678	8.9518	7.4466	4.4179	4.8867	4.3728	4.1506	3.7236	4.2938		

MATERIAL : MANG-QUARTZ
 APPLIED POTENTIAL : 15.0 KV

----- EXPERIMENTAL DATA -----

SAMPLE ALPHEA	242	243	244	245	246	247	248	249	250	251
WEIGHT BEFORE CRUSHING (GM.)	2.0543	2.0455	2.0450	2.0532	2.0508	2.0443	2.0475	2.0429	2.0497	2.0516
WEIGHT AFTER CRUSHING (GM.)	6.51	13.36	14.60	21.64	30.80	41.00	42.10	53.20	54.60	29.24

----- SCREEN ANALYSIS -----

PLSP NUMBER	ALPHEA APERTURE (MM)	SAMPLE WEIGHTS (GM.)
10	2.003	1.0400
12	1.750	0.9431
14	1.400	0.2420
16	1.180	0.1285
18	1.002	0.0824
20	0.850	0.0514
22	0.710	0.0344
24	0.600	0.0270
26	0.500	0.0233
28	0.425	0.0164
30	0.355	0.0062
32	0.300	0.0121
34	0.255	0.0055
36	0.214	0.0041
38	0.180	0.0040
40	0.150	0.0039
42	0.125	0.0020
44	0.100	0.0018
46	0.075	0.0016
48	0.050	0.0014
50	0.035	0.0012
52	0.025	0.0009
54	0.018	0.0007
56	0.014	0.0005
58	0.010	0.0003
60	0.007	0.0002
62	0.005	0.0001
64	0.003	0.0001
66	0.002	0.0001
68	0.001	0.0001
70	0.001	0.0001
72	0.001	0.0001
74	0.001	0.0001
76	0.001	0.0001
78	0.001	0.0001
80	0.001	0.0001
82	0.001	0.0001
84	0.001	0.0001
86	0.001	0.0001
88	0.001	0.0001
90	0.001	0.0001
92	0.001	0.0001
94	0.001	0.0001
96	0.001	0.0001
98	0.001	0.0001
100	0.001	0.0001

----- COMPUTED DATA -----

TOTAL SCREENED WEIGHT (GM.)	2.0493	2.0117	2.0501	2.0422	2.0390	2.0385	2.0348	2.0318	2.0290	2.0260
CRUSHING & SCREEN LOSS (GMS)	0.13	1.03	2.11	2.50	2.93	4.00	3.12	3.45	3.60	2.10
UNIT AREA (SQUARE INCHES)	0.2771	0.5097	0.2370	0.5215	1.0759	1.7860	1.7567	2.2743	2.3252	1.2459
UNIT AREA (SQUARE INCHES)	0.0770	0.1583	0.2325	0.2500	0.4111	0.4702	0.4691	0.6318	0.6468	0.3401
PERCENT (LOG SIZE UNITS)	0.0702	0.2056	0.3435	0.5322	0.9423	1.3024	1.1196	1.4930	1.6600	0.7660
PERCENT (LOG SIZE UNITS)	0.0625	0.4710	0.7804	0.7422	1.1577	1.4435	1.3458	1.6405	1.8049	0.9908
STANDARD DEVIATION (M)	0.0116	0.7450	0.9159	0.5249	1.0706	1.1275	1.1104	1.1430	1.1406	1.0392
STANDARD DEVIATION (M)	15.3718	7.7859	3.5111	3.5275	1.5015	0.9499	1.2533	0.8426	0.6735	2.4219
STANDARD DEVIATION (M)	23.9076	13.6963	7.7775	7.8649	4.7427	4.2447	4.4450	3.9761	3.7629	5.9410

MATERIAL : MCNC-OLARIZ
APPLIED POTENTIAL : 30.0 KV

* EXPERIMENTAL DATA *										
SAMPLE NUMBER	335	336	337	338	339	340	341	342	343	344
WEIGHT BEFORE CRUSHING, (GM.)	4.0666	4.0452	4.0664	4.0645	4.0647	4.0515	4.0783	4.0608	4.0564	4.0593
WAK DONE, (INCH-POUNDS)	3.78	8.08	11.88	14.94	19.24	25.10	29.70	17.32	22.72	33.40

* SCREEN ANALYSES *										
MESH NUMBER	NOMINAL APERTURE (MM)	SAMPLE WEIGHTS, GM.								
10	2.000	1.8154	1.8351	1.3052	0.6673	1.1050	0.5923	0.7264	0.7754	0.7014
12	1.700	1.6656	1.1025	1.1159	1.2414	0.7919	0.7460	0.5372	0.6274	0.8549
14	1.400	0.2634	0.2838	0.3005	0.4346	0.3239	0.3938	0.4672	0.4265	0.3437
16	1.180	0.0558	0.2212	0.4252	0.4178	0.4057	0.3596	0.3458	0.5105	0.3857
18	1.000	0.0493	0.1882	0.2710	0.2523	0.2363	0.4967	0.4408	0.4609	0.4099
20	0.850	0.0527	0.0846	0.1274	0.2115	0.1829	0.2994	0.2678	0.1740	0.2530
25	0.710	0.0285	0.0526	0.1072	0.1150	0.1435	0.1644	0.2276	0.1555	0.1635
30	0.600	0.0336	0.0568	0.0586	0.1539	0.1586	0.1951	0.2285	0.1651	0.2032
35	0.500	0.0178	0.0359	0.0443	0.0785	0.1118	0.1395	0.1400	0.0990	0.1179
40	0.425	0.0124	0.0300	0.0419	0.0611	0.0831	0.1148	0.1216	0.0779	0.0753
45	0.353	0.0058	0.0230	0.0257	0.0454	0.0586	0.0719	0.0852	0.0512	0.0714
50	0.300	0.0057	0.0155	0.0313	0.0506	0.0616	0.0827	0.0806	0.0563	0.0778
60	0.250	0.0058	0.0140	0.0168	0.0265	0.0393	0.0511	0.0588	0.0321	0.0478
70	0.212	0.0050	0.0095	0.0148	0.0239	0.0317	0.0375	0.0456	0.0304	0.0372
80	0.180	0.0037	0.0096	0.0149	0.0225	0.0273	0.0377	0.0414	0.0239	0.0334
100	0.150	0.0041	0.0100	0.0172	0.0221	0.0317	0.0387	0.0441	0.0268	0.0360
120	0.125	0.0028	0.0067	0.0100	0.0157	0.0197	0.0247	0.0299	0.0183	0.0224
140	0.106	0.0029	0.0079	0.0114	0.0158	0.0193	0.0280	0.0230	0.0193	0.0250
170	0.090	0.0016	0.0045	0.0065	0.0106	0.0141	0.0164	0.0213	0.0116	0.0160
200	0.075	0.0018	0.0044	0.0061	0.0080	0.0105	0.0156	0.0197	0.0111	0.0126
230	0.063	0.0015	0.0035	0.0052	0.0082	0.0097	0.0126	0.0116	0.0078	0.0083
270	0.053	0.0019	0.0051	0.0079	0.0105	0.0127	0.0178	0.0252	0.0150	0.0152
325	0.045	0.0021	0.0056	0.0095	0.0117	0.0154	0.0201	0.0225	0.0131	0.0149
400	0.038	0.0021	0.0044	0.0060	0.0090	0.0108	0.0159	0.0205	0.0109	0.0138
400		0.0015	0.0052	0.0064	0.0120	0.0144	0.0181	0.0279	0.0105	0.0174

* COMPUTED DATA *										
TOTAL SCREENED WEIGHT, (GM.)	4.0563	4.0278	4.0343	4.0259	4.0135	3.9906	4.0102	4.0174	3.9757	3.9630
CRUSHING & SCREEN LOSS, (AT%)	0.18	0.52	0.67	0.95	1.26	1.50	1.67	1.07	1.89	2.37
UNIT WORK, (JULLES/GM.)	0.1050	0.2255	0.3301	0.4153	0.5348	0.7000	0.8228	0.4819	0.6328	0.9296
UNIT WORK, (KWH/TONNE)	0.0252	0.0626	0.0817	0.1154	0.1486	0.1945	0.2286	0.1339	0.1758	0.2583
MODIAN, (LOG. SIZE UNITS)	0.0315	0.0405	0.1401	0.3100	0.3348	0.6830	0.7417	0.4868	0.5582	0.8548
PLAN, (")	0.1740	0.3393	0.5102	0.7071	0.7886	1.0180	1.1062	0.8109	0.9333	1.2158
STANDARD DEVIATION, (")	0.3484	0.7880	0.8532	1.0012	1.1137	1.1848	1.2444	1.0623	1.1552	1.2715
SKEWNESS, (")	27.9523	12.2760	8.1178	5.7370	4.0342	3.1588	2.6470	4.7056	3.4076	2.3041
KURTOSIS, (")	36.9922	18.3884	13.6533	9.8565	7.4895	6.4179	5.7202	8.5534	6.7812	5.2263

MATERIAL : POLY-SPHALERITE
 APPLIED POTENTIAL : 15.0 KV

----- EXPERIMENTAL DATA -----

SAMPLE NUMBER	324	325	326	327	328	329	331	332	333	334
WEIGHT BEFORE CRUSHING, (GM.)	4.0340	4.0663	4.0436	4.0530	4.0557	4.0747	4.0566	4.0410	4.0654	4.0399
WEIR DUNE, (INCH-FOUNDS)	4.10	32.00	8.16	11.54	15.52	20.04	22.30	35.30	28.20	12.16

----- SCREEN ANALYSES -----

WESP NUMBER	APERTURE (MM)	SAMPLE WEIGHTS, GM.									
10	2.500	1.9251	0.3860	1.3529	1.1313	0.5923	1.0192	0.7251	0.3699	0.4012	1.0534
12	1.700	1.3955	0.6711	1.2434	1.1718	1.0746	0.6095	0.8230	0.7200	0.6582	1.1818
14	1.500	0.3014	0.3985	0.4214	0.5715	0.4431	0.4008	0.2920	0.3172	0.4621	0.4201
16	1.190	0.1339	0.3260	0.3248	0.2742	0.3267	0.3810	0.4152	0.2611	0.3787	0.2867
18	1.000	0.0080	0.4860	0.2270	0.2024	0.3523	0.4422	0.4747	0.4600	0.5176	0.2248
20	0.850	0.0041	0.2731	0.0501	0.1295	0.2369	0.2261	0.2412	0.3052	0.2450	0.1951
25	0.710	0.0246	0.2320	0.0627	0.0923	0.1233	0.1633	0.1625	0.2448	0.2208	0.1100
30	0.500	0.0217	0.2477	0.0610	0.0953	0.1276	0.1697	0.1818	0.2403	0.2408	0.0568
35	0.425	0.0173	0.1608	0.0326	0.0560	0.0831	0.1207	0.1206	0.1962	0.1395	0.0716
40	0.355	0.0155	0.1360	0.0337	0.0500	0.0756	0.0888	0.0536	0.1438	0.1294	0.0577
45	0.300	0.0072	0.1031	0.0171	0.0354	0.0448	0.0613	0.0562	0.1136	0.0907	0.0366
50	0.250	0.0103	0.1078	0.0215	0.0325	0.0536	0.0675	0.0525	0.1232	0.0515	0.0391
60	0.212	0.0064	0.0627	0.0140	0.0191	0.0293	0.0418	0.0374	0.0634	0.0555	0.0219
70	0.180	0.0021	0.0523	0.0111	0.0173	0.0274	0.0338	0.0300	0.0557	0.0468	0.0187
80	0.150	0.0047	0.0520	0.0110	0.0153	0.0238	0.0338	0.0310	0.0590	0.0426	0.0176
100	0.125	0.0035	0.0315	0.0065	0.0100	0.0151	0.0180	0.0201	0.0467	0.0272	0.0101
150	0.106	0.0033	0.0308	0.0059	0.0111	0.0151	0.0218	0.0206	0.0403	0.0323	0.0119
170	0.090	0.0022	0.0226	0.0049	0.0076	0.0110	0.0138	0.0124	0.0237	0.0199	0.0072
200	0.075	0.0008	0.0215	0.0039	0.0045	0.0100	0.0120	0.0128	0.0241	0.0192	0.0071
230	0.063	0.0018	0.0126	0.0028	0.0041	0.0063	0.0082	0.0095	0.0142	0.0106	0.0036
270	0.053	0.0006	0.0042	0.0008	0.0050	0.0134	0.0154	0.0167	0.0297	0.0222	0.0097
325	0.045	0.0032	0.0231	0.0054	0.0073	0.0111	0.0149	0.0149	0.0242	0.0203	0.0031
400	0.038	0.0018	0.0020	0.0005	0.0064	0.0099	0.0115	0.0104	0.0224	0.0166	0.0076
430	0.022	0.0022	0.0200	0.0041	0.0067	0.0094	0.0105	0.0123	0.0234	0.0213	0.0105

----- COMPUTED DATA -----

TOTAL SCREENED WEIGHT, (GM.)	4.0009	3.9645	4.0216	4.0231	4.0051	4.0157	3.9534	3.9814	3.9524	3.9916
CRUSHING & SCREEN LOSS, (WT%)	0.02	2.50	0.54	0.74	1.25	1.45	2.53	1.48	2.63	1.19
UNIT NUM., (JULES/GRAM.)	0.1148	0.8891	0.4280	0.3217	0.4324	0.5557	0.6211	0.4970	0.7817	0.3401
UNIT WORK, (KWH/TONNE)	0.0519	0.2470	0.0633	0.0894	0.1201	0.1544	0.1725	0.2742	0.2177	0.0945
MILLIAN, (LCS. SIZE UNITS)	0.0147	0.8455	0.1240	0.1878	0.2853	0.4865	0.5462	0.4253	0.7672	0.1994
PLATE, (JULES/GRAM.)	0.1470	1.2055	0.3926	0.5176	0.7184	0.8624	0.8696	1.2798	1.1274	0.5819
STANDARD DEVIATION, (")	0.5768	1.2630	0.7396	0.8538	1.0389	1.1211	1.0558	1.3031	1.2066	0.9412
SLEWNESS, (")	22.7879	2.3316	11.9522	8.4252	5.3379	3.9729	3.8441	1.9787	2.7230	6.9605
KLATCSES, (")	33.2904	5.2912	18.4510	13.4055	9.2862	7.1948	7.5004	4.8250	5.8421	11.6458

MATERIAL : POLY-SPHALERITE
APPLIED POTENTIAL : 30.0 KV

----- * EXPERIMENTAL DATA * -----

SAMPLE NUMBER	253	255	256	257	258	259	260	261	262
WEIGHT (LPGMC CRUSHING, (GM.) ...)	4.0064	4.0150	4.0659	3.9709	4.0143	4.0018	4.0353	4.0061	4.0028
WEAR DUNE, (INCH-FLUNDS)	28.50	3.61	8.40	11.38	15.68	18.32	21.30	5.70	10.14

----- * SCREEN ANALYSES * -----

MESH NUMBER	APERTURE (MM)	SAMPLE WEIGHTS, GM.
10	2.000	0.0896
12	1.750	0.1321
14	1.500	0.1327
16	1.250	0.2347
18	1.000	0.3450
20	0.850	0.3917
25	0.710	0.3806
30	0.600	0.4756
35	0.500	0.2997
40	0.425	0.2441
45	0.355	0.1827
50	0.300	0.1493
60	0.250	0.1272
70	0.212	0.1042
80	0.180	0.0765
100	0.150	0.0363
120	0.125	0.0265
140	0.100	0.0057
170	0.075	0.0037
200	0.055	0.0030
230	0.043	0.0018
270	0.035	0.0009
325	0.025	0.0001
400	0.018	0.0000
480	0.015	0.0000

----- * COMPUTED DATA * -----

SAMPLE NUMBER	253	255	256	257	258	259	260	261	262
0.0896	1.2622	0.6059	0.2122	0.2754	0.1382	0.1699	0.5284	0.6225	0.6225
0.1321	1.3211	0.7401	0.6149	0.5147	0.2811	0.4593	0.4521	0.4224	0.4224
0.1327	0.4420	0.1393	0.3862	0.2565	0.1940	0.1538	0.5062	0.3303	0.3303
0.2347	0.2495	0.4219	0.4524	0.3616	0.3550	0.2258	0.4300	0.4769	0.4769
0.3450	0.2278	0.5531	0.5363	0.5480	0.4460	0.5148	0.3554	0.5317	0.5317
0.3917	0.1055	0.2733	0.4038	0.2906	0.4291	0.4141	0.1570	0.2909	0.2909
0.3806	0.0652	0.1920	0.2156	0.3124	0.3545	0.3265	0.1149	0.2005	0.2005
0.4756	0.0733	0.2100	0.2641	0.2942	0.3984	0.4269	0.1162	0.2251	0.2251
0.2997	0.0345	0.1330	0.1365	0.1859	0.2368	0.2607	0.0739	0.1344	0.1344
0.2441	0.0310	0.0873	0.1116	0.1559	0.1898	0.2233	0.0570	0.1163	0.1163
0.1827	0.0241	0.0626	0.0810	0.1088	0.1336	0.1655	0.0455	0.0672	0.0672
0.1493	0.0273	0.0711	0.0970	0.1278	0.1536	0.1655	0.0455	0.0672	0.0672
0.1272	0.0165	0.0427	0.0637	0.0723	0.0969	0.1004	0.0274	0.0382	0.0382
0.1042	0.0121	0.0346	0.0475	0.0608	0.0747	0.0866	0.0211	0.0382	0.0382
0.0765	0.0131	0.0317	0.0424	0.0578	0.0726	0.0786	0.0157	0.0350	0.0350
0.0363	0.0126	0.0329	0.0454	0.0576	0.0724	0.0820	0.0120	0.0214	0.0214
0.0265	0.0065	0.0172	0.0254	0.0309	0.0400	0.0455	0.0120	0.0214	0.0214
0.0057	0.0083	0.0195	0.0273	0.0362	0.0470	0.0493	0.0131	0.0245	0.0245
0.0037	0.0054	0.0115	0.0164	0.0263	0.0263	0.0295	0.0083	0.0154	0.0154
0.0030	0.0047	0.0100	0.0124	0.0197	0.0249	0.0255	0.0047	0.0116	0.0116
0.0018	0.0033	0.0052	0.0072	0.0104	0.0155	0.0144	0.0050	0.0079	0.0079
0.0009	0.0069	0.0127	0.0149	0.0192	0.0251	0.0275	0.0053	0.0139	0.0139
0.0001	0.0060	0.0110	0.0137	0.0172	0.0224	0.0249	0.0023	0.0125	0.0125
0.0000	0.0033	0.0066	0.0105	0.0125	0.0153	0.0191	0.0053	0.0079	0.0079
0.0000	0.0036	0.0126	0.0117	0.0406	0.0153	0.0216	0.0058	0.0051	0.0051

----- * COMPUTED DATA * -----

UNIT	253	255	256	257	258	259	260	261	262
0.0896	1.2622	0.6059	0.2122	0.2754	0.1382	0.1699	0.5284	0.6225	0.6225
0.1321	1.3211	0.7401	0.6149	0.5147	0.2811	0.4593	0.4521	0.4224	0.4224
0.1327	0.4420	0.1393	0.3862	0.2565	0.1940	0.1538	0.5062	0.3303	0.3303
0.2347	0.2495	0.4219	0.4524	0.3616	0.3550	0.2258	0.4300	0.4769	0.4769
0.3450	0.2278	0.5531	0.5363	0.5480	0.4460	0.5148	0.3554	0.5317	0.5317
0.3917	0.1055	0.2733	0.4038	0.2906	0.4291	0.4141	0.1570	0.2909	0.2909
0.3806	0.0652	0.1920	0.2156	0.3124	0.3545	0.3265	0.1149	0.2005	0.2005
0.4756	0.0733	0.2100	0.2641	0.2942	0.3984	0.4269	0.1162	0.2251	0.2251
0.2997	0.0345	0.1330	0.1365	0.1859	0.2368	0.2607	0.0739	0.1344	0.1344
0.2441	0.0310	0.0873	0.1116	0.1559	0.1898	0.2233	0.0570	0.1163	0.1163
0.1827	0.0241	0.0626	0.0810	0.1088	0.1336	0.1655	0.0455	0.0672	0.0672
0.1493	0.0273	0.0711	0.0970	0.1278	0.1536	0.1655	0.0455	0.0672	0.0672
0.1272	0.0165	0.0427	0.0637	0.0723	0.0969	0.1004	0.0274	0.0382	0.0382
0.1042	0.0121	0.0346	0.0475	0.0608	0.0747	0.0866	0.0211	0.0382	0.0382
0.0765	0.0131	0.0317	0.0424	0.0578	0.0726	0.0786	0.0157	0.0350	0.0350
0.0363	0.0126	0.0329	0.0454	0.0576	0.0724	0.0820	0.0120	0.0214	0.0214
0.0265	0.0065	0.0172	0.0254	0.0309	0.0400	0.0455	0.0120	0.0214	0.0214
0.0057	0.0083	0.0195	0.0273	0.0362	0.0470	0.0493	0.0131	0.0245	0.0245
0.0037	0.0054	0.0115	0.0164	0.0263	0.0263	0.0295	0.0083	0.0154	0.0154
0.0030	0.0047	0.0100	0.0124	0.0197	0.0249	0.0255	0.0047	0.0116	0.0116
0.0018	0.0033	0.0052	0.0072	0.0104	0.0155	0.0144	0.0050	0.0079	0.0079
0.0009	0.0069	0.0127	0.0149	0.0192	0.0251	0.0275	0.0053	0.0139	0.0139
0.0001	0.0060	0.0110	0.0137	0.0172	0.0224	0.0249	0.0023	0.0125	0.0125
0.0000	0.0033	0.0066	0.0105	0.0125	0.0153	0.0191	0.0053	0.0079	0.0079
0.0000	0.0036	0.0126	0.0117	0.0406	0.0153	0.0216	0.0058	0.0051	0.0051

----- * COMPUTED DATA * -----

UNIT	253	255	256	257	258	259	260	261	262
0.0896	1.2622	0.6059	0.2122	0.2754	0.1382	0.1699	0.5284	0.6225	0.6225
0.1321	1.3211	0.7401	0.6149	0.5147	0.2811	0.4593	0.4521	0.4224	0.4224
0.1327	0.4420	0.1393	0.3862	0.2565	0.1940	0.1538	0.5062	0.3303	0.3303
0.2347	0.2495	0.4219	0.4524	0.3616	0.3550	0.2258	0.4300	0.4769	0.4769
0.3450	0.2278	0.5531	0.5363	0.5480	0.4460	0.5148	0.3554	0.5317	0.5317
0.3917	0.1055	0.2733	0.4038	0.2906	0.4291	0.4141	0.1570	0.2909	0.2909
0.3806	0.0652	0.1920	0.2156	0.3124	0.3545	0.3265	0.1149	0.2005	0.2005
0.4756	0.0733	0.2100	0.2641	0.2942	0.3984	0.4269	0.1162	0.2251	0.2251
0.2997	0.0345	0.1330	0.1365	0.1859	0.2368	0.2607	0.0739	0.1344	0.1344
0.2441	0.0310	0.0873	0.1116	0.1559	0.1898	0.2233	0.0570	0.1163	0.1163
0.1827	0.0241	0.0626	0.0810	0.1088	0.1336	0.1655	0.0455	0.0672	0.0672
0.1493	0.0273	0.0711	0.0970	0.1278	0.1536	0.1655	0.0455	0.0672	0.0672
0.1272	0.0165	0.0427	0.0637	0.0723	0.0969	0.1004	0.0274	0.0382	0.0382
0.1042	0.0121	0.0346	0.0475	0.0608	0.0747	0.0866	0.0211	0.0382	0.0382
0.0765	0.0131	0.0317	0.0424	0.0578	0.0726	0.0786	0.0157	0.0350	0.0350
0.0363	0.0126	0.0329	0.0454	0.0576	0.0724	0.0820	0.0120	0.0214	0.0214
0.0265	0.0065	0.0172	0.0254	0.0309	0.0400	0.0455	0.0120	0.0214	0.0214
0.0057	0.0083	0.0195	0.0273	0.0362	0.0470	0.0493	0.0131	0.0245	0.0245
0.0037	0.0054	0.0115	0.0164	0.0263	0.0263	0.0295	0.0083	0.0154	0.0154
0.0030	0.0047	0.0100	0.0124	0.0197	0.0249	0.0255	0.0047	0.0116	0.0116
0.0018	0.0033	0.0052	0.0072	0.0104	0.0155	0.0144	0.0050	0.0079	0.0079
0.0009	0.0069	0.0127	0.0149	0.0192	0.0251	0.0275	0.0053	0.0139	0.0139
0.0001	0.0060	0.0110	0.0137	0.0172	0.0224	0.0249	0.0023	0.0125	0.0125
0.0000	0.0033	0.0066	0.0105	0.0125	0.0153	0.0191	0.0053	0.0079	0.0079
0.0000	0.0036	0.0126	0.0117	0.0406	0.0153	0.0216	0.0058	0.0051	0.0051

MATERIAL : MONO-SFHALERITE APPLIED POTENTIAL : 2000 KV

EXPERIMENTAL DATA												
SAMPLE NUMBER	273	274	275	276	277	278	279	280	281	282		
WEIGHT BEFORE CRUSHING, (GM.)	0.0203	0.0120	0.0106	0.0270	0.004	0.0113	0.0166	0.0262	0.0220	0.0062		
SCREEN SIZE, (INCH-FOUNDS)	J.V2	7.27	11.50	16.36	20.52	25.99	29.10	29.60	10.47	14.56		
SCREEN ANALYSIS												
MESH NUMBER	SAMPLE WEIGHTS, GM.											
10	1.1675	0.6802	0.4163	0.1679	0.2691	1.2008	0.0882	0.1498	0.8431	0.3324		
12	1.3617	0.6023	0.6762	0.3781	0.2360	1.5918	0.1894	0.1279	0.6209	0.3691		
14	0.4741	0.8379	0.3416	0.2944	0.2244	0.8080	0.1363	0.1147	0.3829	0.2707		
16	0.2682	0.6786	0.8827	0.4919	0.2657	0.2154	0.2801	0.2268	0.4917	0.4157		
18	0.1684	0.4160	0.6671	0.3242	0.4970	0.1878	0.3008	0.4616	0.4117	0.3257		
20	0.1337	0.2708	0.3740	0.4462	0.4197	0.1034	0.4473	0.2467	0.7118	0.2012		
25	0.0989	0.1620	0.2228	0.3238	0.3128	0.0727	0.3602	0.2654	0.3060	0.2720		
30	0.0677	0.1449	0.2113	0.3171	0.4038	0.0716	0.3894	0.4160	0.1465	0.3241		
35	0.0480	0.1233	0.1411	0.1241	0.2470	0.0344	0.2743	0.2423	0.1248	0.1077		
40	0.0375	0.0878	0.1276	0.1748	0.1963	0.0324	0.2431	0.1550	0.1019	0.1022		
45	0.0278	0.0622	0.0820	0.1145	0.1400	0.0227	0.1700	0.1034	0.0551	0.1024		
50	0.0241	0.0544	0.0638	0.1438	0.1638	0.0222	0.2543	0.1624	0.0564	0.1172		
60	0.0151	0.0362	0.0592	0.0861	0.1301	0.0161	0.1276	0.1139	0.0517	0.0738		
70	0.0111	0.0281	0.0450	0.0670	0.0818	0.0111	0.1013	0.0618	0.0254	0.0594		
80	0.0122	0.0234	0.0366	0.0424	0.0740	0.0094	0.0801	0.0973	0.0354	0.0548		
100	0.0141	0.0243	0.0448	0.0261	0.0608	0.0109	0.0558	0.1136	0.0372	0.0544		
120	0.0082	0.0254	0.0237	0.0366	0.0442	0.0077	0.0475	0.0277	0.0217	0.0122		
140	0.0076	0.0188	0.0179	0.0419	0.0539	0.0098	0.0417	0.0647	0.0240	0.0354		
170	0.0049	0.0080	0.0141	0.0241	0.0314	0.0034	0.0291	0.0322	0.0157	0.0206		
200	0.0040	0.0048	0.0183	0.0268	0.0353	0.0033	0.0245	0.0344	0.0118	0.0171		
250	0.0038	0.0047	0.0088	0.0111	0.0142	0.0029	0.0131	0.0171	0.0095	0.0112		
273	0.0031	0.0077	0.0139	0.0244	0.0253	0.0037	0.0236	0.0340	0.0119	0.0149		
325	0.0024	0.0067	0.0120	0.0186	0.0236	0.0033	0.0212	0.0267	0.0129	0.0133		
400	0.0017	0.0014	0.0071	0.0051	0.0106	0.0018	0.0133	0.0225	0.0052	0.0110		
450	0.0014	0.0018	0.0069	0.0057	0.0102	0.0016	0.0116	0.0222	0.0050	0.0100		
COMPUTED DATA												
TOTAL SCREENED WEIGHT, (GM.)	4.0041	3.9767	3.9619	3.9635	3.9575	4.0074	3.9502	3.9335	4.0075	3.9601		
CRUSHING & SCREEN LOSS, (GTS)	0.40	0.88	1.21	1.82	1.17	0.10	2.80	2.20	0.36	1.11		
LAST BURE, (JOLLS/GHAM.)	0.1102	0.2047	0.3392	0.4540	0.5760	0.0842	0.7601	0.8252	0.2527	0.4107		
UNIT BURE, (KWH/TONNE)	0.0306	0.0504	0.0531	0.1275	0.1608	0.0234	0.1901	0.2293	0.0913	0.1141		
MEAN, (LOG. SIZE UNITS)	0.1581	0.4891	0.8010	1.1356	1.3114	0.1383	1.4522	1.5129	0.5855	0.6942		
STAN. DEVIATION, (")	0.4376	0.7790	1.3826	1.4100	1.5826	0.3797	1.7222	1.8317	0.9279	1.2053		
STANDARD COEFFICIENT, (")	0.7694	0.9326	1.0744	1.1388	1.2401	0.7148	1.1507	1.2312	0.6114	0.8146		
SKETCHES	7.5310	3.5182	2.4362	1.4704	1.2105	5.9898	1.0253	1.0017	2.0703	1.8964		
PLATECIS	12.0824	7.2589	5.8401	4.5017	4.1769	15.9250	4.0018	3.6618	6.3069	5.0786		

MATERIAL : MANG-SPHALLITE APPLIED POTENTIAL : 35.0 KV

----- * EXPERIMENTAL DATA * -----

SAMPLE NUMBER	196	197	198	199	200	201	202	203	204
WEIGHT BEFORE CRUSHING (G.M.)	3.0260	3.0016	3.0313	3.0307	3.0138	3.0269	3.0157	3.0111	3.0296
BUK DUNE (INCH-FOUNDS)	2.77	3.14	6.22	8.56	10.74	4.28	7.53	10.16	1.43

----- * SCREEN ANALYSES * -----

MESH NUMBER	ACMINAL APERTURE (MM)	SAMPLE WEIGHTS (G.M.)									
10	2.00	C.0123	0.4447	0.1670	0.0143	0.0154	0.5594	0.0219	C.C	1.2569	
12	1.70	C.0434	0.4333	0.7253	0.0400	0.0104	0.2967	0.0427	C.C	1.0425	
14	1.40	C.0469	0.4334	0.1142	0.0464	0.0476	0.2108	0.0423	C.0077	0.1614	
16	1.18	C.0130	0.2222	0.2114	0.0356	0.0512	0.2179	0.0723	C.0160	0.1077	
18	1.00	C.1401	0.1446	0.2477	0.1268	0.0905	0.1414	0.1544	0.0769	0.0651	
20	0.85	C.0032	0.0855	0.2196	0.1400	0.1082	0.1193	0.1590	0.1399	0.0248	
25	0.71	C.0537	0.0600	0.1400	0.1451	0.1412	0.0910	0.1543	0.1228	0.0148	
30	0.60	C.0761	0.0762	0.1723	0.2181	0.1443	0.1090	0.1095	0.2085	0.0289	
35	0.50	C.0560	0.0667	0.1171	0.1628	0.1800	0.0751	0.1617	0.1615	0.0154	
40	0.42	C.0358	0.0557	0.1501	0.1462	0.1939	0.0900	0.1832	0.1449	0.0224	
45	0.35	C.0555	0.0527	0.1232	0.1640	0.1834	0.0841	0.1584	0.1721	0.0149	
50	0.30	C.0528	0.0531	0.1590	0.2625	0.2779	0.1432	0.2639	0.2749	0.0352	
60	0.25	C.0659	0.0743	0.1578	0.2008	0.2153	0.1134	0.1594	0.2266	0.0299	
70	0.21	C.0729	0.0748	0.1531	0.1977	0.2050	0.1074	0.1815	0.2252	0.0316	
80	0.18	C.0721	0.0763	0.1526	0.1958	0.1977	0.1103	0.1642	0.2251	0.0331	
100	0.15	C.0965	0.1014	0.1527	0.2323	0.2544	0.1370	0.2403	0.2831	0.0427	
120	0.12	C.0545	0.0510	0.1093	0.1349	0.1304	0.0734	0.1240	0.1501	0.0222	
140	0.10	C.0608	0.0629	0.1172	0.1481	0.1559	0.0834	0.1401	0.1734	0.0267	
170	0.07	C.0314	0.0319	0.0266	0.0753	0.0801	0.0466	0.0792	0.0904	0.0133	
200	0.075	C.0284	0.0259	0.0218	0.0647	0.0655	0.0370	0.0606	0.0743	0.0112	
230	0.063	C.0138	0.0126	0.0218	0.0323	0.0314	0.0153	0.0258	0.0340	0.0059	
270	0.053	C.0205	0.0166	0.0404	0.0454	0.0520	0.0279	0.0461	0.0555	0.0066	
325	0.043	C.0135	0.0114	0.0213	0.0328	0.0360	0.0146	0.0277	0.0374	0.0057	
400	0.038	C.0070	0.0068	0.0122	0.0183	0.0184	0.0096	0.0163	0.0263	0.0015	
480	0.032	C.0052	0.0006	0.0087	0.0116	0.0139	0.0059	0.0110	0.0122	0.0019	

----- * COMPUTED DATA * -----

TOTAL SCREENED WEIGHT (G.M.)	3.0242	3.0119	2.9524	2.9658	2.9539	3.0017	2.9797	2.9607	3.0302
CRUSHING & SCREEN LOSS (G.M.)	0.15	0.48	1.28	2.01	1.99	0.83	1.19	1.67	0.02
UNIT AREA (JCOULES/GRAM)	C.1023	0.1166	0.2256	0.2151	0.4026	0.1548	0.2821	0.3812	0.0533
UNIT AREA (KCAL/CM ²)	0.0287	0.0384	0.0654	0.0887	0.1119	0.0444	0.0784	0.1059	0.0148
MEDIAN (LOG. SIZE UNITS)	C.2666	0.4226	2.1231	2.6765	2.7342	1.0263	2.6233	2.8987	0.0619
MEAN (")	1.1176	1.1520	2.2231	2.6884	2.7611	1.6064	2.6085	2.9147	0.4906
STANDARD DEVIATION (")	1.4867	1.4452	1.4057	1.4969	1.5423	1.2523	1.2844	1.2106	1.1016
SKEWNESS (")	1.3542	1.4252	0.0076	0.0148	0.0124	0.3931	0.0155	0.0303	0.1312
KURTOSIS (")	2.1212	3.2385	2.1763	2.5300	2.6244	2.2262	2.4711	2.5537	2.2567

MATERIAL : INCM CKE
APPLIED POTENTIAL : 25KV

EXPERIMENTAL DATA

SAMPLE ALUMINUM 205 206 207 208 209 210 211 212
 HEIGHT DIFFERENCE (CM.) 3.0187 3.0320 3.0222 3.0305 3.0141 3.0305 3.0317 3.0205
 AREA UNDER (MINI-FLOW) 1.02 3.22 4.73 6.47 7.92 8.67 10.16 2.08

SCREEN ANALYSES

SAMPLE WEIGHTS, GM.

WEIGHT APERTURE (MM)

10	2.000	1.0604	0.4274	0.3845	0.1750	0.0198	0.0325	0.0272	1.0550
12	1.700	0.7301	0.2674	0.4500	0.2612	0.1284	0.0401	0.0465	1.0204
14	1.400	0.7102	0.2529	0.2755	0.1737	0.0939	0.0400	0.0481	0.2205
16	1.100	0.0009	0.2308	0.2152	0.1542	0.1063	0.0647	0.0353	0.0721
18	1.000	0.0011	0.1432	0.2204	0.2634	0.1405	0.1305	0.0443	0.0030
20	0.800	0.0207	0.0000	0.1099	0.1507	0.1910	0.1328	0.0407	0.0476
22	0.710	0.0154	0.0652	0.3607	0.1229	0.1901	0.1574	0.1614	0.0205
24	0.600	0.0255	0.0009	0.0370	0.1406	0.1742	0.2001	0.2045	0.0371
26	0.500	0.0133	0.0301	0.0602	0.1108	0.1342	0.1507	0.1773	0.0219
28	0.420	0.0200	0.0000	0.0611	0.1271	0.1532	0.1909	0.1896	0.0282
30	0.350	0.0117	0.0000	0.0731	0.1105	0.1307	0.1602	0.1594	0.0250
32	0.300	0.0279	0.0740	0.1247	0.1777	0.2177	0.2570	0.2220	0.0412
34	0.250	0.0200	0.0601	0.1016	0.1363	0.1732	0.1948	0.2132	0.0307
36	0.210	0.0244	0.0601	0.1027	0.1425	0.1738	0.1927	0.2096	0.0315
38	0.180	0.0223	0.0600	0.1000	0.1548	0.1774	0.1936	0.2125	0.0305
40	0.150	0.0302	0.0852	0.1235	0.1500	0.2217	0.2400	0.2400	0.0405
42	0.120	0.0104	0.0428	0.0700	0.0870	0.1193	0.1278	0.1367	0.0214
44	0.100	0.0102	0.0501	0.0747	0.1021	0.1374	0.1593	0.1571	0.0206
46	0.070	0.0007	0.0214	0.0429	0.0517	0.0721	0.0700	0.0604	0.0128
48	0.075	0.0076	0.0214	0.0303	0.0437	0.0622	0.0604	0.0605	0.0110
50	0.060	0.0037	0.0110	0.0300	0.0255	0.0249	0.0262	0.0313	0.0059
52	0.053	0.0056	0.0159	0.0236	0.0316	0.0402	0.0455	0.0512	0.0001
54	0.045	0.0036	0.0104	0.0133	0.0201	0.0314	0.0205	0.0346	0.0000
56	0.030	0.0004	0.0000	0.0070	0.0112	0.0174	0.0150	0.0100	0.0027
58	0.013	0.0013	0.0035	0.0047	0.0071	0.0135	0.0107	0.0120	0.0017

COMPUTED DATA

TOTAL SCREENING HEIGHT (CM.) 2.0003 2.0059 2.0151 2.0000 2.0075 2.0000 2.0023 2.0039
 CRUSHING & SCREEN LOSS (GMS) 1.01 1.52 2.22 2.12 1.00 1.77 2.29 1.07
 UNIT WEIGHT (GMS/CM.) 0.0554 0.1200 0.1768 0.2409 0.2591 0.3232 0.3700 0.0777
 UNIT LOSS (GMS/CM.) 0.0154 0.0333 0.0401 0.0809 0.0831 0.0898 0.1052 0.0216
 P-VALUE (LOG. SIZE UNIT) -0.0228 0.0203 0.0703 0.1747 0.2154 0.2619 0.2752 0.0950
 MEAN 0.3717 1.0202 1.4540 1.9714 2.4570 2.9444 3.4771 0.5509
 STANDARD DEVIATION 1.0046 1.4008 1.5003 1.4765 1.3710 1.2739 1.2430 1.1204
 STANDARD DEVIATION () 0.0315 0.0715 0.0715 0.1323 0.1323 0.0026 0.0026 0.0026
 MULTIPLE 11.0262 3.5905 2.3482 2.1244 2.2349 2.0807 2.0767 7.5002

MATERIAL : INCH CSE

APPLIED POTENTIAL : 15.0 KV

* EXPERIMENTAL DATA *									
SAMPLE NUMBER	377	378	379	380	381	382	383	384	385
WEIGHT BEFORE CRUSHING (GM.)	5.2689	5.2735	5.2661	5.2508	5.2555	5.2616	5.2631	5.2755	5.2606
WEIGHT AFTER CRUSHING (GM.)	3.45	7.42	11.52	18.96	20.72	29.60	34.90	42.40	23.52

* SCREEN ANALYSES *									
WASH NUMBER	NOMINAL APERTURE (MM)	SAMPLE WEIGHTS, GM.							
10	2.000	2.9716	2.0447	1.3179	1.1304	1.0630	0.6187	0.5022	0.3312
12	1.700	1.8181	2.1376	2.0488	1.6604	1.4960	1.1375	0.9546	0.8103
14	1.400	0.2947	0.5486	0.7849	0.8600	0.8697	0.7493	0.8600	0.5500
16	1.180	0.0052	0.1407	0.3242	0.5798	0.6701	0.8151	0.6778	0.2275
18	1.000	0.0235	0.0665	0.2295	0.2860	0.3326	0.6123	0.6483	0.9262
20	0.850	0.0132	0.0323	0.0645	0.1400	0.1288	0.2300	0.3033	0.3435
25	0.710	0.0051	0.0229	0.0569	0.0600	0.0899	0.1536	0.1679	0.2061
30	0.600	0.0054	0.0243	0.0520	0.0545	0.0579	0.1254	0.1247	0.1571
35	0.500	0.0045	0.0093	0.0209	0.0315	0.0326	0.0502	0.0610	0.0379
40	0.425	0.0033	0.0113	0.0182	0.0252	0.0270	0.0458	0.0551	0.0750
45	0.355	0.0045	0.0076	0.0162	0.0151	0.0238	0.0306	0.0262	0.0603
50	0.300	0.0046	0.0125	0.0164	0.0254	0.0304	0.0420	0.0527	0.0671
60	0.250	0.00370	0.0050	0.0140	0.0158	0.0229	0.0313	0.0362	0.0523
70	0.212	0.0034	0.0100	0.0141	0.0140	0.0234	0.0346	0.0409	0.0567
80	0.180	0.0040	0.0118	0.0188	0.0224	0.0279	0.0433	0.0526	0.0659
100	0.150	0.0071	0.0174	0.0202	0.0368	0.0440	0.0662	0.0731	0.1052
120	0.125	0.0062	0.0154	0.0227	0.0362	0.0398	0.0630	0.0731	0.0821
140	0.106	0.0075	0.0222	0.0245	0.0376	0.0438	0.0742	0.0985	0.1047
170	0.090	0.0059	0.0167	0.0200	0.0275	0.0253	0.0449	0.0617	0.0754
200	0.075	0.0060	0.0145	0.0235	0.0252	0.0322	0.0468	0.0625	0.0773
230	0.063	0.0049	0.0058	0.0108	0.0151	0.0207	0.0297	0.0386	0.0396
270	0.053	0.0068	0.0165	0.0287	0.0364	0.0378	0.0586	0.0700	0.0900
325	0.045	0.0081	0.0149	0.0241	0.0281	0.0319	0.0433	0.0598	0.0629
400	0.038	0.0041	0.0167	0.0147	0.0233	0.0224	0.0246	0.0377	0.0418
400		0.0051	0.0149	0.0191	0.0121	0.0156	0.0303	0.0356	0.0340

* COMPUTED DATA *									
TOTAL SCREENED WEIGHT (GM.)	5.2865	5.2869	5.2517	5.2166	5.2195	5.2033	5.1535	5.1933	5.1971
CRUSHING & SCREEN LOSS (WTS)	-0.33	-0.25	0.27	0.65	0.69	1.11	1.32	1.56	1.21
UNIT WORK (JULGES/GRAM)	0.0740	0.1590	0.2557	0.4020	0.4454	0.6356	0.7492	0.9081	0.5052
UNIT WORK (KWH/TONNE)	0.0206	0.0442	0.0710	0.1133	0.1237	0.1766	0.2081	0.2523	0.1403
MEDIAN (LOG. SIZE UNITS)	-0.0276	0.0700	0.1546	0.2225	0.2646	0.5295	0.6033	0.8248	0.3712
MEAN (")	0.1131	0.2965	0.4869	0.6252	0.6857	0.9696	1.1462	1.3544	0.7918
STANDARD DEVIATION (")	0.5783	0.8723	1.0346	1.1607	1.1858	1.3195	1.4549	1.5011	1.2403
SKEWNESS (")	46.4281	18.9576	11.0531	8.2556	7.1805	4.1431	3.0226	2.1819	5.1578
KURTOSIS (")	55.3273	22.8372	14.1548	11.0013	6.8239	6.3834	4.9560	4.1204	7.4336

MATERIAL : POLY-MENATITE
APPLIED POTENTIAL : ZERO KV

EXPERIMENTAL DATA									
SAMPLE NAME	369	370	371	372	373	374	375	376	
WEIGHT BEFORE CRUSHING, (GM.)	5.2020	5.2756	5.2879	5.2668	5.2561	5.2575	5.2629	5.2701	
WORK DONE, (INCH-POUNDS)	4.89	9.78	15.76	20.82	23.56	32.40	27.90	39.50	
SCREEN ANALYSES									
MESH NUMBER	APERTURE (MM)	SAMPLE WEIGHTS, GM.							
10	2.000	2.5921	1.8953	1.6580	1.2522	0.6339	0.6917	C.7C02	0.3926
12	1.750	2.0818	1.3331	1.3176	1.5047	1.2733	0.8205	1.3250	1.0042
14	1.500	C.3155	0.4921	0.6553	0.8126	0.6465	0.7623	C.5411	0.6523
16	1.180	C.0764	0.3029	0.4840	C.5217	C.7273	C.9122	C.7177	0.7055
18	1.000	0.0427	0.1126	0.2752	0.3671	C.5106	C.5379	C.8432	C.6561
20	0.850	0.0115	0.0350	0.0773	0.1010	0.2057	0.2749	0.2397	0.3449
25	0.710	0.0034	0.0079	0.0506	0.0873	C.1129	0.1555	C.1410	0.1955
30	0.600	0.0081	0.0185	0.0376	0.0644	0.0922	0.1103	C.1360	0.1360
35	0.500	0.0042	0.0139	0.0203	0.0310	C.0401	0.0679	0.0493	C.0795
40	0.425	0.0036	0.0144	0.0196	0.0315	0.0347	0.0500	0.0473	0.0606
45	0.355	0.0040	0.0050	0.0167	0.0225	0.0291	0.0376	0.0238	0.0471
50	0.300	0.0034	0.0121	0.0204	0.0274	C.0356	C.0513	0.0296	0.0571
60	0.250	0.0037	0.0077	0.0162	0.0211	0.0273	C.0383	0.0261	0.0423
70	0.212	0.0043	0.0115	0.0188	0.0241	0.0255	0.0417	0.0342	0.0458
80	0.180	0.0062	0.0124	0.0222	0.0272	C.0375	C.0506	C.0471	0.0561
100	0.150	0.0054	0.0212	0.0369	0.0446	0.0602	0.0759	C.0709	0.0528
120	0.125	0.0076	0.0160	0.0291	0.0343	0.0515	0.0683	C.0602	0.0733
140	0.106	C.0100	0.0205	0.0414	0.0515	0.0724	C.0895	C.0791	0.1043
170	0.090	0.0065	C.0137	0.0263	0.0334	C.0487	0.0598	0.0484	0.0637
200	0.075	C.0072	0.0144	0.0285	0.0353	C.0500	0.0567	0.0459	0.0663
250	0.063	0.0053	0.0093	0.0164	0.0219	C.0318	C.0343	0.0325	0.0354
270	0.053	0.0074	0.0154	0.0312	0.0431	0.0556	0.0655	C.0508	0.0722
325	0.045	0.0068	C.0151	0.0262	0.0335	C.0434	0.0502	0.0291	0.0567
400	0.038	0.0036	0.0092	0.0165	0.0205	C.0289	0.0345	C.0280	0.0359
450	0.030	0.0047	C.0047	0.0211	0.0256	0.0269	0.0228	C.0220	0.0316
COMPUTED DATA									
TOTAL SCREENED WEIGHT, (GP.)	5.2512	5.2555	5.2228	5.2410	5.2056	5.2002	5.1611	5.1608	
CRUSHING & SCREEN LOSS, (WT.)	0.19	0.37	0.65	0.49	0.96	1.09	1.93	2.07	
UNIT WORK, (JOULES/GRAM.)	C.1050	C.2095	0.3287	C.4475	C.5064	0.6903	0.8590	0.8426	
UNIT WORK, (KWH/TONNE)	0.0292	0.0582	0.0841	0.1244	0.1407	0.1934	0.1664	C.2341	
POULIN, (LOG. SIZE UNITS)	0.0033	0.0055	0.1505	0.2272	C.4030	0.5892	C.5050	0.6883	
WEAR, (MM)	0.1436	0.3163	0.5326	0.6740	0.8945	1.0943	0.9599	1.2075	
STANDARD DEVIATION, (MM)	0.6042	0.8543	1.1119	1.2086	1.3536	1.4207	1.3479	1.4529	
SPREADS, (MM)	35.3487	18.0761	9.1037	6.8175	4.5007	3.3067	4.0219	2.7071	
ELUSTIS, (MM)	47.0665	22.3071	11.6829	5.3136	6.6753	5.3689	6.3407	4.7101	

MATERIAL: POLY-HEMATITE

APPLIED POTENTIAL: 15.0 KV

* EXPERIMENTAL DATA *										
SAMPLE NUMBER	360	361	362	363	364	365	366	367	368	
WEIGHT BEFORE CRUSHING, (GM.)	5.2607	5.2576	5.2667	5.2639	5.2824	5.2767	5.2636	5.2565	5.2656	
WCHK DONE, (INCH-POUNDS)	39.70	45.30	31.60	35.60	26.32	22.16	16.60	10.42	5.05	

* SCREEN ANALYSES *										
WESH NUMBER	NOHINAL APERTURE (MM)	SAMPLE WEIGHTS, GM.								
10	2.000	0.4815	0.3158	0.6244	0.5383	0.6688	1.2112	1.2502	1.5051	2.4216
12	1.700	0.8043	0.7055	0.9855	1.0306	1.2571	1.2353	2.0772	1.9879	2.2587
14	1.400	0.6360	0.5969	0.6794	0.5281	0.5364	0.8271	0.5406	0.6783	0.3504
16	1.180	0.6668	0.5729	0.8112	0.7154	0.7204	0.5874	0.5237	0.1914	0.0456
18	1.000	0.7826	0.6687	0.7155	0.7929	0.6448	0.4732	0.2593	0.1355	0.0318
20	0.850	0.3350	0.3519	0.3344	0.2903	0.2406	0.1667	0.0893	0.0214	0.0113
25	0.710	0.1702	0.2214	0.1153	0.1642	0.1385	0.0708	0.0558	0.0266	0.0055
30	0.600	0.1563	0.1801	0.1366	0.1355	0.1056	0.0743	0.0408	0.0356	0.0112
35	0.500	0.0747	0.0884	0.0591	0.0606	0.0496	0.0330	0.0260	0.0119	0.0045
40	0.425	0.0611	0.0754	0.0500	0.0565	0.0480	0.0352	0.0206	0.0125	0.0071
45	0.355	0.0449	0.0507	0.0357	0.0446	0.0345	0.0200	0.0176	0.0092	0.0035
50	0.300	0.0564	0.0653	0.0438	0.0537	0.0408	0.0296	0.0216	0.0142	0.0061
60	0.250	0.0425	0.0513	0.0342	0.0357	0.0355	0.0200	0.0166	0.0097	0.0047
75	0.212	0.0470	0.0559	0.0380	0.0371	0.0342	0.0240	0.0167	0.0118	0.0064
80	0.180	0.0578	0.0608	0.0459	0.0461	0.0409	0.0288	0.0200	0.0152	0.0071
100	0.150	0.0907	0.1128	0.0743	0.0720	0.0703	0.0447	0.0327	0.0211	0.0103
120	0.125	0.0805	0.0901	0.0664	0.0610	0.0558	0.0360	0.0258	0.0179	0.0093
140	0.106	0.1089	0.1315	0.0890	0.0835	0.0799	0.0511	0.0373	0.0233	0.0112
170	0.090	0.0723	0.0863	0.0590	0.0550	0.0456	0.0300	0.0234	0.0148	0.0069
200	0.075	0.0789	0.0942	0.0639	0.0563	0.0466	0.0330	0.0252	0.0163	0.0073
230	0.063	0.0391	0.0446	0.0331	0.0327	0.0326	0.0199	0.0149	0.0098	0.0054
270	0.053	0.0654	0.0481	0.0698	0.0603	0.0504	0.0385	0.0206	0.0150	0.0092
325	0.045	0.0630	0.0763	0.0519	0.0528	0.0380	0.0312	0.0235	0.0160	0.0076
400	0.038	0.0446	0.0502	0.0382	0.0254	0.0262	0.0213	0.0156	0.0092	0.0040
-400		0.0465	0.0651	0.0332	0.0316	0.0159	0.0244	0.0170	0.0105	0.0041

* COMPUTED DATA *										
TOTAL SCREENED WEIGHT, (GM.)	5.1500	5.1214	5.1885	5.0860	5.1710	5.1657	5.2222	5.2342	5.2518	
CRUSHING & SCREEN LOSS, (WTX)	2.10	2.59	1.48	3.36	2.11	2.10	0.79	0.42	0.26	
UNIT WORK, (JULLES/GRAM.)	0.8528	0.9735	0.6643	0.7641	0.5630	0.4745	0.3563	0.2240	0.1084	
UNIT WORK, (KWH/TONNE)	0.2369	0.2704	0.1801	0.2123	0.1564	0.1318	0.0990	0.0622	0.0301	
MEDIAN, (LOG. SIZE UNITS)	0.7378	0.8555	0.6245	0.6550	0.5080	0.2912	0.1638	0.0855	0.0226	
MEAN, (")	1.2876	1.4609	1.1179	1.0556	0.8579	0.7123	0.5231	0.3333	0.1531	
STANDARD DEVIATION, (")	1.5230	1.5784	1.4364	1.3795	1.3389	1.1950	1.0664	0.8861	0.6221	
SKWNESS, (")	2.3864	1.7698	3.3050	3.3056	4.0357	6.6132	10.0136	16.5445	38.2469	
KURTOSIS, (")	4.2865	3.5784	5.3255	5.4719	6.2777	9.2721	13.0180	20.3798	45.0496	

MATERIAL : FCLY-HEMATITE

APPLIED POTENTIAL : 30.0 KV

----- MODAL ANALYSIS -----										
SAMPLE NUMBER	UNIT #CMK JULLES/GRAM		X = LOCATION OF PEAK ; Y = PEAK HEIGHT. (WTX / SCREEN INTERVAL).							
145	0.225	X	0.020	0.230	1.600	2.110	2.550	3.570	4.790	5.400
		Y	46.6	2.7	1.0	0.5	0.3	0.1	0.0	0.0
146	0.604	X	0.130	1.550	2.100	2.610	3.600			
		Y	29.4	2.6	1.3	3.9	0.5			
147	0.828	X	0.130	0.720	2.610	3.340	4.090	5.100		
		Y	19.8	15.4	1.5	0.6	0.2	0.1		
148	1.159	X	0.130	0.820	1.590	2.590	4.080	6.470		
		Y	15.2	15.3	7.9	2.4	0.6	0.0		
149	1.417	X	0.140	0.880	2.600	3.580	4.080	5.100		
		Y	8.5	15.5	3.3	1.3	1.0	0.4		
150	1.742	X	0.140	0.880	1.590	2.600	3.580	4.110	4.570	5.110
		Y	4.8	14.8	10.0	3.8	1.7	1.0	0.7	0.6
151	1.840	X	0.140	0.900	1.600	2.610	3.570	4.110	5.110	
		Y	5.6	12.6	11.7	4.7	2.1	1.2	0.6	
152	2.135	X	-0.040	0.920	1.620	2.600	3.590	4.110	5.140	
		Y	4.3	9.3	14.0	5.2	2.7	1.7	0.8	
153	2.471	X	-0.040	0.370	1.630	2.600	3.590	4.120	5.130	
		Y	3.6	5.2	13.8	6.1	2.7	1.7	1.0	
154	2.836	X	0.140	0.930	1.630	2.610	3.590	4.110	4.580	5.140
		Y	1.9	8.4	10.0	6.9	3.3	2.0	1.2	1.0

..... MATERIAL : QUARTZITE APPLIED POTENTIAL : 25KV

----- MEDAL ANALYSIS -----									
SAMPLE NUMBER	UNIT FLUX JULTS/GMM	X = LOCATION OF PEAK :		Y = PEAK HEIGHT. (WTS / SCREEN INTERVAL).					
146	0.742	X	-0.040	1.310	2.610	3.540	4.040	5.140	
		Y	47.4	1.3	0.4	0.2	0.1	0.1	
147	0.116	X	0.120	2.610	3.370	3.490	4.100	5.110	6.390
		Y	28.5	0.7	0.4	0.4	0.2	0.1	0.0
148	0.443	X	0.080	0.890	2.000	3.590	4.090	5.090	
		Y	21.9	12.7	1.3	0.7	0.4	0.1	
149	1.077	X	0.140	0.830	2.600	3.590	4.060	5.000	6.350
		Y	18.3	16.8	1.9	0.9	0.6	0.2	0.0
150	1.390	X	0.140	0.800	1.590	2.590	3.590	4.090	5.130
		Y	10.7	15.1	7.7	2.9	1.3	0.9	0.4
151	1.114	X	0.090	1.270	2.600	3.590	4.090	5.120	
		Y	13.6	10.8	3.6	1.7	1.1	0.4	
152	7.110	X	0.160	0.500	1.610	2.610	3.590	4.100	5.120
		Y	6.0	13.1	12.8	4.7	2.1	1.3	0.5
153	2.377	X	1.340	1.610	2.610	3.590	4.100	5.130	
		Y	11.1	13.6	5.1	2.2	1.4	0.6	
154	2.704	X	-0.050	1.010	1.620	2.590	3.590	4.100	5.150
		Y	0.6	9.1	14.6	6.2	2.9	1.8	0.8
155	3.140	X	1.630	2.070	2.600	3.590	4.110	5.130	
		Y	15.0	9.8	7.1	3.4	2.1	1.0	

MATERIAL : OLARTZITL APPLIED POTENTIAL : 7.5 KV



----- * MCDAL ANALYSIS * -----

SAMPLE NUMBER	UNIT WORK JOULES/GRAM		X = LOCATION OF PEAK ; Y = PEAK HEIGHT, (WTX / SCREEN INTERVAL).									
165	0.526	X	-0.040	0.810	1.640	3.390	3.830	4.560	5.360			
		Y	44.6	4.6	0.8	0.2	6.2	0.1	0.1			
166	0.555	X	0.060	1.360	1.550	2.610	3.590	4.570	5.090	6.360		
		Y	32.3	2.3	2.3	0.8	0.3	0.1	0.1	0.0		
167	0.799	X	0.110	2.550	3.550	4.600	5.210	6.450				
		Y	24.8	1.2	0.6	0.2	0.2	0.0				
175	1.145	X	0.150	0.830	1.600	2.600	3.590	4.060	4.600	5.140	6.300	
		Y	10.1	15.6	6.4	2.2	1.1	0.7	0.4	0.4	0.0	
169	1.474	X	0.020	0.350	0.880	1.590	2.590	3.550	4.070	4.610	5.180	
		Y	8.6	11.0	14.9	8.1	2.8	1.3	0.8	0.5	0.4	
170	1.640	X	0.140	0.880	2.550	3.370	3.530	4.070	4.600	5.150		
		Y	10.2	17.1	3.1	1.5	1.5	0.9	0.6	0.6		
171	2.033	X	0.220	0.550	1.600	2.600	3.550	5.110				
		Y	5.7	11.5	11.9	4.4	2.0	0.5				
172	2.258	X	0.140	0.550	1.610	2.590	3.560	4.060	4.590	5.130		
		Y	5.7	12.2	12.5	5.1	2.3	1.4	0.8	0.7		
173	2.638	X	0.130	1.610	2.610	3.590	4.100	4.590	5.140			
		Y	3.3	13.7	6.4	2.9	1.9	1.1	0.9			
174	3.007	X	0.210	0.980	1.630	2.600	3.580	4.100	4.590	5.140		
		Y	2.9	6.1	14.2	7.0	3.2	2.1	1.2	1.1		

MATERIAL : CLARTZITE

APPLIED POTENTIAL : 15.0 KV

----- * PCUAL ANALYSIS * -----

SAMPLE NUMBER	UNIT WCHK JOLLES/GHAM		X = LOCATION OF PEAK : Y = PEAK HEIGHT. (WT% / SCREEN INTERVAL).								
176	0.290	X	0.020	1.380	2.570	3.100	3.550	4.880	5.350	6.400	
		Y	44.5	1.2	0.3	0.2	0.2	0.1	0.1	0.0	
177	0.354	X	-0.040	0.840	1.360	1.580	2.100	2.610	3.610	4.090	5.130
		Y	41.0	4.7	1.7	1.9	0.6	0.6	0.3	0.2	0.1
178	0.047	X	-0.060	0.630	1.600	2.610	3.550	5.080			
		Y	24.1	11.8	4.2	1.3	0.7	0.1			
179	1.280	X	0.190	0.840	1.580	2.610	3.540	4.090	5.130		
		Y	13.0	14.4	6.6	2.0	1.0	0.6	0.3		
180	1.503	X	0.400	0.880	2.600	3.590	5.120				
		Y	10.1	15.4	2.6	1.2	0.3				
181	1.701	X	0.150	0.890	1.580	2.610	3.560	4.080	5.120		
		Y	9.2	15.9	8.6	3.4	1.6	1.0	0.4		
182	1.962	X	0.140	0.540	1.600	2.600	3.580	4.080	5.130		
		Y	5.4	12.2	10.9	4.3	2.0	1.3	0.6		
183	2.438	X	-0.050	0.530	1.610	2.610	3.550	4.080	5.150		
		Y	3.3	11.5	12.9	4.9	2.3	1.5	0.6		
185	2.728	X	0.080	1.610	2.600	3.590	4.100	5.170			
		Y	3.8	12.4	5.9	2.8	1.9	0.8			

 MATERIAL : OLARTZITE APPLIED POTENTIAL : 22.5 KV

----- * PCCAL ANALYSIS * -----											
SAMPLE NUMBER	UNIT WLHK JULIES/GHAM		X = LOCATION OF PEAK ; Y = PEAK HEIGHT, (WTX / SCREEN INTERVAL).								
155	0.110	X	-0.050	0.580	2.110	2.620	3.590	4.050	5.150		
		Y	53.4	5.9	6.2	0.2	0.1	0.1	0.0		
156	0.200	X	0.050	0.820	1.310	1.800	2.590	3.540	4.610	5.230	
		Y	43.4	3.8	1.9	0.9	0.6	0.3	0.1	0.1	
157	0.124	X	0.100	0.540	1.590	2.600	3.550	4.590	5.130	6.330	
		Y	25.9	12.9	3.5	1.1	0.5	0.2	0.1	0.0	
158	1.207	X	-0.010	0.860	1.360	1.560	2.600	3.560	4.590	5.220	6.450
		Y	18.3	14.5	6.0	6.2	1.9	0.7	0.2	0.2	0.0
159	1.479	X	0.100	0.870	1.610	2.610	3.600	4.600	5.160	6.420	
		Y	12.9	15.1	7.4	2.7	1.2	0.4	0.4	0.0	
160	1.821	X	0.000	1.610	2.590	3.570	4.070	4.610	5.180	6.310	
		Y	16.7	10.0	3.4	1.6	1.0	0.6	0.5	0.0	
161	1.946	X	0.150	0.900	1.590	2.070	2.600	3.580	4.570	5.080	
		Y	7.4	13.9	11.6	6.2	4.2	1.8	0.6	0.4	
162	2.294	X	0.140	0.940	1.600	2.600	3.570	4.090	5.320		
		Y	5.4	12.1	11.9	4.7	2.2	1.4	0.6		
163	2.075	X	0.210	1.620	2.600	3.590	4.070	5.050	6.410		
		Y	4.3	14.2	6.0	2.6	1.6	0.6	0.0		
164	2.841	X	-0.040	1.040	1.130	1.620	2.680	2.600	3.580	4.080	4.580
		Y	2.5	5.5	9.5	14.0	6.3	6.1	3.0	1.9	1.1
										5.130	0.9

MATERIAL : QUARTZITE APPLIED POTENTIAL : 30.0 KV

----- * PLDIAL ANALYSIS * -----										
SAMPLE NUMBER	UNIT WGR JOULES/GRAM	X = LOCATION OF PEAK ; Y = PEAK HEIGHT. (WT% / SCREEN INTERVAL).								
222	2.712	X	0.070	0.900	1.640	2.600	3.270	4.070	4.600	5.130
		Y	4.9	8.2	14.1	5.9	2.6	1.6	0.9	0.7
223	0.200	X	-0.070	1.080	1.600	2.610	3.640	4.610	5.060	5.590
		Y	54.8	2.1	0.9	0.4	0.2	0.1	0.1	0.0
224	0.573	X	-0.060	0.590	1.350	2.060	2.600	4.630	5.080	5.640
		Y	39.4	9.5	2.5	1.4	0.9	0.1	0.1	0.0
225	0.842	X	0.050	0.860	1.560	2.610	3.590	4.850		
		Y	22.7	13.0	4.7	1.8	0.6	0.1		
226	1.054	X	-0.010	0.890	1.580	2.610	4.210	6.430		
		Y	17.0	11.5	6.9	2.8	0.2	0.0		
227	1.331	X	0.050	0.880	1.540	2.600	3.520	4.540	5.150	
		Y	11.7	13.5	7.5	2.6	1.1	0.4	0.3	
228	1.531	X	0.050	0.130	0.900	1.570	2.610	3.600	4.650	5.360
		Y	9.4	9.4	12.2	9.4	3.6	1.4	0.4	0.3
229	1.711	X	-0.020	1.030	1.620	2.590	3.590	4.600	5.110	
		Y	8.7	10.1	12.9	4.7	1.9	0.4	0.4	
230	1.792	X	-0.020	1.120	1.630	2.610	3.350	3.580	4.580	5.120
		Y	9.9	8.5	10.4	4.6	1.9	2.0	0.5	0.5
231	2.065	X	0.130	0.890	1.680	2.600	3.540	4.550	5.130	
		Y	6.0	8.9	11.4	6.8	2.8	0.8	0.7	

MATERIAL : MCNC-GLARTZ APPLIED POTENTIAL : ZERO KV

----- * LOCAL ANALYSIS * -----											
SAMPLE NUMBER	UNIT BLK JULLES/GRAM	X = LOCATION OF PEAK ; Y = PEAK HEIGHT, (WT% / SCREEN INTERVAL).									
232	0.275	X	-0.050	1.370	2.610	3.590	4.100	5.100	5.600		
		Y	51.1	1.6	0.4	0.2	0.1	0.1	0.0		
233	0.535	X	-0.050	1.610	2.600	3.600	4.530	5.140			
		Y	35.7	2.2	0.7	0.3	0.1	0.1			
234	0.886	X	-0.030	0.700	1.600	2.610	3.560	4.080	4.590	5.140	
		Y	29.2	11.1	3.5	1.2	0.5	0.3	0.2	0.1	
235	1.175	X	0.110	0.650	2.590	3.520	4.690	5.140			
		Y	17.1	15.5	1.6	0.7	0.3	0.2			
236	1.524	X	0.120	0.900	1.570	2.600	3.360	3.590	4.710	5.310	6.480
		Y	12.4	14.3	9.3	3.8	6.9	1.0	0.3	0.1	6.0
237	1.676	X	0.120	0.900	1.600	2.040	2.610	3.340	3.470	4.610	5.130
		Y	11.5	13.1	9.5	5.4	3.5	1.4	1.4	0.4	0.3
238	2.103	X	0.130	0.950	1.620	2.610	3.320	4.600	5.150		
		Y	9.6	10.2	11.2	4.7	1.7	0.5	0.5		
239	2.160	X	-0.040	0.940	1.610	2.600	4.620	5.140			
		Y	8.7	9.5	11.6	4.8	6.5	0.6			
240	2.327	X	0.0	0.910	1.630	2.600	3.360	3.570	4.610	5.140	
		Y	6.3	9.5	12.4	5.8	2.1	2.1	0.6	0.6	
241	1.897	X	0.130	0.910	1.620	2.570	3.380	3.820	5.140		
		Y	11.2	9.8	11.2	3.9	1.7	1.6	0.4		

MATERIAL : MONO-QUARTZ APPLIED POTENTIAL : 15.0 KV

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ANALYSIS									
SAMPLE NOUGH	UNIT ACUM JOULES/GHAM	X	Y	X	Y	X	Y	X	Y
X = LOCATION UP PEAK I Y = PEAK HEIGHT. (WTS / SCREEN INTERVAL).									
242	0.077	-0.040	2.020	1.350	4.000	0.390	0.1		
		47.7	0.5	1.0	0.2	0.1			
243	0.070	0.080	1.850	2.910	4.390	0.110	0.1		
		32.8	2.3	7.0	0.1	0.1			
244	0.037	0.0	0.030	2.410	1.310	4.870	0.2	0.2	
		23.6	14.9	1.3	0.7	0.2			
245	0.022	0.010	0.030	1.970	2.000	3.100	0.3	0.2	
		22.4	11.6	14.8	1.4	0.6			
246	1.000	-0.010	0.500	1.600	2.010	3.390	4.000	0.3	0.3
		14.9	14.2	7.0	2.7	1.2	0.3		
247	1.706	0.070	0.040	1.610	2.030	3.500	4.390	0.4	0.4
		10.4	9.3	10.6	3.9	1.0	0.4		
248	1.747	0.140	0.040	1.600	2.010	3.890	4.390	0.4	0.4
		10.3	12.6	9.1	3.6	1.6	0.4		
249	2.274	0.140	1.130	1.640	2.000	3.600	4.390	0.6	0.6
		8.5	10.2	16.7	4.9	2.2	0.5		
250	2.328	0.130	1.020	1.450	2.090	3.600	4.390	0.6	0.6
		6.1	9.0	14.1	5.4	2.6	0.7		
251	1.040	-0.030	0.070	1.600	2.010	3.610	5.160	0.3	0.3
		17.4	13.0	9.7	2.2	1.0	0.3		

MATERIAL: MONO-CRYSTALLINE APPLIED POTENTIAL: 1.20.0 KV

----- * MUDAL ANALYSIS * -----

SAMPLE NUMBER	UNIT WCHK JCOLES/GHAM		X = LOCATION OF PEAK ; Y = PEAK HEIGHT. (WTR / SCREEN INTERVAL).								
311	0.901	X	0.080	0.280	1.540	2.610	3.590	4.110	4.590	5.160	5.610
		Y	15.4	12.2	5.0	2.6	1.4	1.0	0.6	0.7	0.7
312	0.967	X	0.120	0.250	1.570	2.610	3.590	4.110	4.590	5.200	5.620
		Y	16.8	12.1	6.5	3.2	1.7	1.2	0.6	0.8	0.8
313	0.608	X	0.040	0.260	1.600	2.610	3.590	4.110	5.180		
		Y	21.0	10.1	4.8	2.0	1.0	0.7	0.5		
314	0.110	X	-0.050	1.210	2.590	3.570	4.100	4.610	5.240		
		Y	53.2	0.5	0.3	0.1	0.1	0.0	0.1		
315	0.222	X	-0.060	0.600	2.590	4.090	5.190				
		Y	46.3	6.2	0.6	0.3	0.2				
316	0.335	X	-0.060	2.620	3.580	4.110	5.340				
		Y	35.5	6.9	0.4	0.3	0.2				
318	0.461	X	0.010	0.250	1.610	2.610	3.590	4.110	4.610	5.380	
		Y	27.2	16.6	4.0	1.6	0.7	0.5	0.3	0.4	
319	0.531	X	-0.040	0.620	1.600	2.610	3.600	4.090	4.590	5.200	
		Y	26.3	11.4	4.2	1.5	0.8	0.6	0.3	0.4	
320	0.670	X	-0.050	0.880	1.590	2.610	3.590	4.110	4.590	5.170	
		Y	23.3	11.4	5.6	2.1	1.1	0.8	0.5	0.6	
321	0.741	X	-0.040	0.260	2.610	3.580	4.110	4.580	5.190		
		Y	18.2	12.1	2.5	1.2	0.9	0.5	0.6		

 MATERIAL : POLY-SPHALERITE APPLIED POTENTIAL : ZERO KV

----- MODAL ANALYSIS -----													
SAMPLE NUMBER	UNIT WCHK JULCJ/GRAM	X = LOCATION OF PEAK ; Y = PEAK HEIGHT. (WTS / SCREEN INTERVAL).											
335	0.105	X	-0.040	0.570	0.870	1.080	1.600	2.360	3.600	4.080	4.620	5.510	0.1
		Y	53.9	1.7	1.2	1.3	0.8	0.2	0.1	0.1	0.0		
336	0.225	X	-0.070	0.610	1.600	3.570	4.100	4.590	5.330				
		Y	51.4	5.5	1.4	0.3	0.2	0.1	0.1				
337	0.330	X	-0.050	0.620	1.310	2.000	2.610	3.590	4.100	4.590	5.350		
		Y	38.2	10.5	2.7	1.1	0.8	0.4	0.3	0.2	0.2		
338	0.415	X	0.110	0.610	1.610	2.590	3.090	3.530	4.080	5.340			
		Y	30.9	10.4	3.8	1.3	0.6	0.6	0.4	0.3			
339	0.435	X	-0.060	0.630	1.600	2.590	3.600	4.080	5.360				
		Y	31.6	10.1	4.0	1.6	0.8	0.5	0.4				
340	0.700	X	0.010	0.870	1.620	2.600	3.560	4.100	4.590	5.350			
		Y	16.7	12.5	4.9	2.4	1.0	0.7	0.4	0.5			
341	0.823	X	-0.060	0.640	1.560	2.590	3.660	4.100	4.540	5.170			
		Y	20.7	11.0	5.8	2.1	1.1	0.8	0.5	0.6			
342	0.882	X	-0.020	0.670	1.370	1.580	2.590	3.080	3.600	4.090	4.580	5.170	0.4
		Y	23.9	12.9	3.9	4.2	1.4	0.8	0.7	0.5	0.3		
343	0.913	X	0.010	0.620	1.610	2.590	3.580	4.100	5.200				
		Y	23.2	10.5	5.1	2.0	0.9	0.6	0.4				
344	0.930	X	0.130	0.870	1.590	2.580	3.550	4.110	4.570	5.170			
		Y	17.3	12.3	6.3	2.8	1.3	1.0	0.6	0.7			

MATERIAL : POLY-SPHALERITE
 AFFLIED POTENTIAL : 15.0 KV

----- * MOLAL ANALYSIS * -----

SAMPLE NUMBER	UNIT WORK JOULES/GRAM		X = LOCATION OF PEAK :		Y = PEAK HEIGHT, (WT% / SCREEN INTERVAL).					
324	0.115	X	-0.060	1.610	2.050	2.420	4.630	4.610	5.350	
		Y	55.0	0.8	0.4	0.3	0.1	0.1	0.1	
325	0.509	X	0.120	0.870	1.590	2.580	3.600	4.110	4.570	5.170
		Y	17.4	12.3	6.3	2.8	1.3	0.9	0.6	0.7
326	0.428	X	-0.040	0.580	1.500	2.090	2.620	3.590	4.100	5.160
		Y	41.2	8.3	1.0	0.9	0.5	0.3	0.2	0.2
327	0.322	X	-0.030	0.830	2.000	3.060	3.590	4.100	5.160	
		Y	34.6	6.7	0.8	0.4	0.4	0.3	0.2	
328	0.432	X	0.010	0.640	1.600	2.020	2.610	3.090	3.580	4.090 5.100
		Y	28.6	8.9	3.2	2.0	1.3	0.7	0.6	0.4 0.3
329	0.550	X	-0.070	0.640	1.590	2.600	3.580	4.110	5.210	
		Y	28.5	11.1	4.3	1.7	0.9	0.5	0.4	
331	0.621	X	0.010	0.830	1.600	2.000	3.600	4.080	4.600	5.180
		Y	24.3	12.2	4.6	1.6	0.8	0.5	0.3	0.4
332	0.487	X	0.120	0.880	1.560	2.590	3.580	4.100	4.590	5.170
		Y	18.1	11.6	6.4	3.1	1.5	1.0	0.6	0.8
333	0.784	X	0.130	0.880	1.370	1.580	2.070	2.580	3.580	4.110 4.570 5.180
		Y	16.6	12.1	5.6	6.2	3.3	2.4	1.2	0.8 0.5 0.6
334	0.340	X	-0.010	0.840	2.590	3.580	4.110	4.570	5.180	
		Y	33.6	7.5	1.0	0.4	0.3	0.2	0.2	

MATERIAL : POLY-SPHALERITE APPLIED POTENTIAL : 30.0 KV

----- * MODAL ANALYSIS * -----

SAMPLE NUMBER	UNIT WORK JULIES/GRAM		X = LOCATION OF PEAK ; Y = PEAK HEIGHT. (WT% / SCREEN INTERVAL).							
253	0.804	X	0.170	0.550	1.610	2.590	3.570	4.100	5.160	
		Y	3.4	17.4	12.2	5.1	2.6	1.7	0.9	
255	0.101	X	-0.020	0.820	1.600	2.600	3.360	3.510	4.110	5.180
		Y	38.9	5.8	17.8	0.7	0.3	0.3	0.2	0.2
256	0.237	X	0.010	0.850	1.600	2.600	3.570	4.100	5.180	
		Y	20.1	14.1	5.5	1.8	0.9	0.5	0.3	
257	0.324	X	0.130	0.860	1.610	2.610	3.580	4.100	5.190	
		Y	15.6	13.6	6.7	2.5	1.2	0.7	0.4	
258	0.441	X	0.120	0.880	1.510	2.600	3.540	4.100	4.580	5.180
		Y	13.0	13.8	7.7	3.2	1.5	0.9	0.5	0.5
259	0.517	X	0.140	0.940	1.590	2.600	3.350	3.540	4.110	4.580 5.170
		Y	7.3	11.7	10.4	4.0	1.9	1.9	1.2	0.7 0.7
260	0.596	X	0.130	0.910	1.600	2.600	3.570	4.100	5.180	
		Y	6.5	13.1	10.8	4.2	2.1	1.3	0.7	
261	0.161	X	-0.030	1.580	2.610	3.540	4.100	5.250		
		Y	28.4	3.0	1.1	0.5	0.3	0.2		
262	0.286	X	-0.040	0.820	1.600	2.610	3.570	4.110	5.180	
		Y	19.1	13.6	5.7	2.0	1.0	0.6	0.4	

MATERIAL : MONO-SPHALERITE

APPLIED POTENTIAL : ZERO KV

----- MODAL ANALYSIS -----													
SAMPLE NUMBER	UNIT CHRG. Joules/gram	X = LOCATION OF PEAK : Y = PEAK HEIGHT. (INTS / SCREEN INTERVAL).											
263	0.108	X -0.060	1.610	2.570	3.370	3.540	4.110	4.520	5.270				
		Y 30.6	2.3	0.7	0.4	0.4	0.2	0.1	0.1				
264	0.225	X -0.010	0.610	1.580	2.550	3.560	4.120	4.590	5.350				
		Y 21.2	12.8	4.3	1.5	0.7	0.4	0.2	0.2				
265	0.341	X -0.060	0.240	1.550	2.800	3.570	4.100	4.940					
		Y 13.2	13.3	7.1	2.6	1.2	0.7	0.4					
266	0.442	X -0.050	0.480	1.600	2.060	2.600	3.550	4.620	5.060				
		Y 11.5	14.2	7.9	4.5	3.2	1.5	0.5	0.4				
267	0.573	X -0.050	1.410	0.520	1.550	2.600	3.580	4.110	4.610	5.130			
		Y 4.5	7.6	14.0	9.7	4.1	2.0	1.3	0.6	0.6			
268	0.693	X 0.130	0.450	1.590	2.610	3.570	4.120	4.580	5.120				
		Y 7.1	13.4	10.5	4.6	2.3	1.4	0.6	0.7				
269	0.765	X 0.150	0.420	1.600	2.610	3.550	4.090	5.130					
		Y 6.9	11.7	10.1	4.5	2.4	1.4	0.7					
270	0.872	X 0.020	0.430	1.580	2.530	3.580	4.070	5.020					
		Y 18.0	11.3	6.2	2.6	6.9	0.5	0.2					
271	0.910	X 0.130	0.460	1.600	2.590	3.590	4.070	5.190					
		Y 13.9	13.3	7.7	2.7	1.3	0.7	0.4					
272	0.502	X -0.060	0.480	1.610	2.600	3.580	4.080	5.120					
		Y 11.6	13.8	8.6	3.3	1.6	0.9	0.5					

MATERIAL : MONO-SIALKINITE
APPLIED POTENTIAL : 15.0 KV

----- * EQUAL ANALYSIS * -----										
SAMPLE NUMBER	UNIT eLRK JULLES/GRAM	X = LOCATION OF PEAK ; Y = PEAK HEIGHT. (WT% / SCREEN INTERVAL).								
273	0.110	X	0.0	2.550	3.600	4.060	4.220			
		Y	37.6	0.7	0.4	0.2	0.1			
274	0.205	X	-0.310	1.560	3.590	4.060	5.130	6.450		
		Y	21.9	3.8	0.7	0.4	0.2	0.0		
275	0.335	X	0.050	0.650	1.600	2.540	3.590	4.100	4.570	5.160
		Y	14.8	14.0	6.4	2.1	1.1	0.7	0.3	0.4
276	0.405	X	0.130	0.900	1.570	2.610	3.580	4.100	5.170	
		Y	9.6	13.2	8.1	3.6	1.8	1.1	0.6	
277	0.375	X	-0.050	0.910	1.610	2.600	3.580	4.110	5.140	
		Y	7.7	12.7	10.2	4.2	2.1	1.4	0.7	
278	0.684	X	0.010	0.830	1.570	2.570	3.580	4.090	4.600	5.170
		Y	39.4	4.8	1.8	0.6	0.3	0.1	0.1	0.1
279	0.706	X	0.140	0.620	1.600	2.610	3.520	4.110	4.540	5.180
		Y	4.4	13.1	10.0	5.2	2.5	1.6	0.7	0.6
280	0.625	X	-0.050	0.910	1.610	2.610	3.570	4.100	4.550	5.170
		Y	4.3	12.4	11.0	5.2	2.7	1.7	0.9	0.9
281	0.293	X	-0.060	0.650	1.350	2.620	3.520	4.100	5.320	
		Y	24.2	12.4	5.1	2.2	0.9	0.6	0.3	
282	0.411	X	-0.030	0.180	0.870	1.600	2.600	3.580	4.100	5.150
		Y	10.3	9.4	13.3	8.2	3.0	1.5	0.9	0.5

 MATERIAL : MONO-SPHALERITE APPLIED POTENTIAL : 30.0 KV

----- MODAL ANALYSIS -----													
SAFETY NUMBER	UNIT GUNK JULLES/GRAM	A. = LOCATION OF PEAK ; Y = PEAK HEIGHT. (WTS / SCREEN INTERVAL).											
205	0.055	X -0.080	0.600	1.620	2.150	2.630	3.230	3.600	4.100	4.560	5.120		
		Y 21.5	3.1	0.9	0.7	0.9	0.8	1.0	0.6	0.3	0.2		
206	0.120	X -0.080	2.130	2.460	3.120	3.600	4.110	5.120					
		Y 31.8	1.9	2.5	2.2	2.9	1.8	0.5					
207	0.177	X 0.020	0.820	1.600	2.130	2.680	3.590	4.100	5.120				
		Y 57.4	7.8	3.3	2.7	4.2	4.4	2.6	0.8				
208	0.241	X 0.120	0.870	1.620	2.110	2.640	3.530	4.100	5.120				
		Y 4.8	8.9	4.9	4.3	6.0	5.4	3.5	1.1				
209	0.299	X 0.150	1.040	1.610	2.120	2.640	3.140	3.600	4.100	4.530	5.130		
		Y 4.4	0.5	0.1	5.2	7.4	5.9	7.5	4.7	2.2	1.6		
210	0.323	X 0.130	0.930	1.630	2.130	2.640	3.130	3.600	4.100	5.130			
		Y 2.9	4.8	7.0	6.4	8.6	6.5	8.1	4.7	1.5			
211	0.379	X 0.150	1.650	2.110	2.650	3.120	3.600	4.100	4.540	5.130			
		Y 2.9	7.0	6.4	8.9	7.0	9.1	5.3	2.5	1.7			
212	0.078	X -0.040	0.660	1.620	2.140	2.640	3.550	4.110	4.550	5.130			
		Y 44.5	2.6	1.2	0.9	1.4	1.4	0.9	0.4	0.3			

APPLIED POTENTIAL : 15.0 KV

WATSON : 1000 LRE

MODAL ANALYSIS									
SAMPLE NUMBER	UNIT JULIES/GRAM	X = LOCATION OF PEAK		Y = PEAK HEIGHT, (IN / SCREEN INTERVAL)					
377	0.074	X	-0.070	1.620	2.520	3.660	4.120	4.590	5.340
		Y	63.5	0.1	0.1	0.1	0.1	0.1	0.2
378	0.159	X	-0.020	1.580	2.120	2.630	3.650	4.130	5.180
		Y	48.2	0.5	0.2	0.2	0.3	0.4	0.3
379	0.250	X	0.080	1.530	2.160	2.580	3.630	4.120	5.160
		Y	33.4	1.0	0.3	0.3	0.6	0.7	0.6
380	0.108	X	-0.070	1.580	2.630	3.650	4.670	5.150	
		Y	32.1	0.1	0.5	0.7	0.7	0.7	
381	0.445	X	0.060	2.620	3.660	4.090	4.620	5.160	
		Y	29.0	0.6	0.9	0.8	0.6	0.7	
382	0.036	X	0.140	0.610	2.090	2.630	3.670	4.100	5.150
		Y	21.9	15.7	0.9	0.8	1.3	1.4	0.9
383	0.799	X	0.120	0.750	2.080	2.630	3.650	4.120	5.170
		Y	18.7	13.0	1.1	1.0	1.6	1.9	1.4
384	0.408	X	0.140	0.600	2.010	3.640	4.120	4.580	5.140
		Y	15.7	17.9	1.3	2.0	2.1	1.5	1.7
385	0.505	X	-0.050	1.550	2.620	3.650	4.110	4.580	5.150
		Y	25.5	1.7	0.7	1.1	1.3	0.8	1.1
									0.0

MATERIAL: POLY-DECATIDE

APPLIED POTENTIAL: ZINC KV

----- * TOTAL ANALYSIS * -----												
SAMPLE NUMBER	UNIT g/LK J/ULES/GRAM	X = LOCATION OF PEAK : Y = PEAK HEIGHT, (WT% / SCREEN INTERVAL).										
365	0.135	X -0.050	0.570	0.830	1.370	1.230	2.620	3.640	4.120	4.610	5.190	
		Y 57.9	1.6	0.9	0.3	0.2	0.1	0.2	0.2	0.1	0.1	
370	0.204	X -0.010	0.560	1.350	2.080	2.620	3.640	4.120	4.590	5.210		
		Y 40.2	6.0	0.7	0.3	0.2	0.4	0.4	0.3	0.3		
371	0.339	X -0.050	1.320	2.100	2.620	3.640	4.120	4.590	5.160			
		Y 38.0	1.0	0.4	0.4	0.7	0.6	0.6	0.6			
372	0.448	X 0.0	1.560	2.100	2.620	3.640	4.120	4.590	5.150			
		Y 31.0	1.7	0.6	0.5	0.9	1.0	0.7	0.8			
373	0.506	X 0.040	0.610	2.090	2.620	3.650	4.120	4.590	5.150			
		Y 25.1	14.0	0.7	0.7	1.2	1.4	1.0	1.1			
374	0.646	X -0.010	0.140	0.600	2.630	3.650	4.120	4.560	5.150			
		Y 16.8	15.0	17.0	1.0	1.5	1.7	1.1	1.3			
375	0.545	X 0.110	0.650	2.090	2.640	3.640	4.110	4.600	5.120	5.600		
		Y 25.7	14.0	0.9	0.2	1.4	1.5	0.9	1.0	0.5		
376	0.843	X 0.140	0.740	2.220	3.640	4.120	4.590	5.150				
		Y 19.5	14.1	1.1	1.0	2.0	1.3	1.4				

MATERIAL : POLY-PHENYLENE
 APPLIED POTENTIAL : 15.0 KV

----- MODAL ANALYSIS -----											
SAMPLE NUMBER	UNIT WORK JOULES/GRAM		X = LOCATION OF PEAK ; Y = PEAK HEIGHT, (WT% / SCREEN INTERVAL).								
300	0.055	X	0.140	0.630	1.570	2.620	3.650	4.120	4.590	5.150	
		Y	15.7	15.5	3.1	1.1	1.0	2.1	1.6	1.7	
301	0.475	X	0.160	0.660	2.040	2.630	3.640	4.120	4.590	5.150	
		Y	14.0	17.0	1.5	1.3	2.2	2.6	1.9	1.9	
302	0.084	X	0.080	0.130	0.650	1.610	2.070	2.620	3.650	4.120	4.590 5.150
		Y	17.0	17.1	15.7	2.7	1.0	0.8	1.4	1.7	1.2 1.4
303	0.754	X	0.120	0.610	2.080	2.610	3.640	4.120	4.580	5.200	
		Y	20.3	16.1	1.2	1.1	1.4	1.6	1.1	1.2	
304	0.505	X	0.120	0.690	2.100	2.630	3.640	4.110	4.600	5.140	
		Y	26.3	14.1	0.9	0.8	1.4	1.5	0.9	1.0	
305	0.474	X	-0.030	1.000	2.100	2.630	3.640	4.120	4.600	5.160	
		Y	26.5	1.5	0.7	0.6	0.6	1.0	0.6	0.8	
306	0.350	X	0.090	0.610	2.020	3.640	4.120	4.590	5.150		
		Y	40.3	10.1	0.4	0.6	0.7	0.5	0.6		
307	0.224	X	-0.020	0.820	1.600	2.110	2.630	3.640	4.110	4.600	5.170
		Y	45.1	2.7	0.7	0.2	0.3	0.4	0.4	0.3	0.4
308	0.100	X	-0.040	0.860	1.640	2.120	2.640	3.640	4.120	4.600	5.200
		Y	55.7	0.6	0.2	0.1	0.1	0.2	0.2	0.1	0.2

..... MATERIAL : POLY-HEPATITE

APPLIED POTENTIAL : 30.0 KV

MESH RANGE	-50+100	-100+140	-140+200	-200+400

ZERO kV

Weight floats (g)	3.6613	0.8341	0.1735	0.1617
Weight sinks (g)	1.6321	0.9223	0.2385	0.5911
Total weight (g)	5.2934	1.7564	0.4120	0.7528

Weight % floats	69.2	47.5	42.0	21.5

15.0 kV

Weight floats (g)	1.9962	0.5007	0.1928	0.1059
Weight sinks (g)	1.0727	0.5134	0.3086	0.3268
Total weight (g)	3.0689	0.0141	0.5014	0.4327

Weight % floats	65.1	49.3	38.3	24.5

30.0 kV

Weight floats (g)	2.0013	0.4350	0.8176	0.1201
Weight sinks (g)	0.9818	0.4624	1.3845	0.4144
Total weight (g)	2.9831	0.8974	2.2021	0.5345

Weight % floats	67.0	48.0	37.1	22.5

Float and Sink Analysis Data.

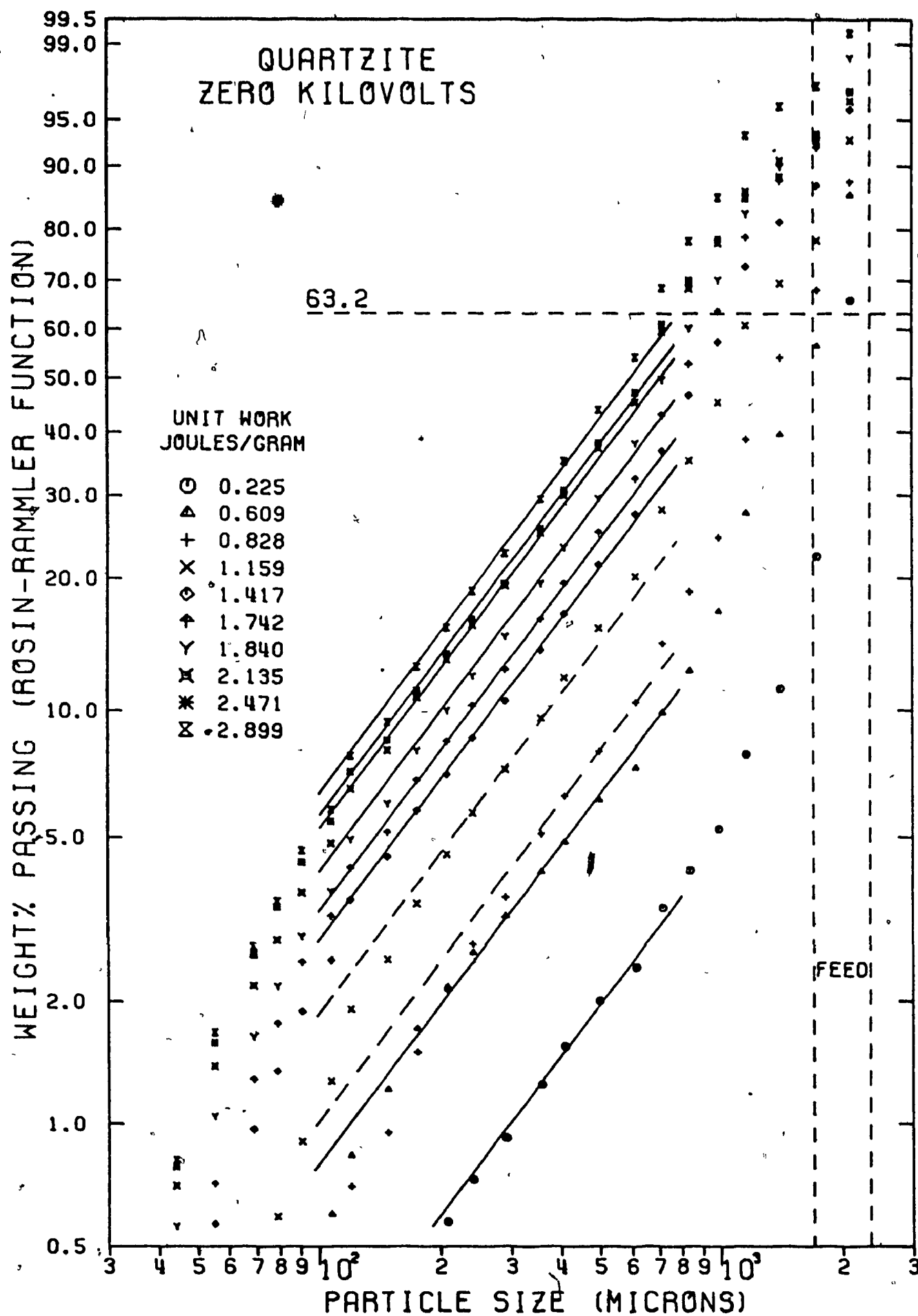
A.VII. COMPUTER GENERATED GRAPHS

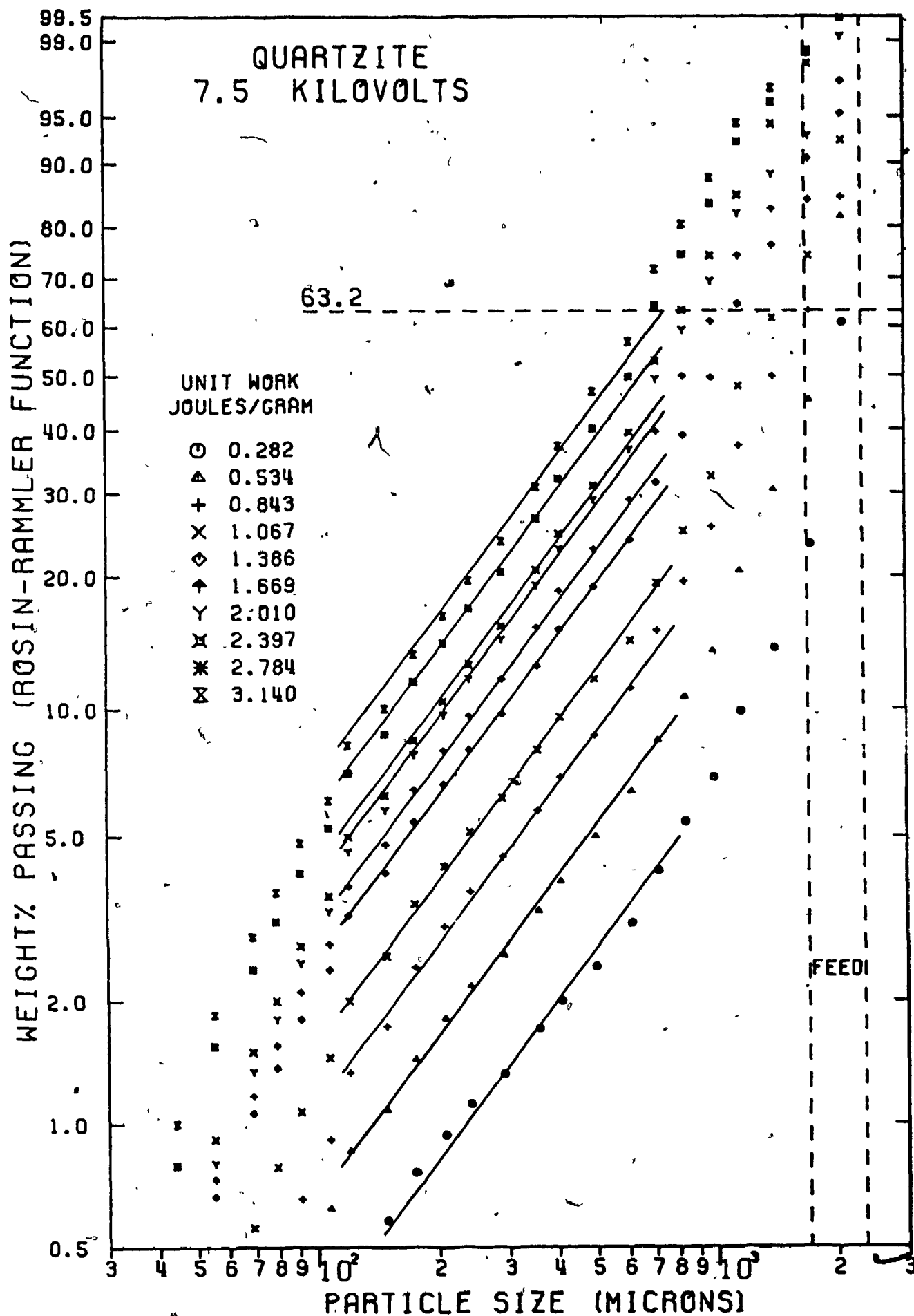
The following plots were made on the McGill CALCOMP Plotter using the programs given in Appendix V.1. and .2.

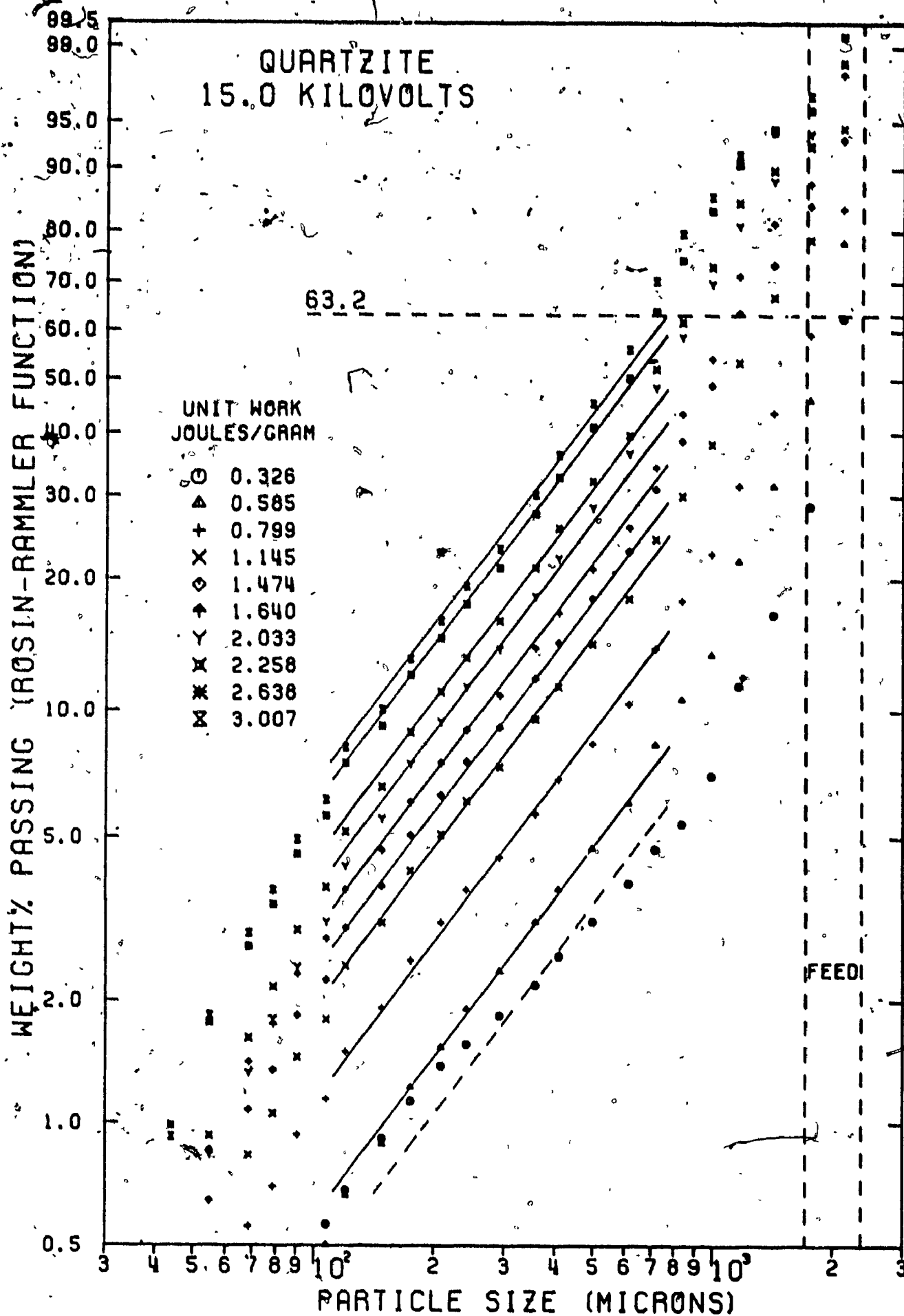
1. Rosin-Rammler Plots
2. Frequency Distributions

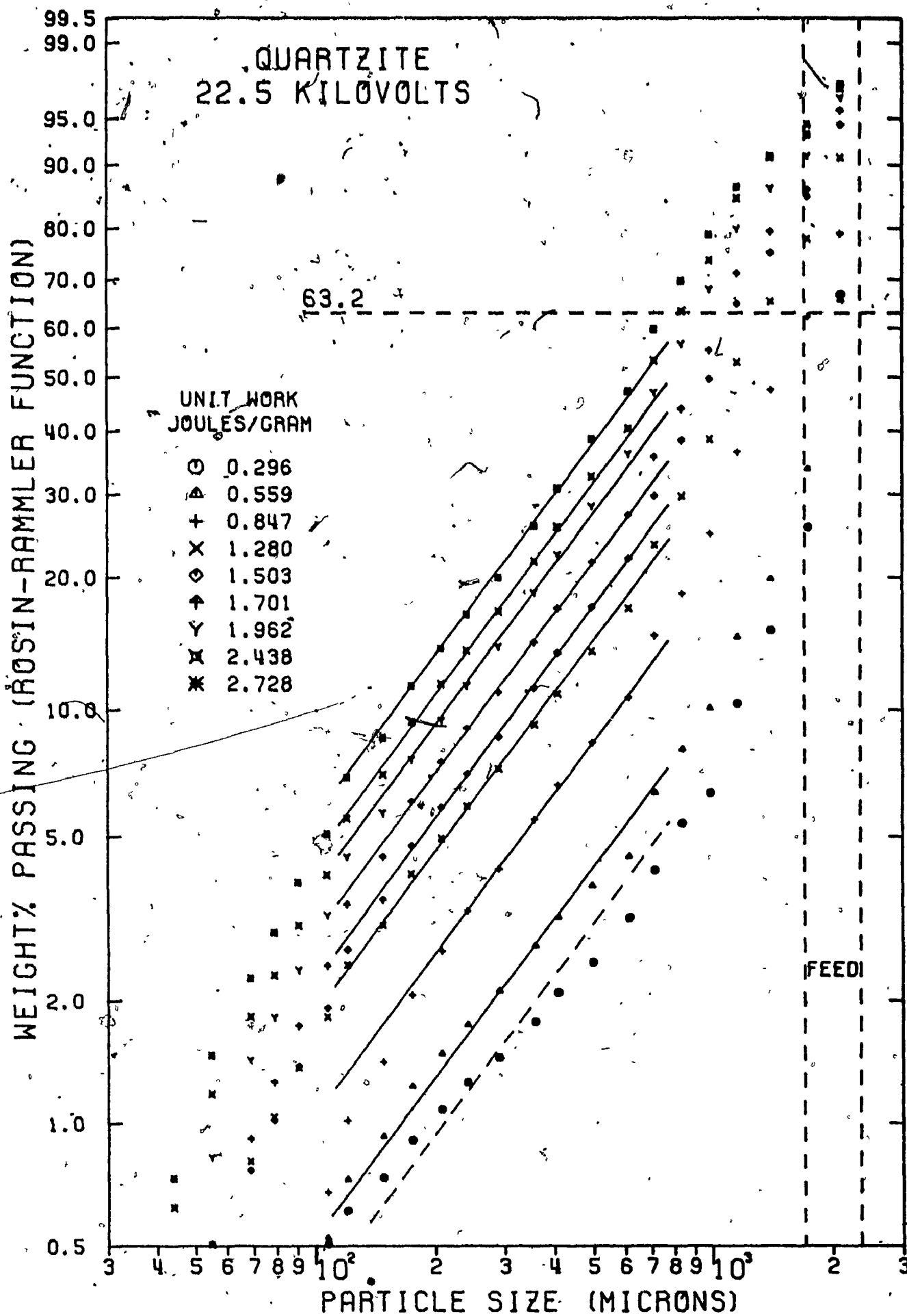
Pages 298-317

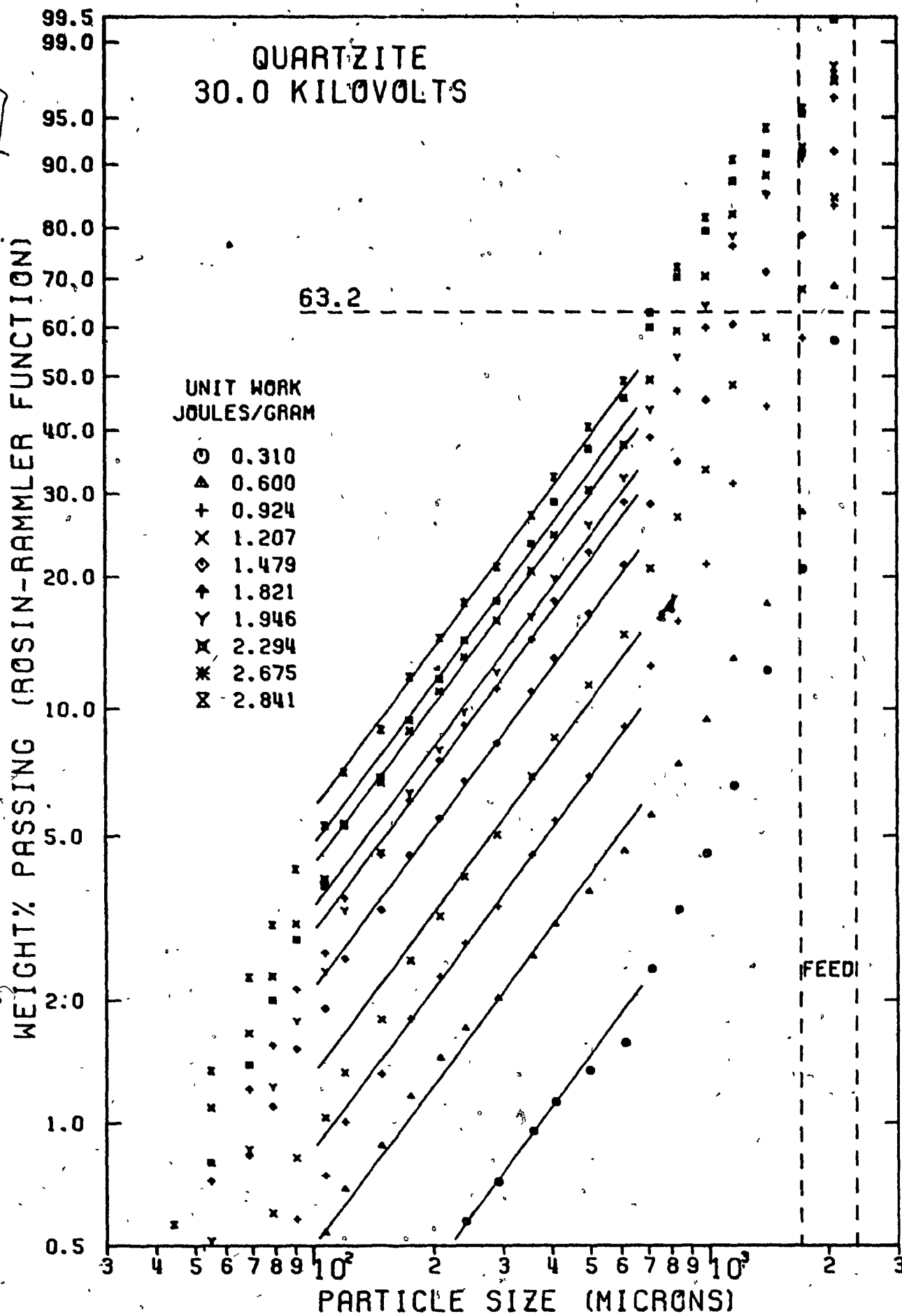
318-337

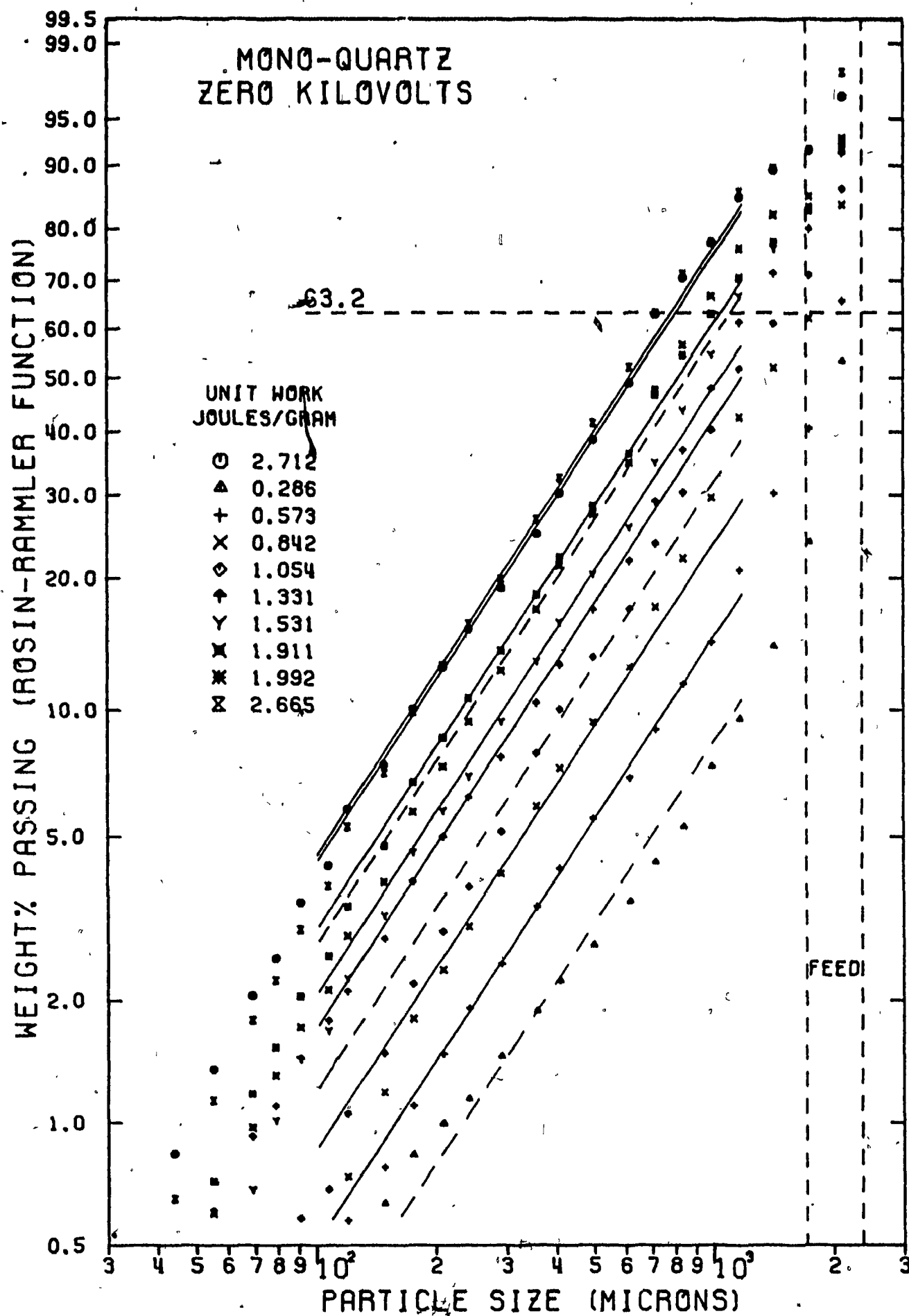


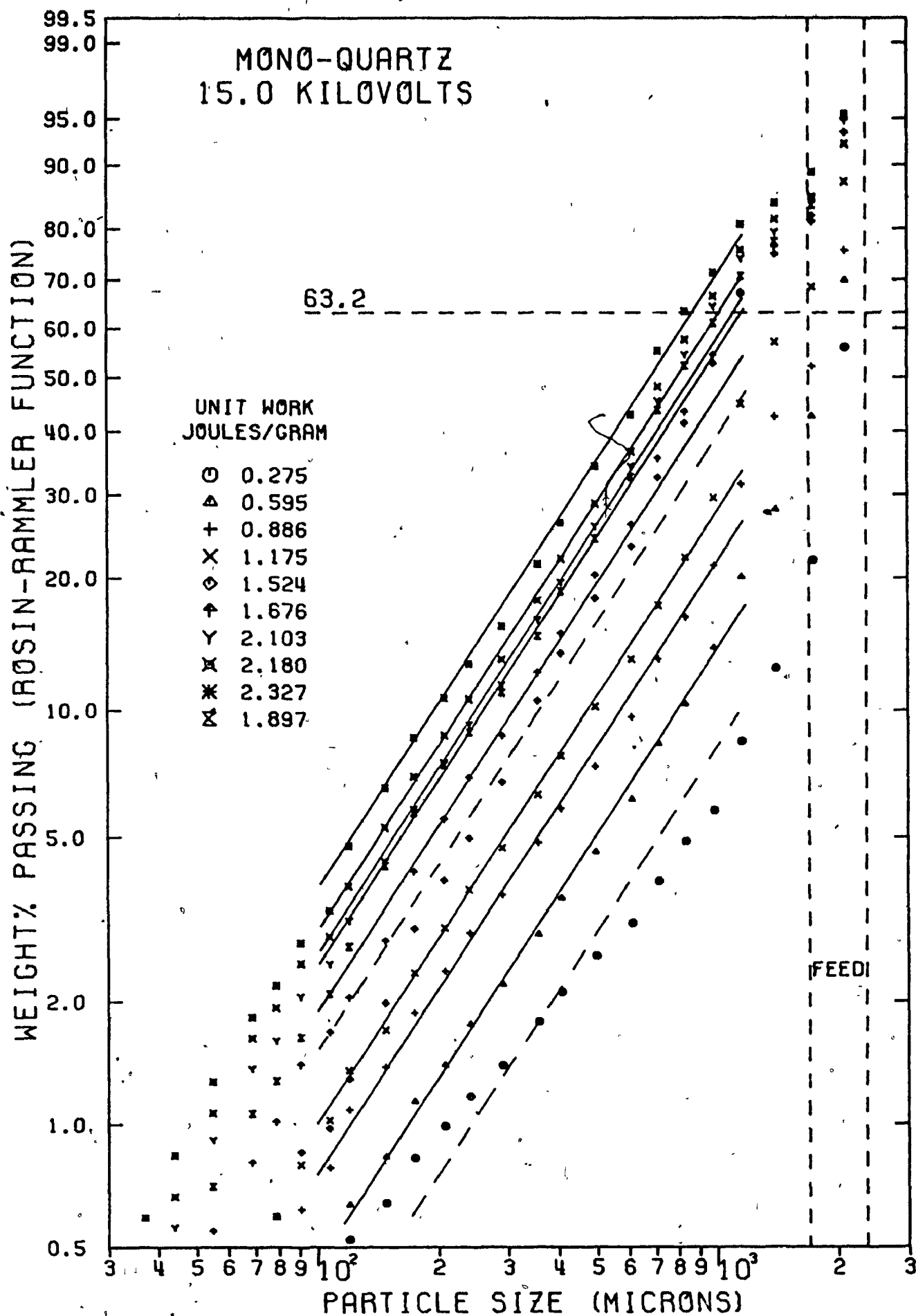


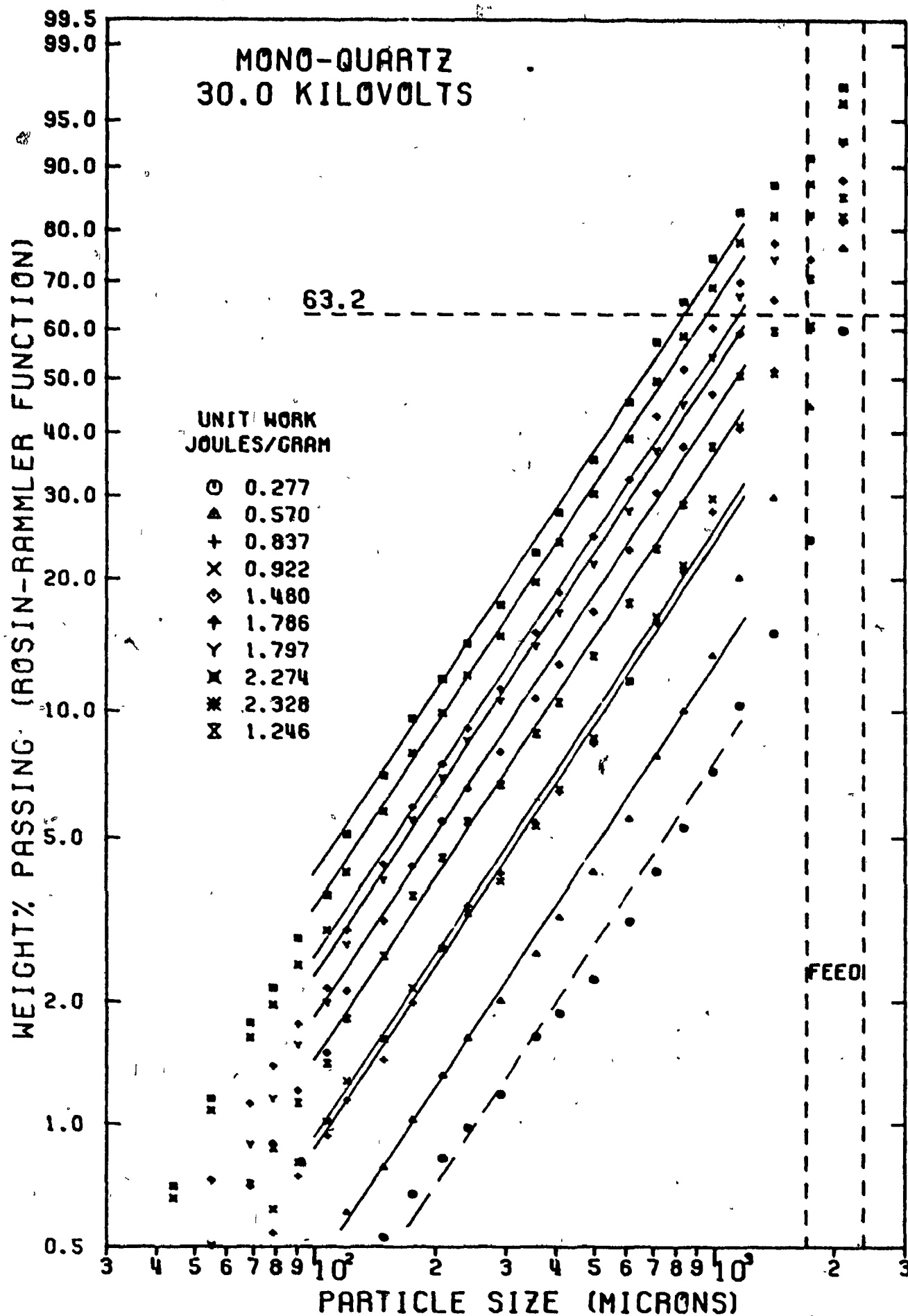


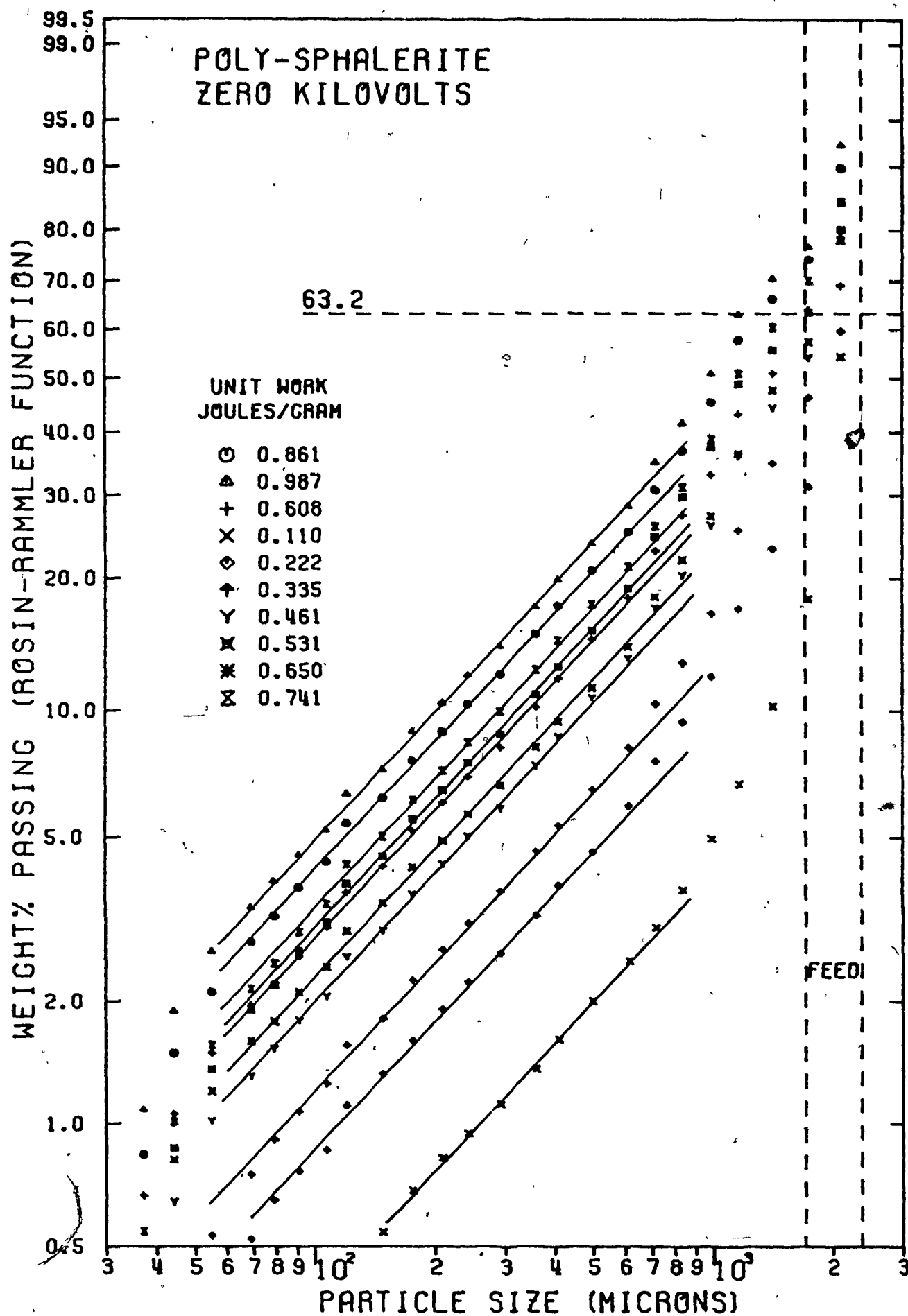


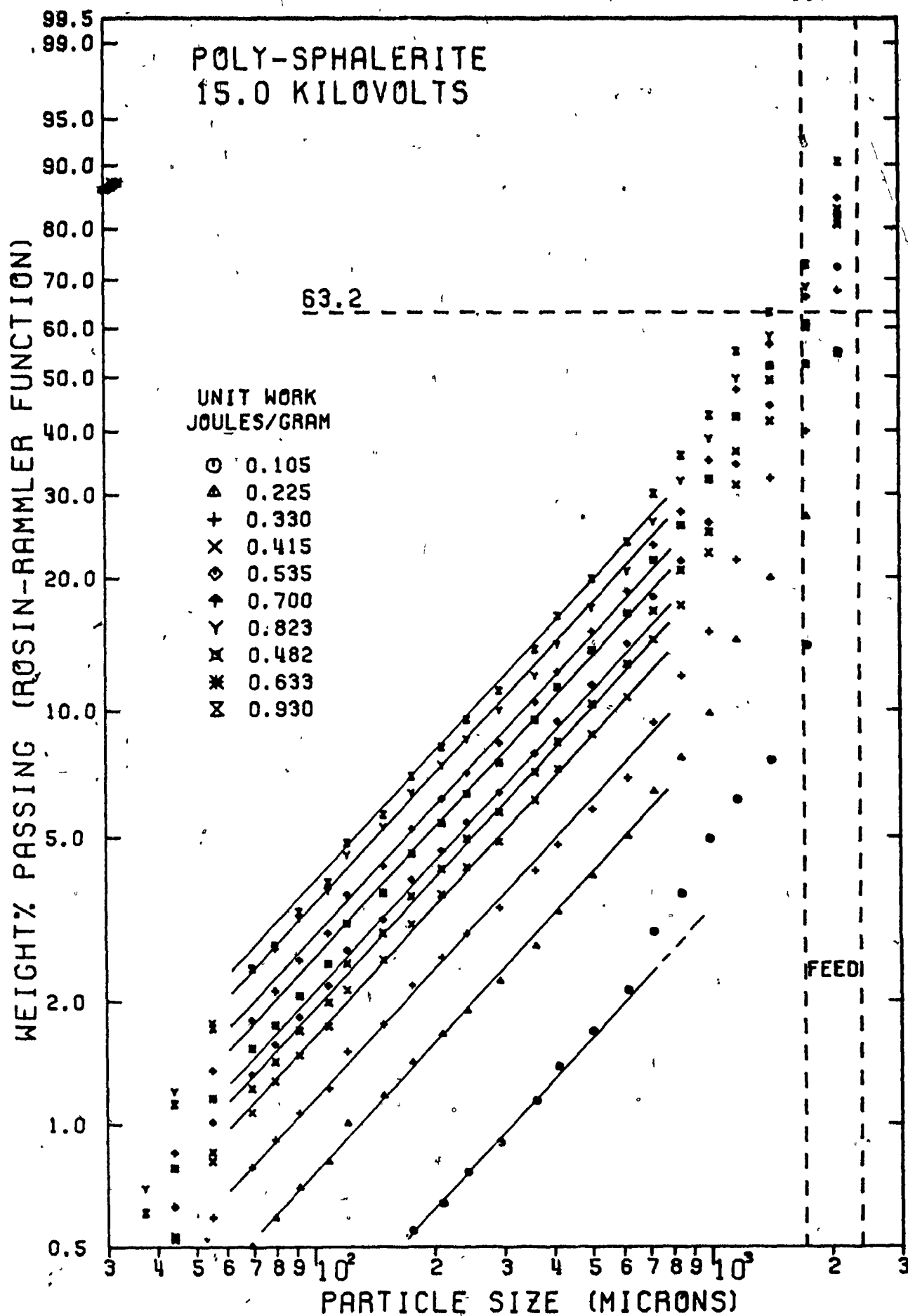


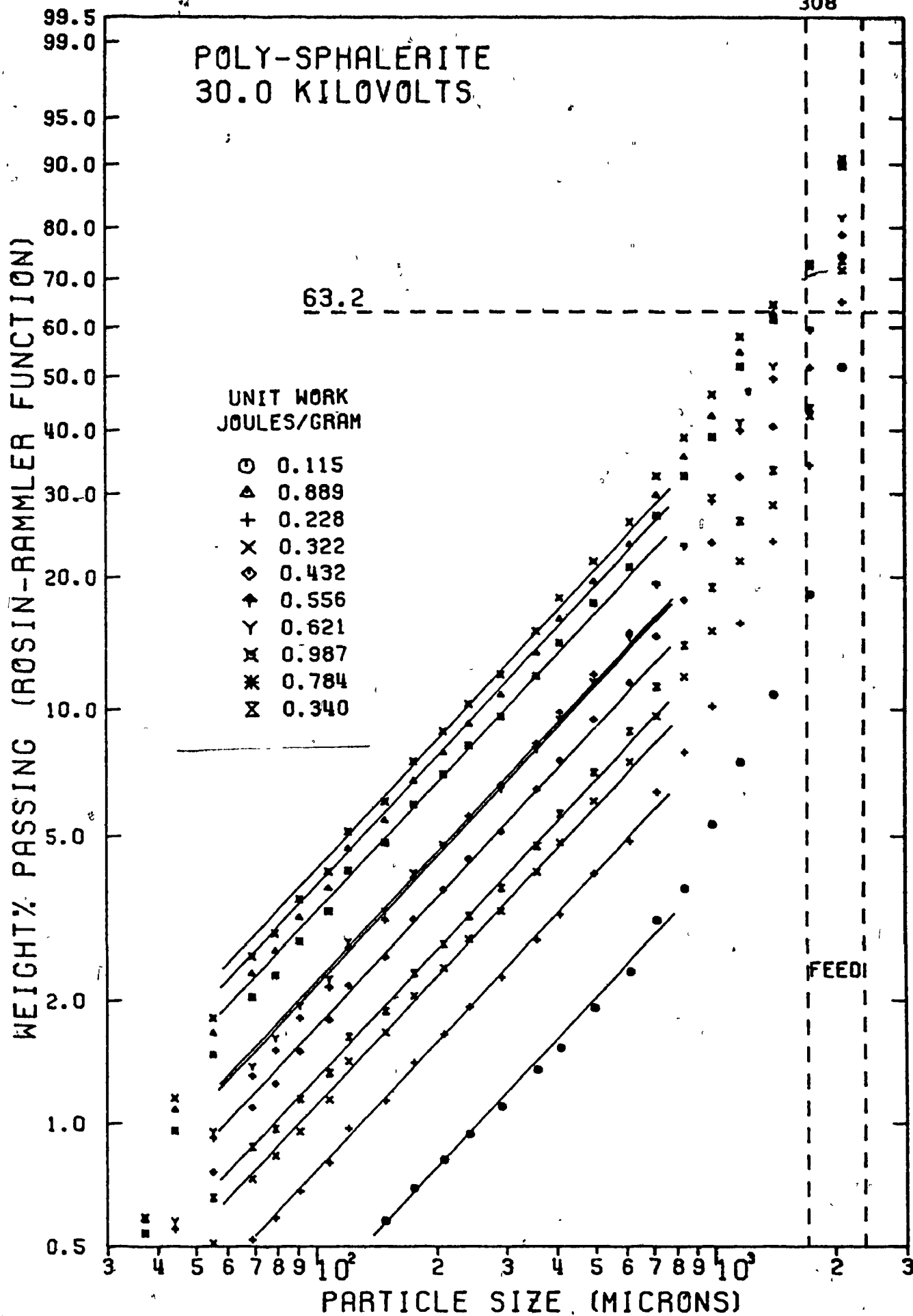


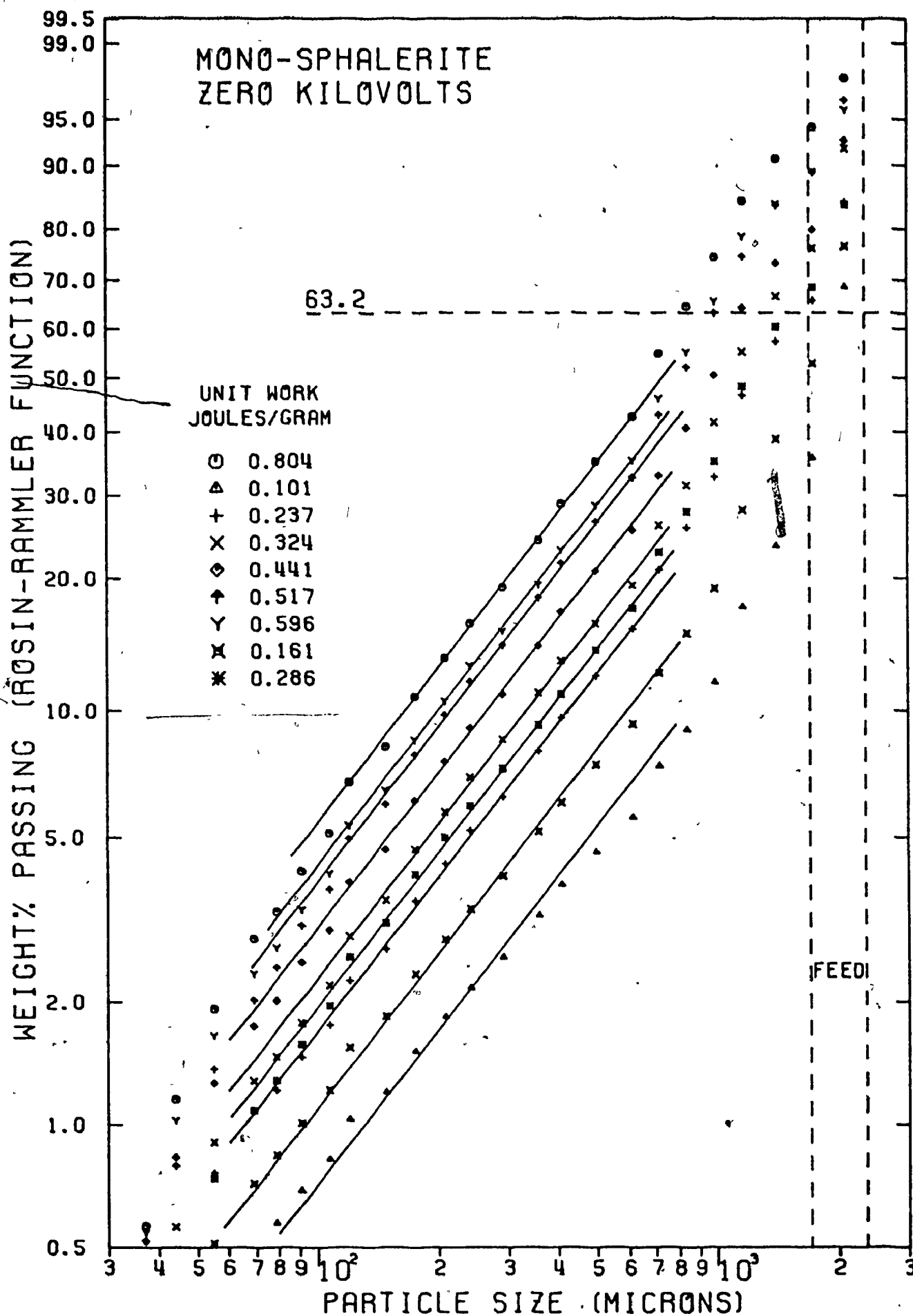


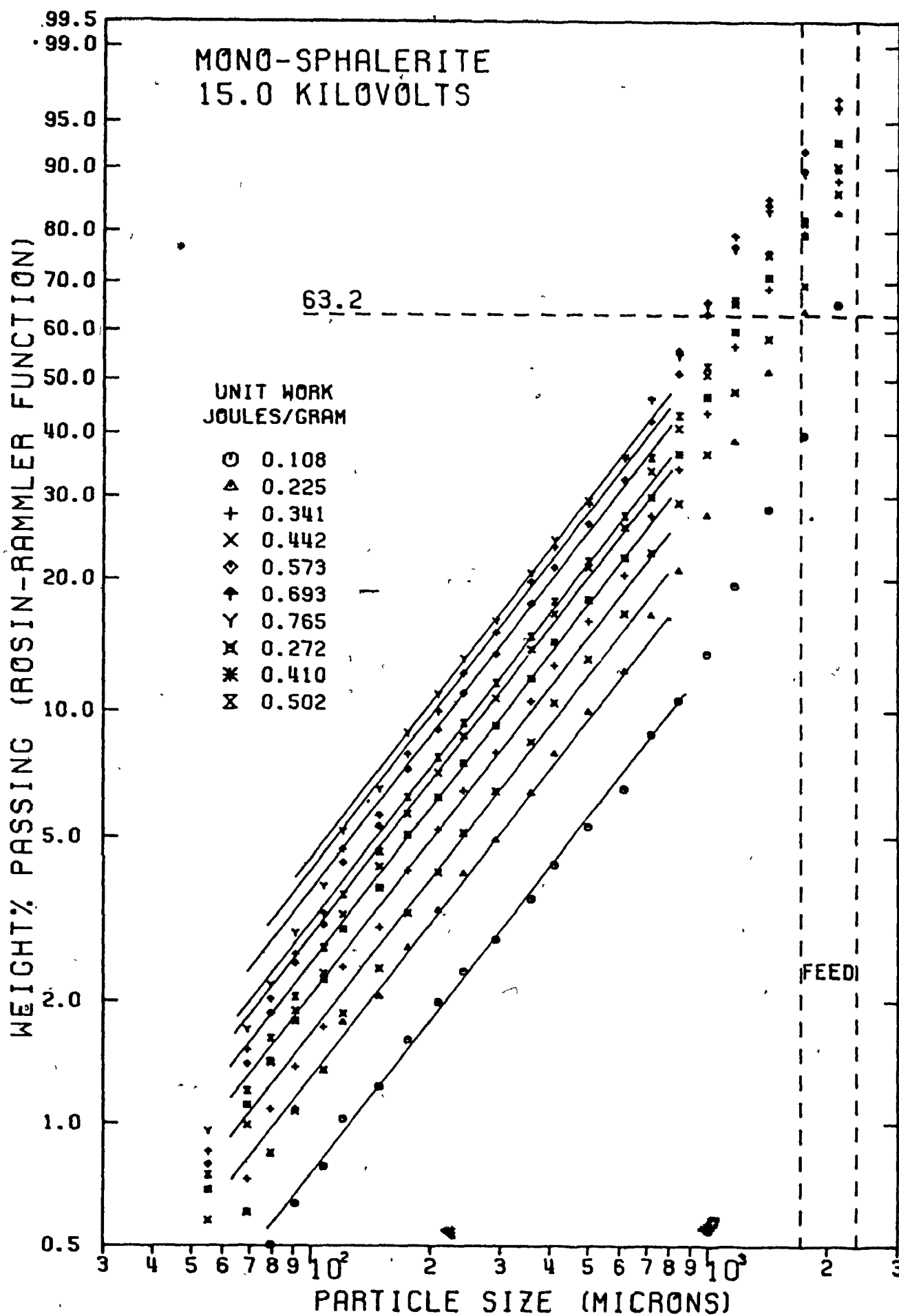


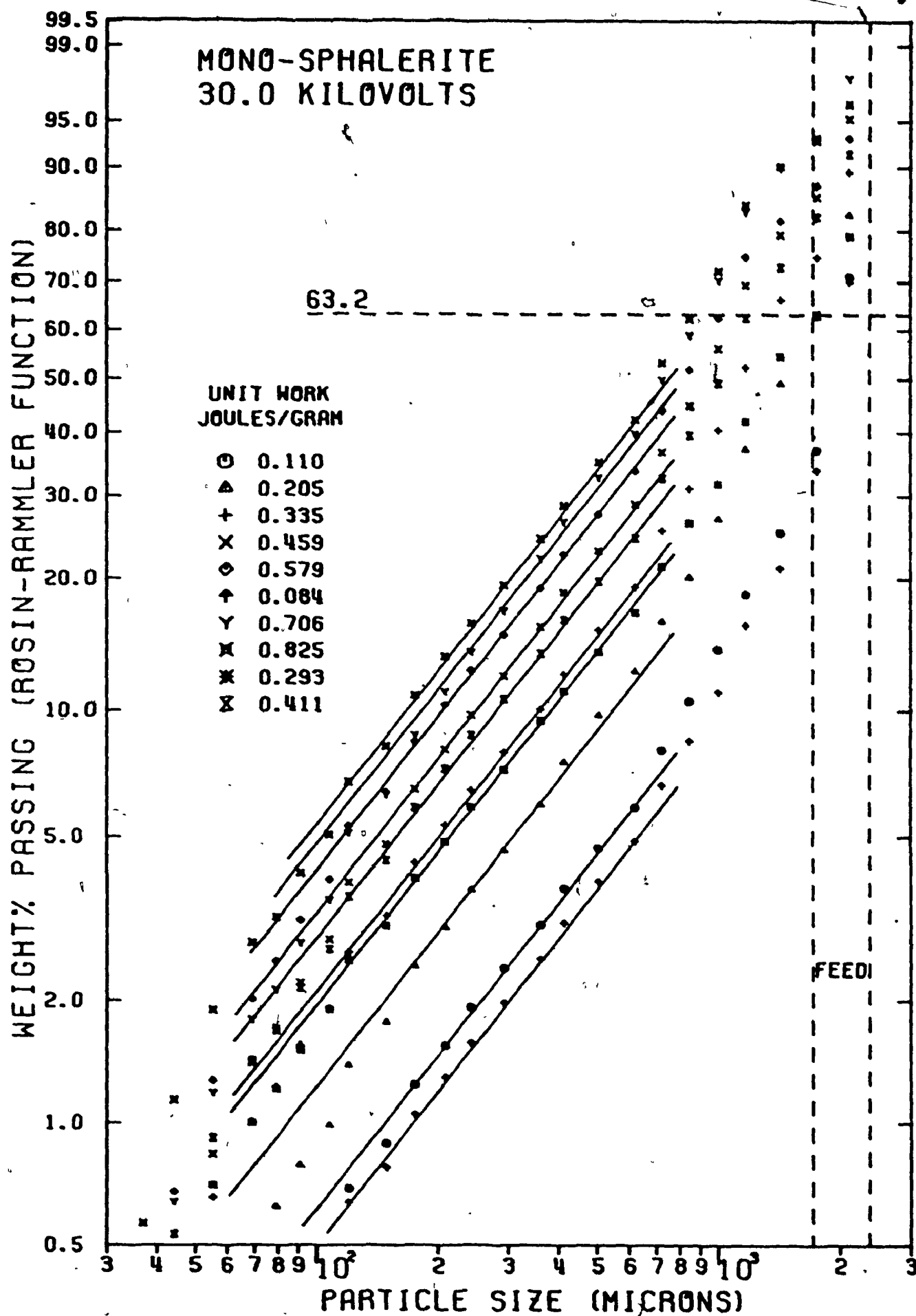


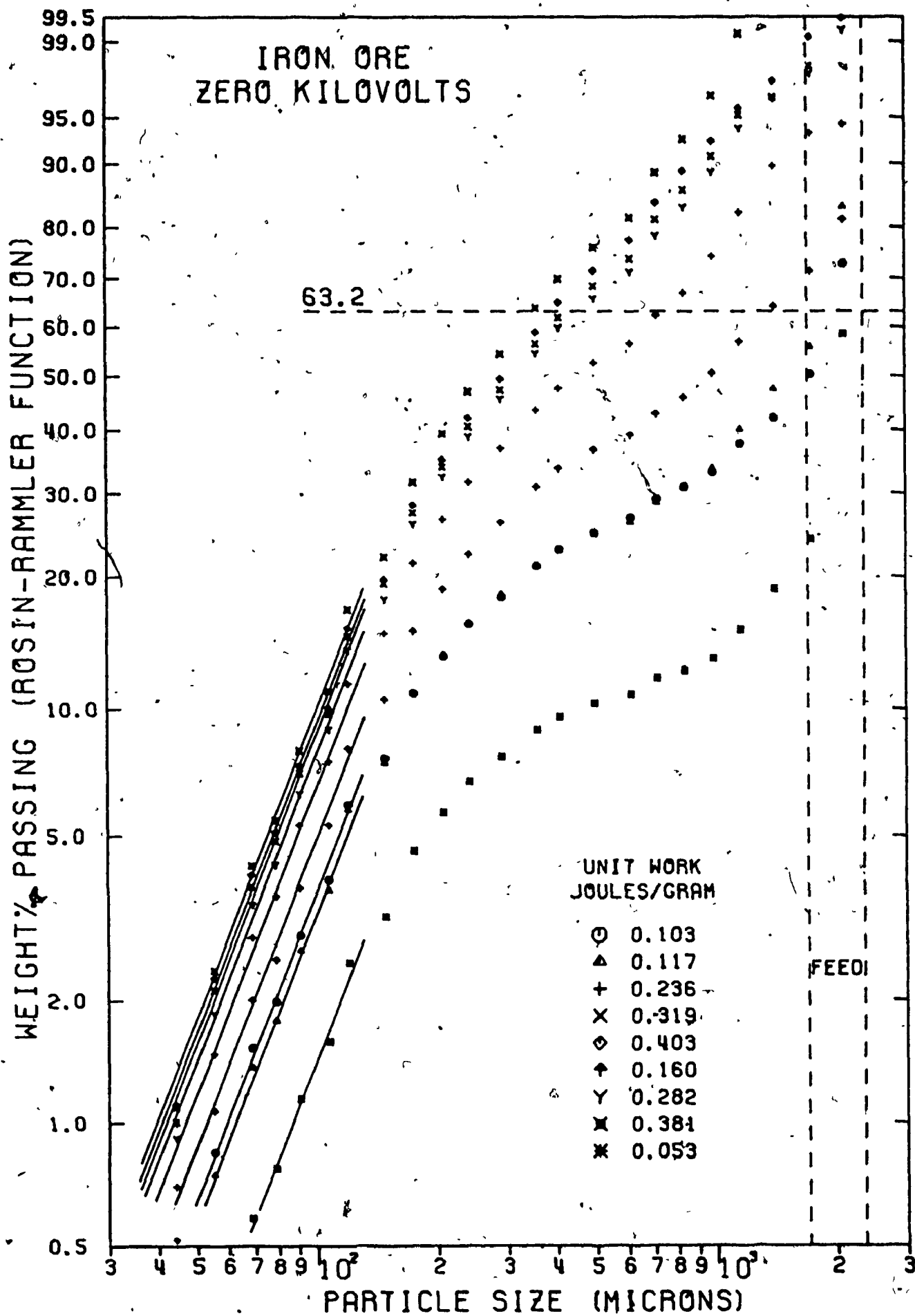


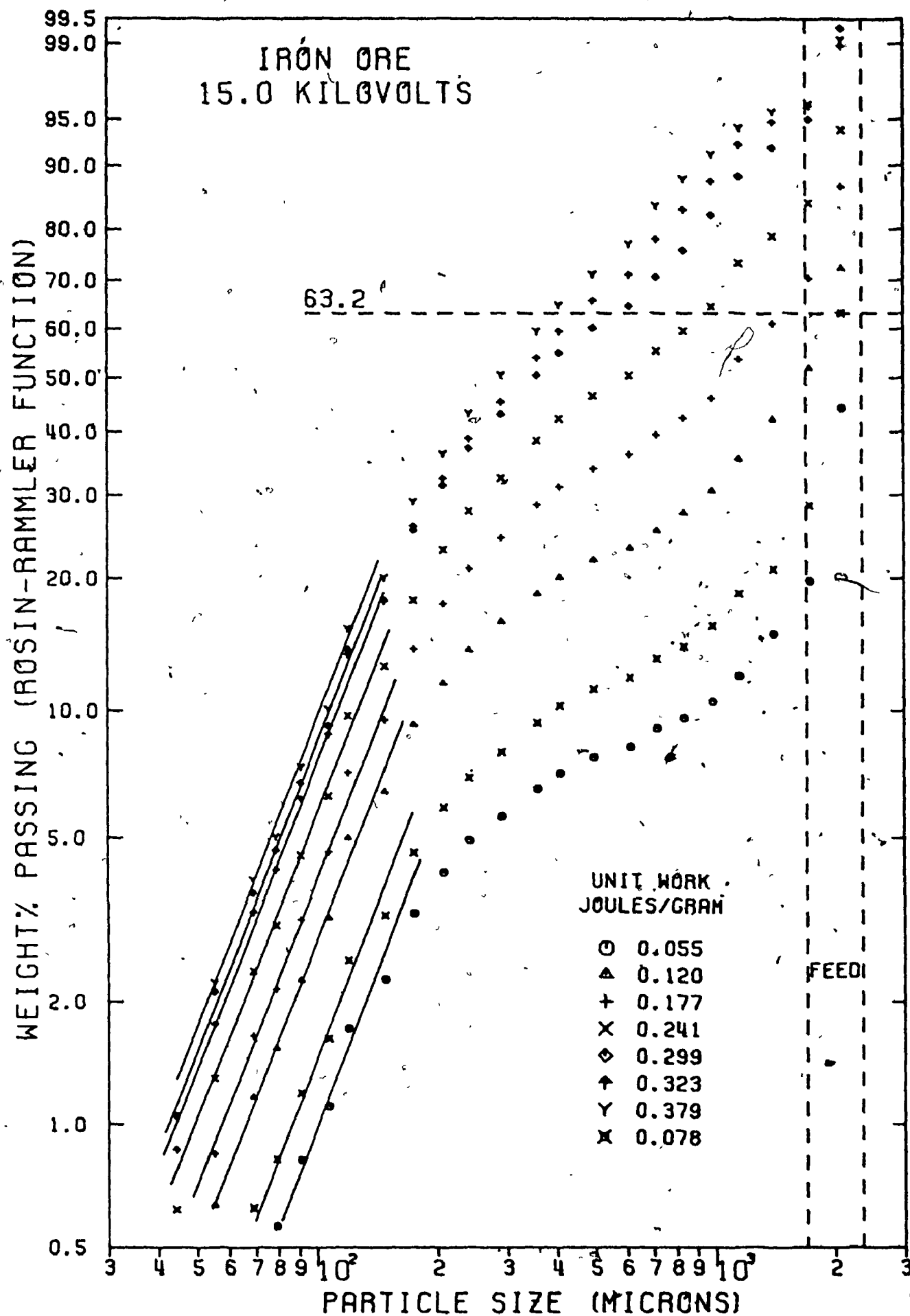


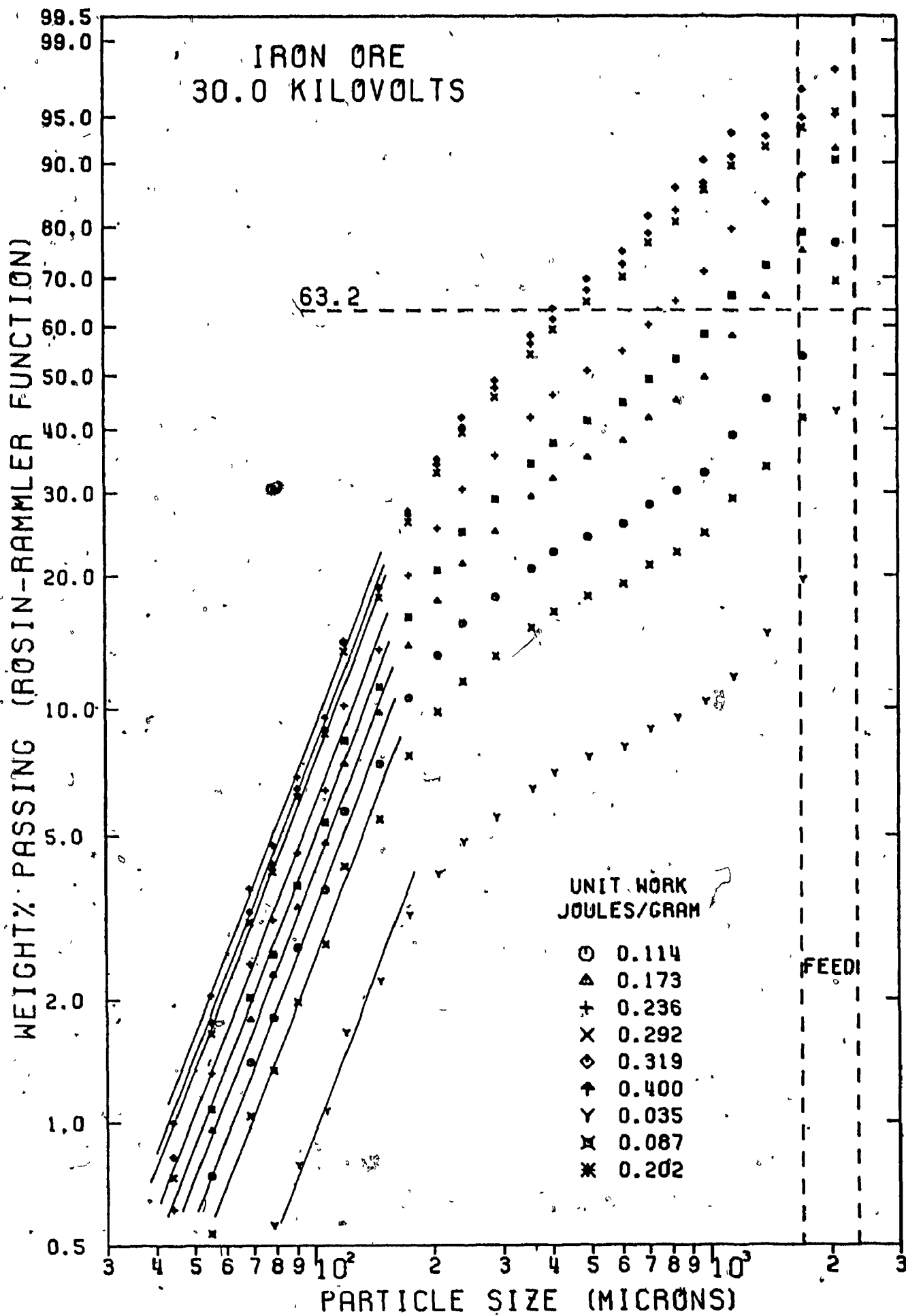


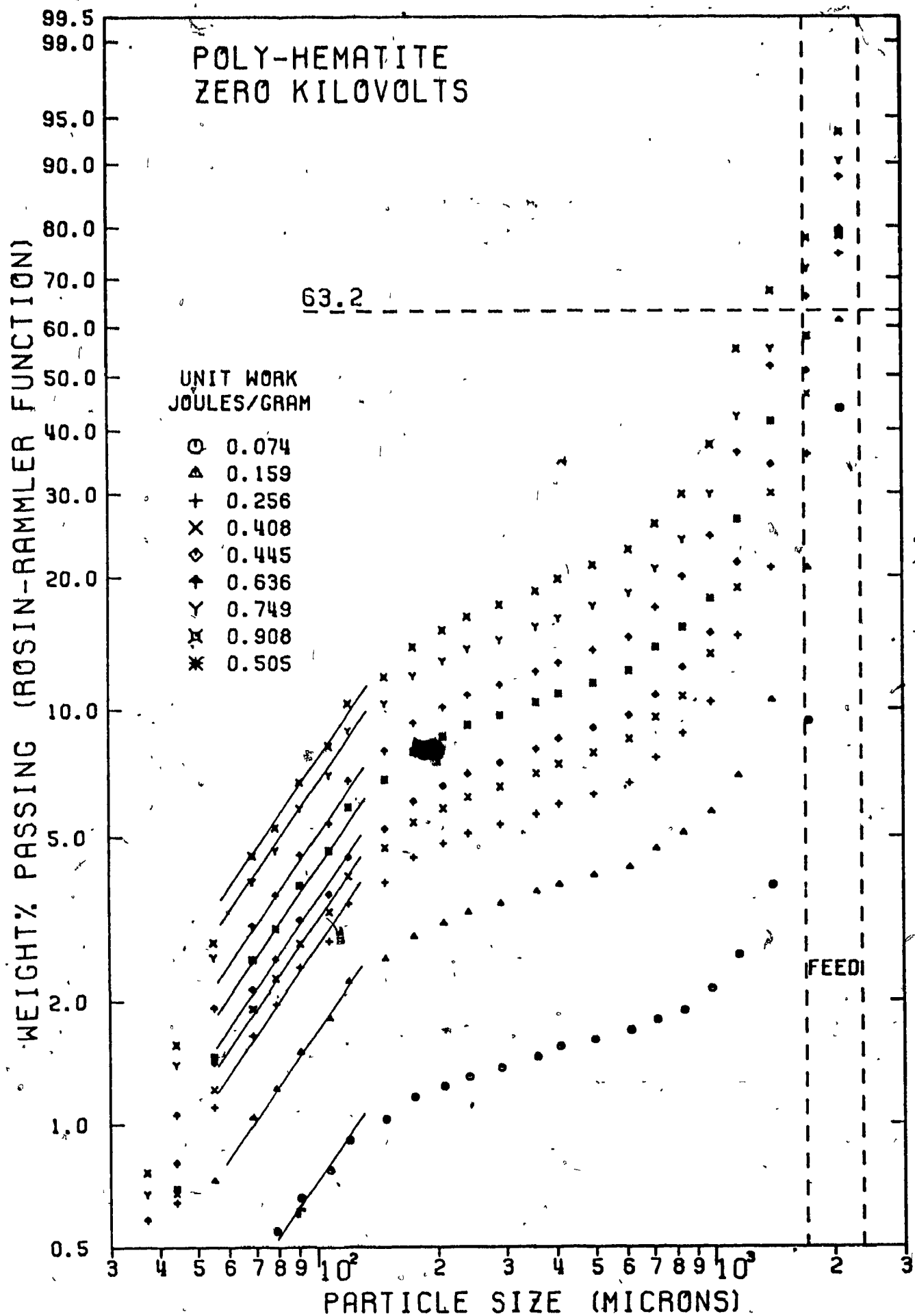


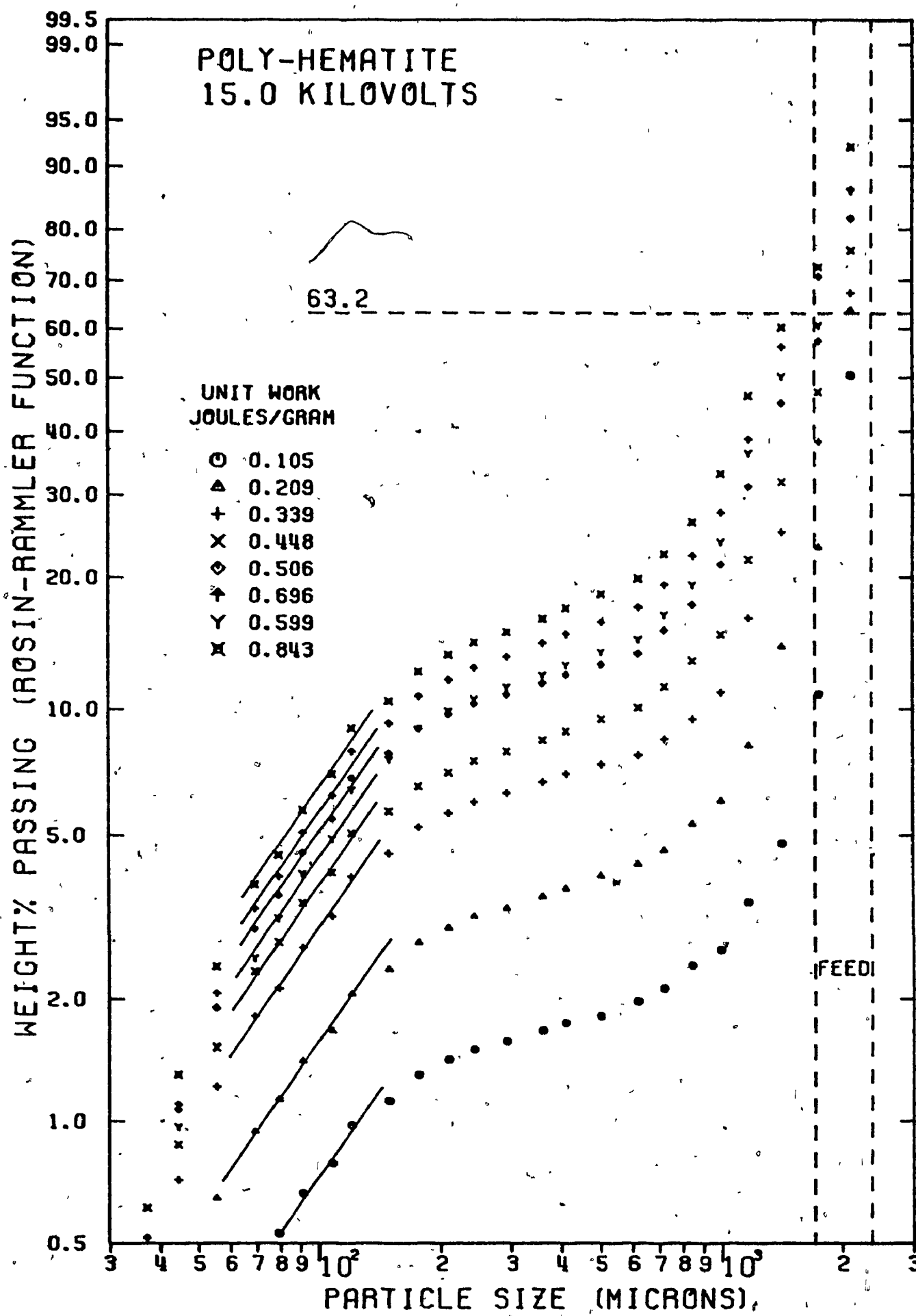


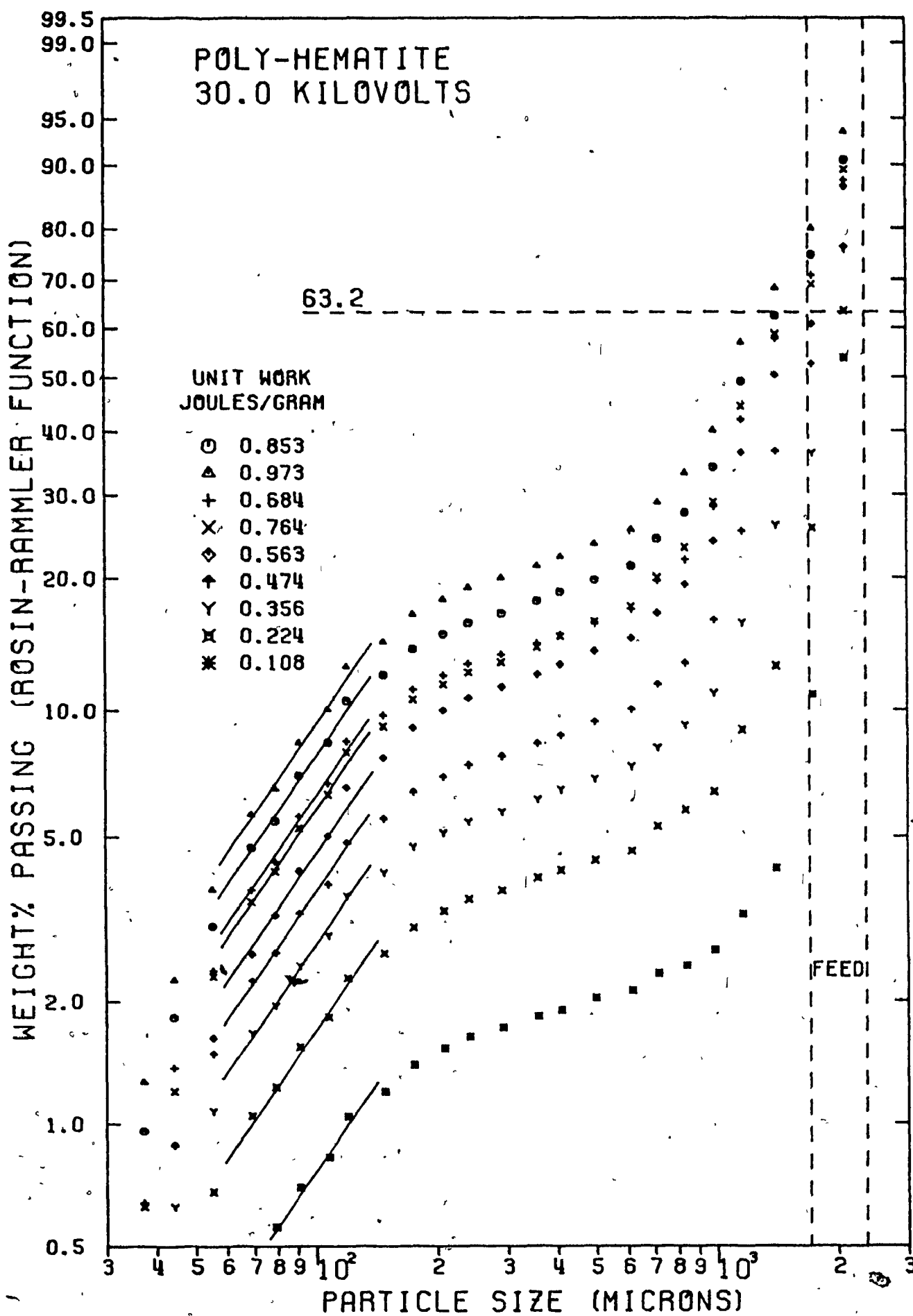


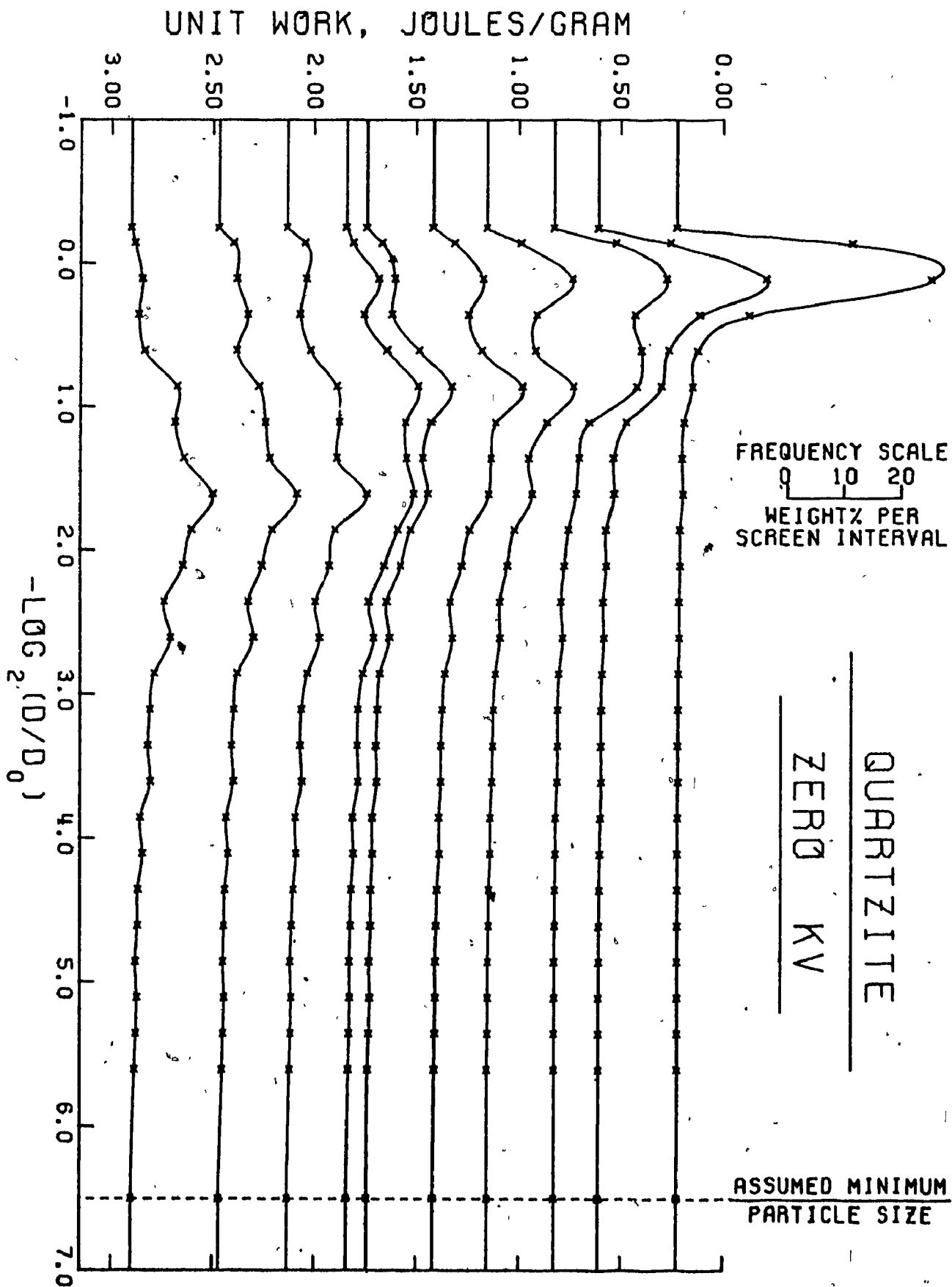




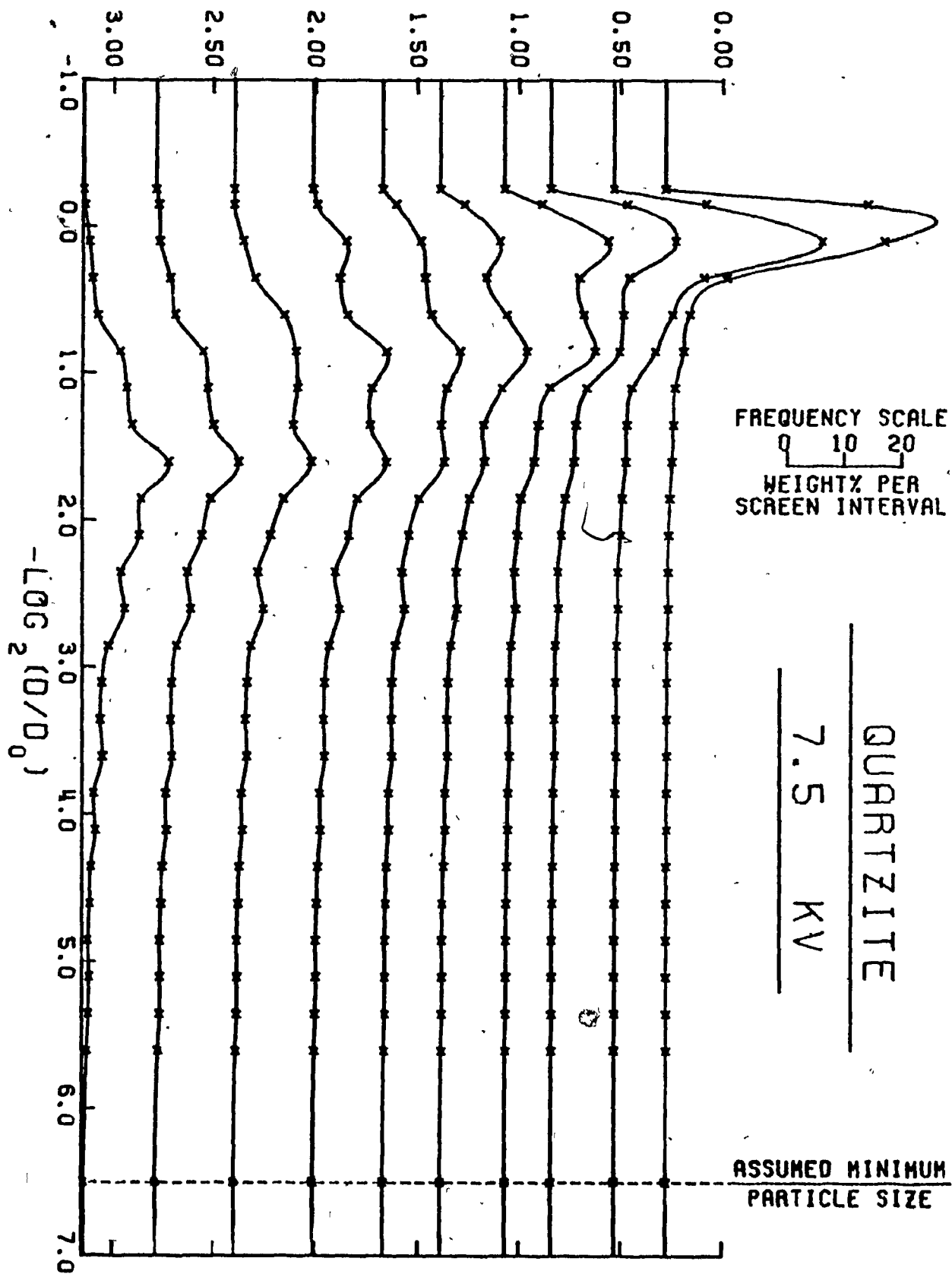




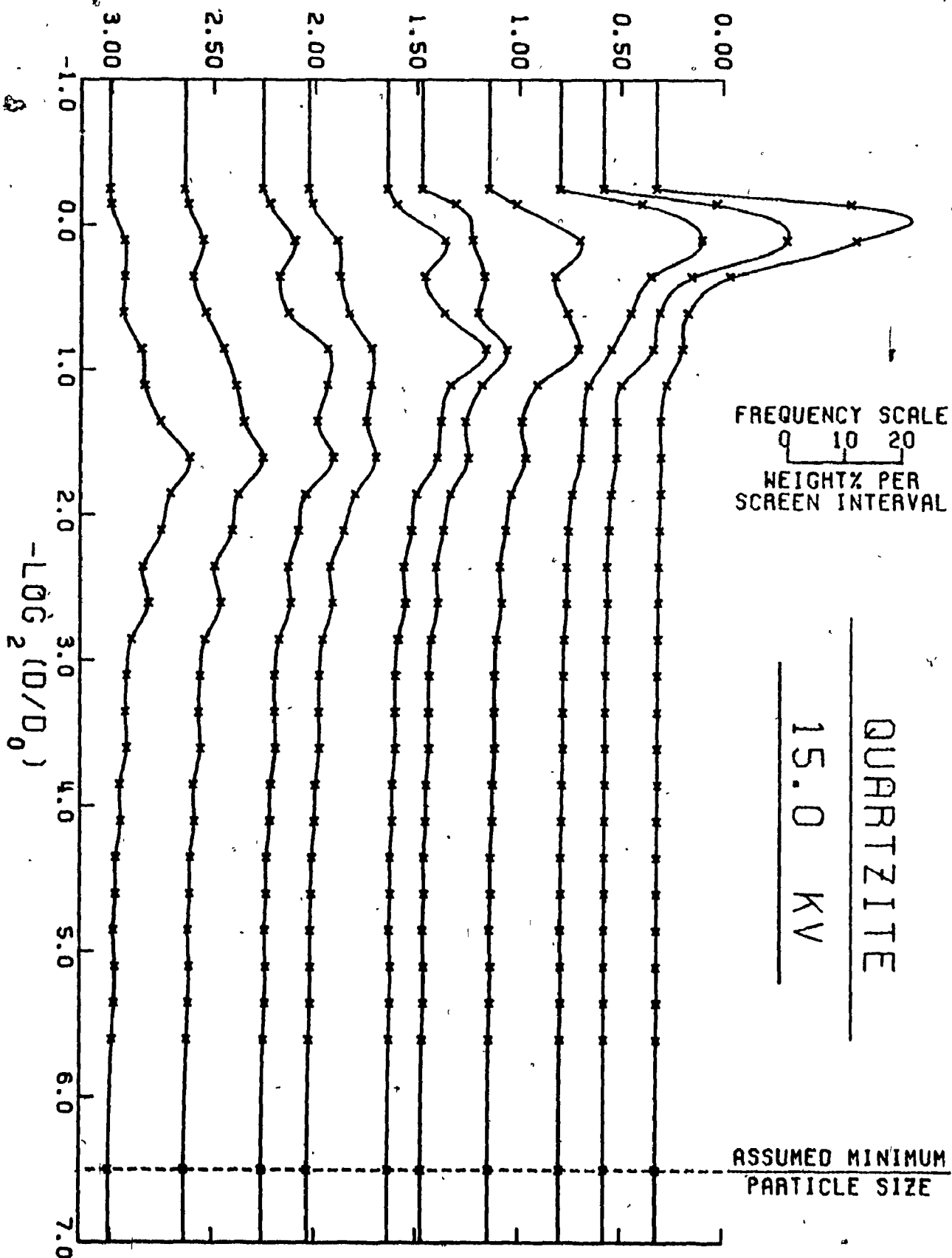


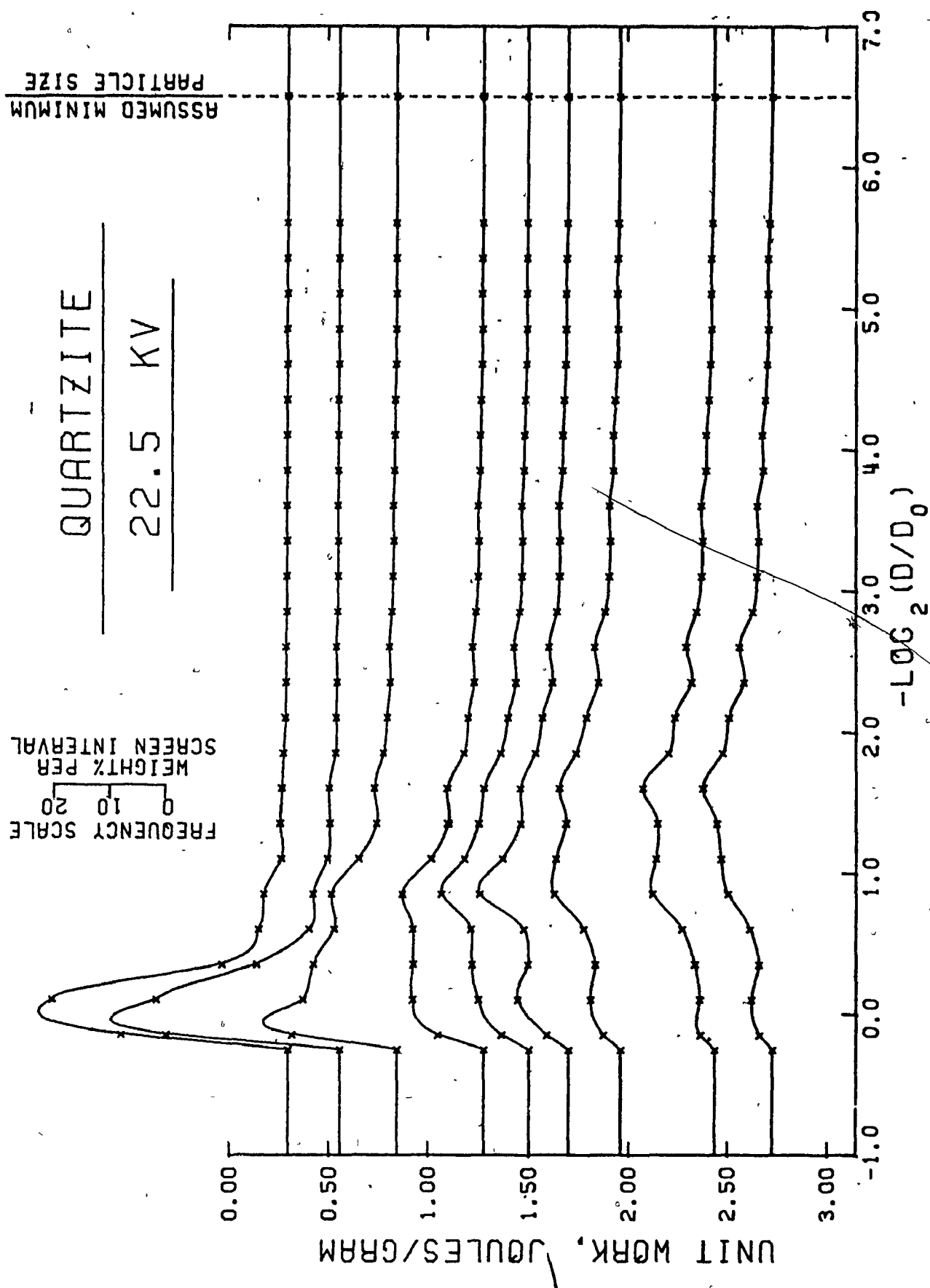


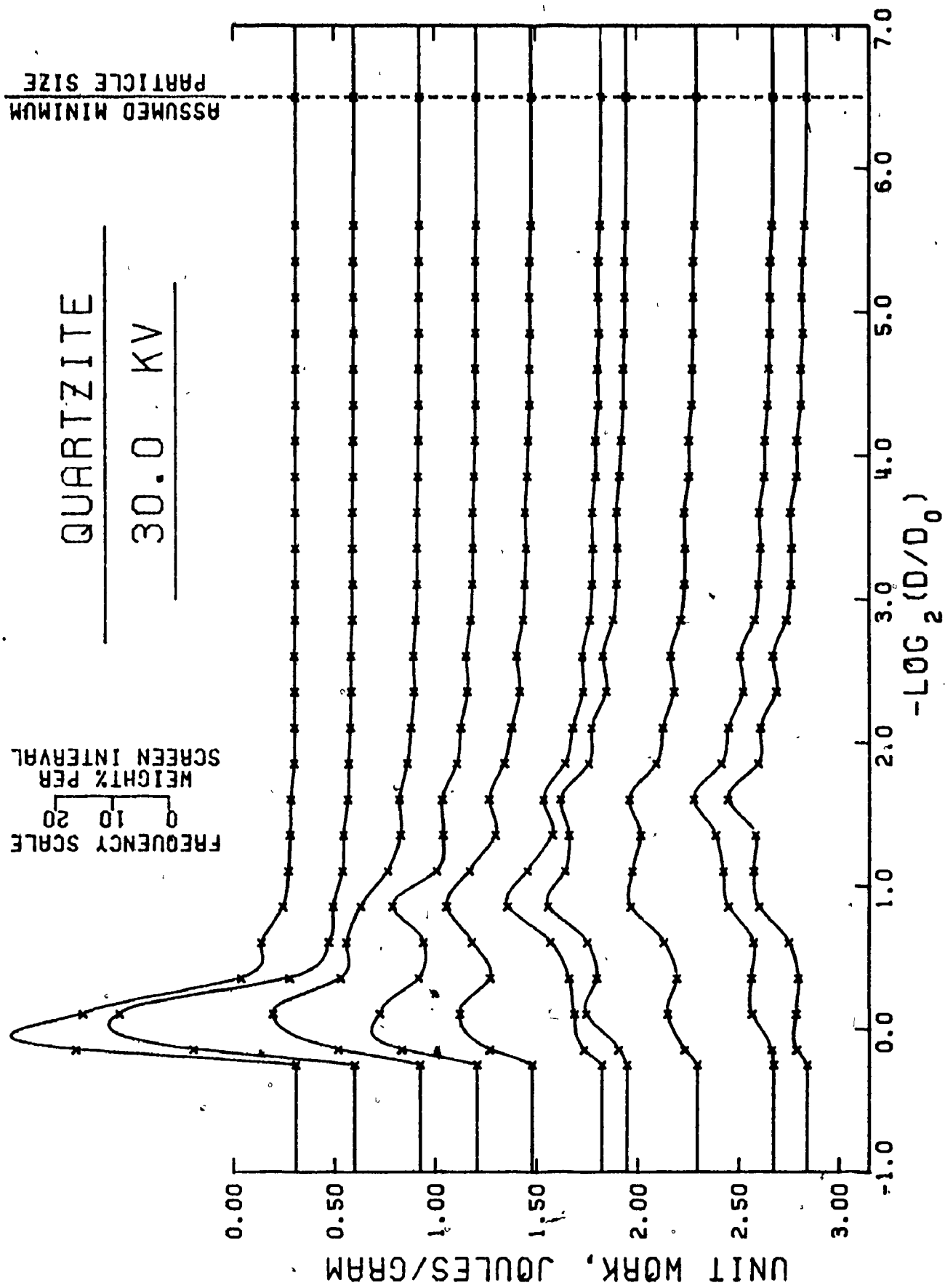
UNIT WORK, JOULES/GRAM

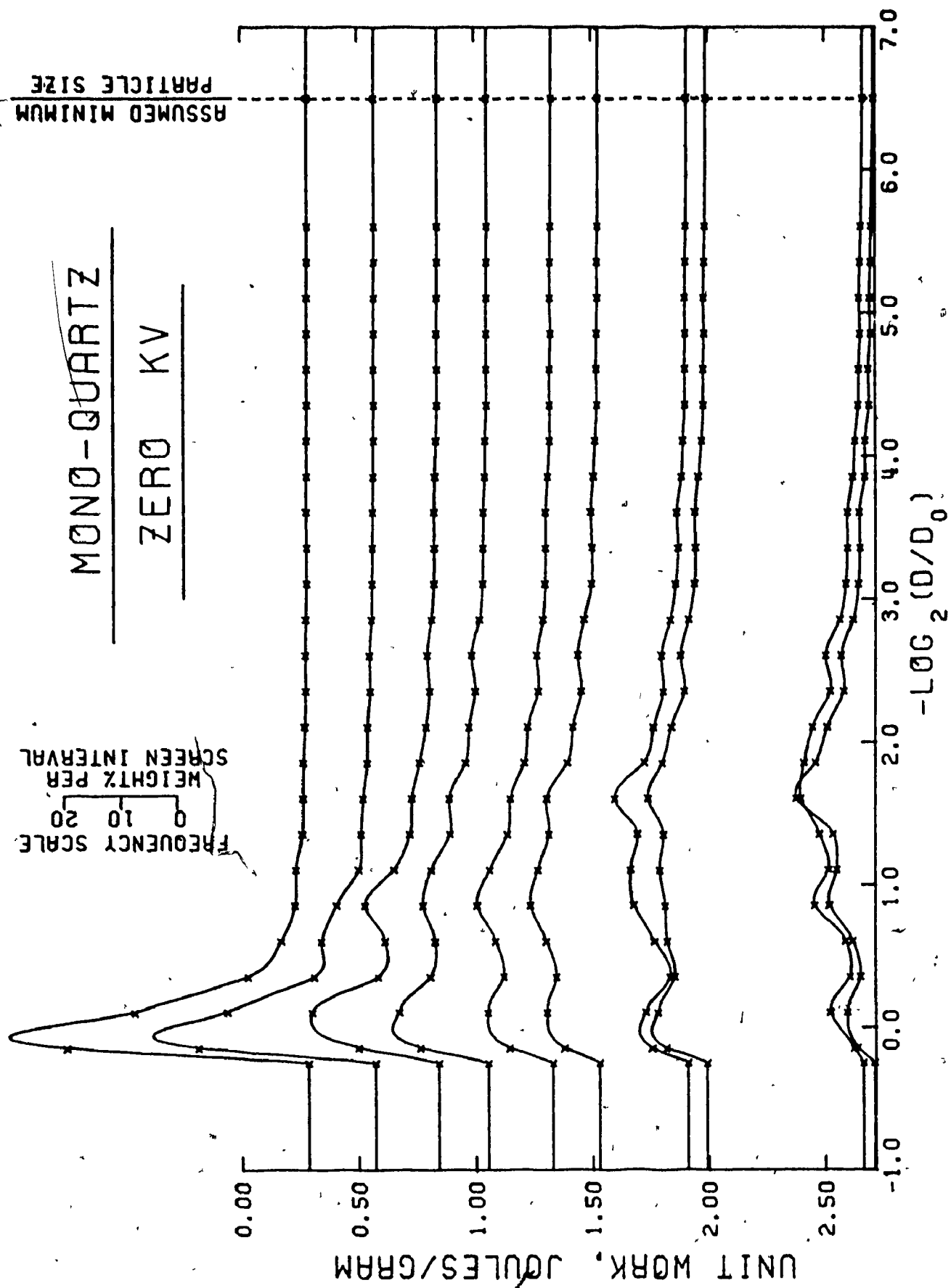


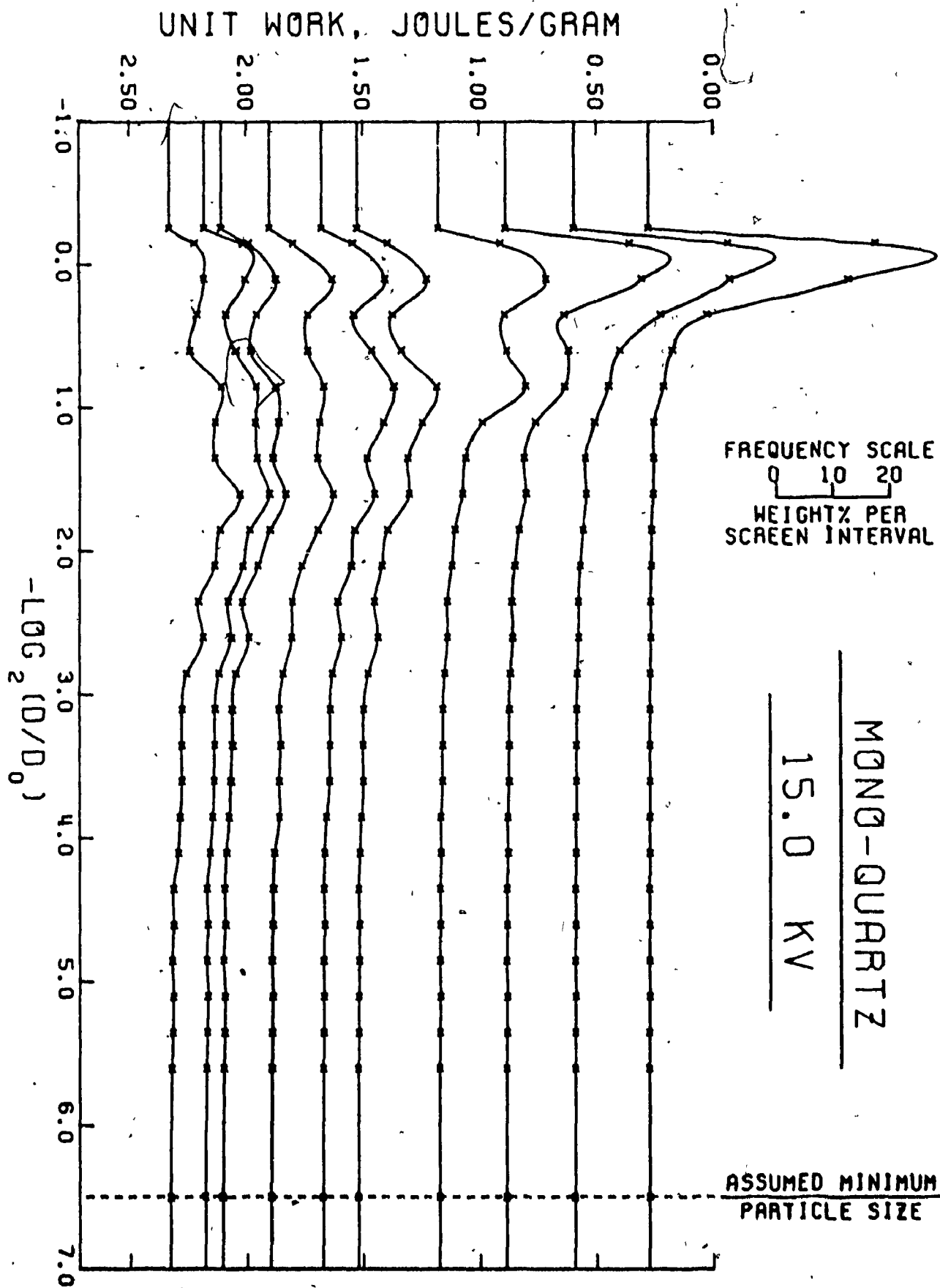
UNIT WORK, JOULES/GRAM

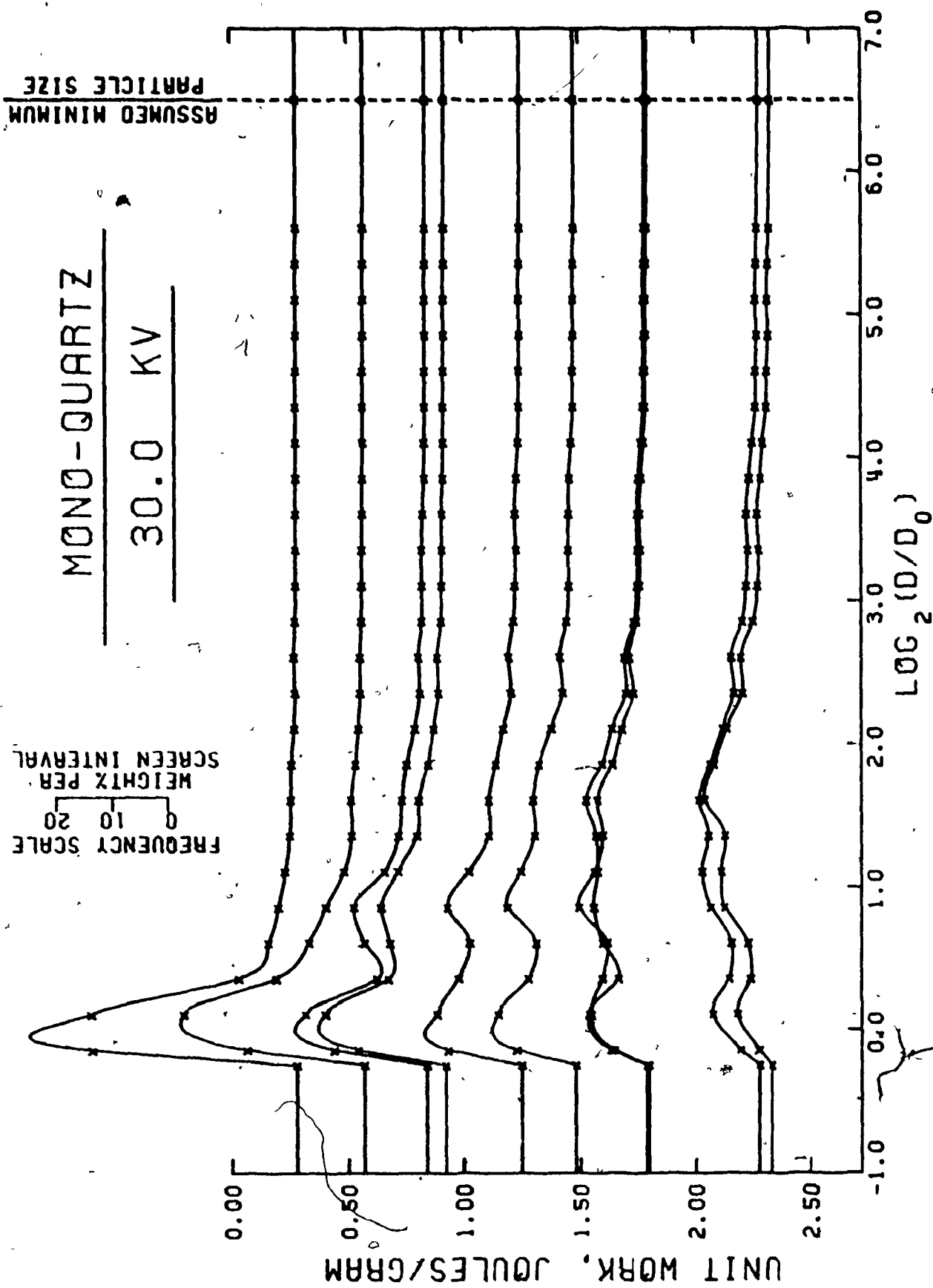


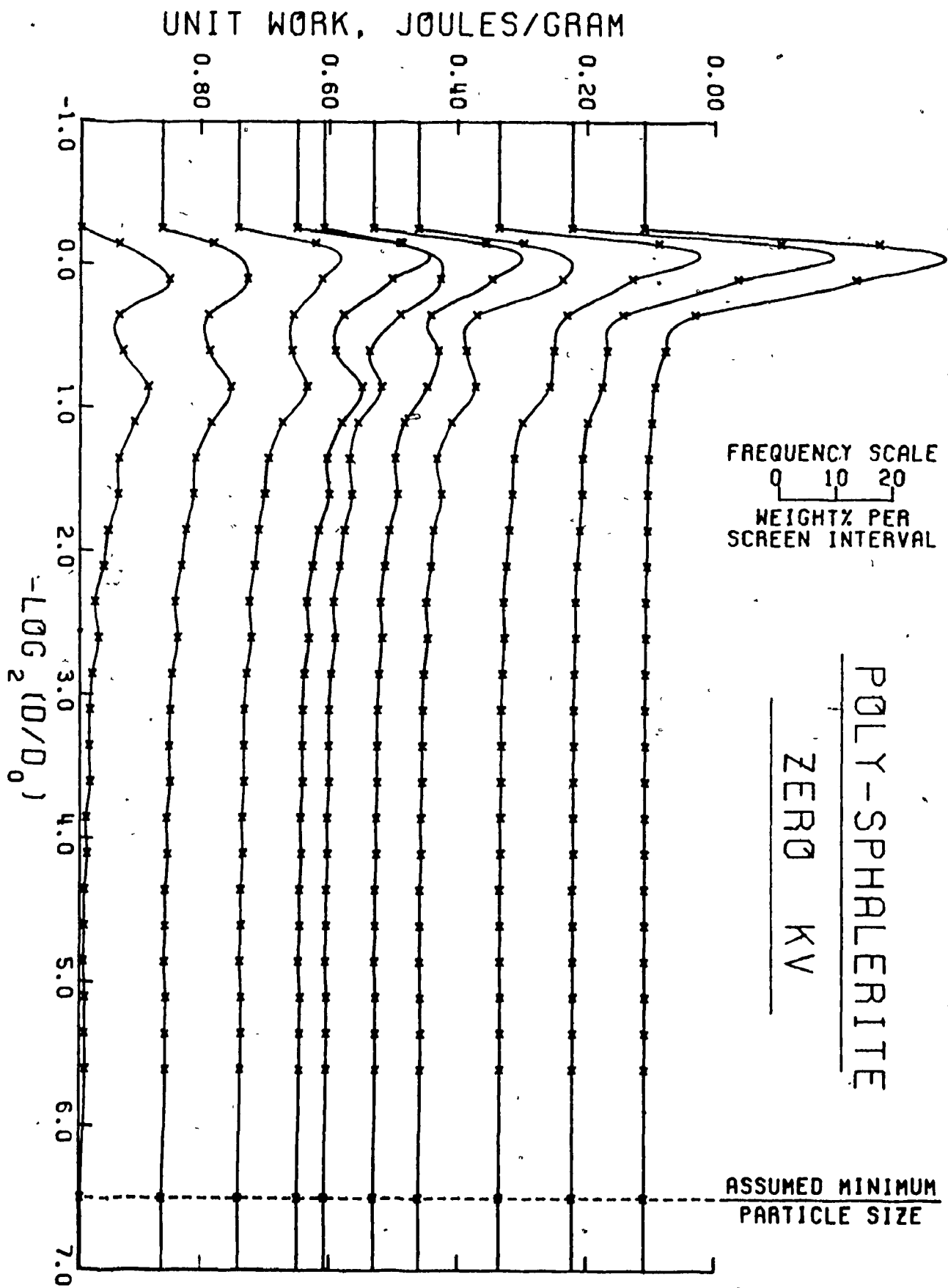




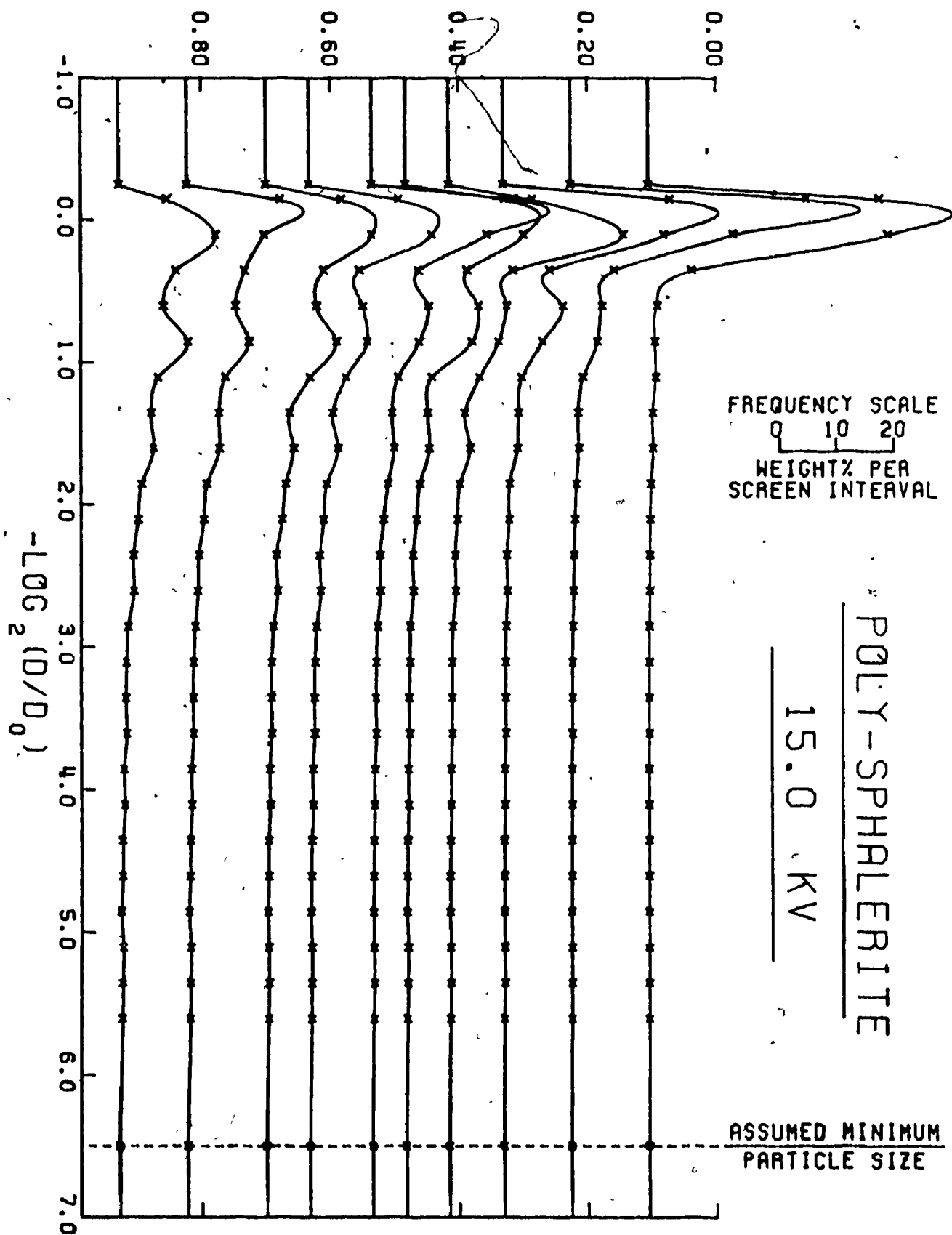




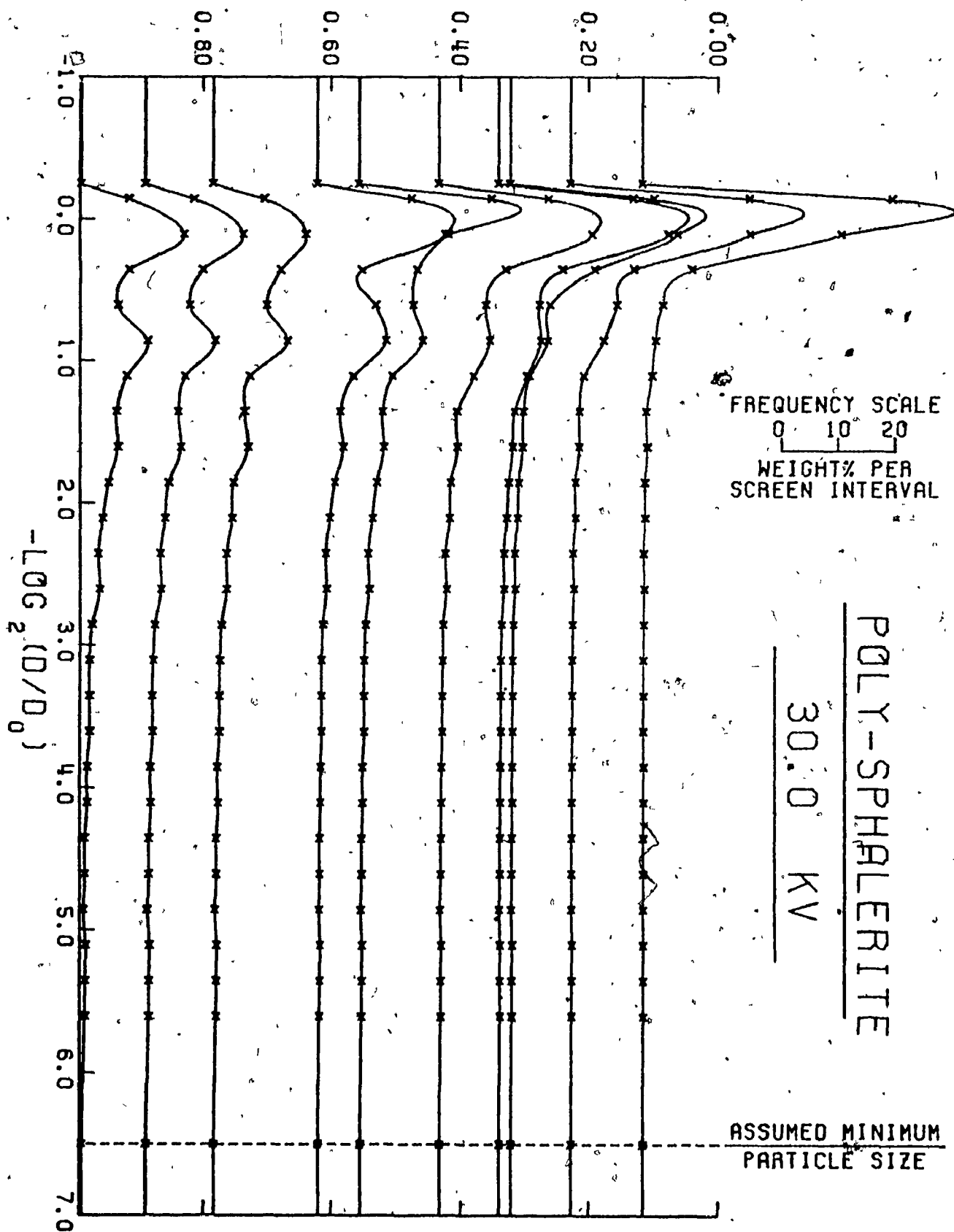




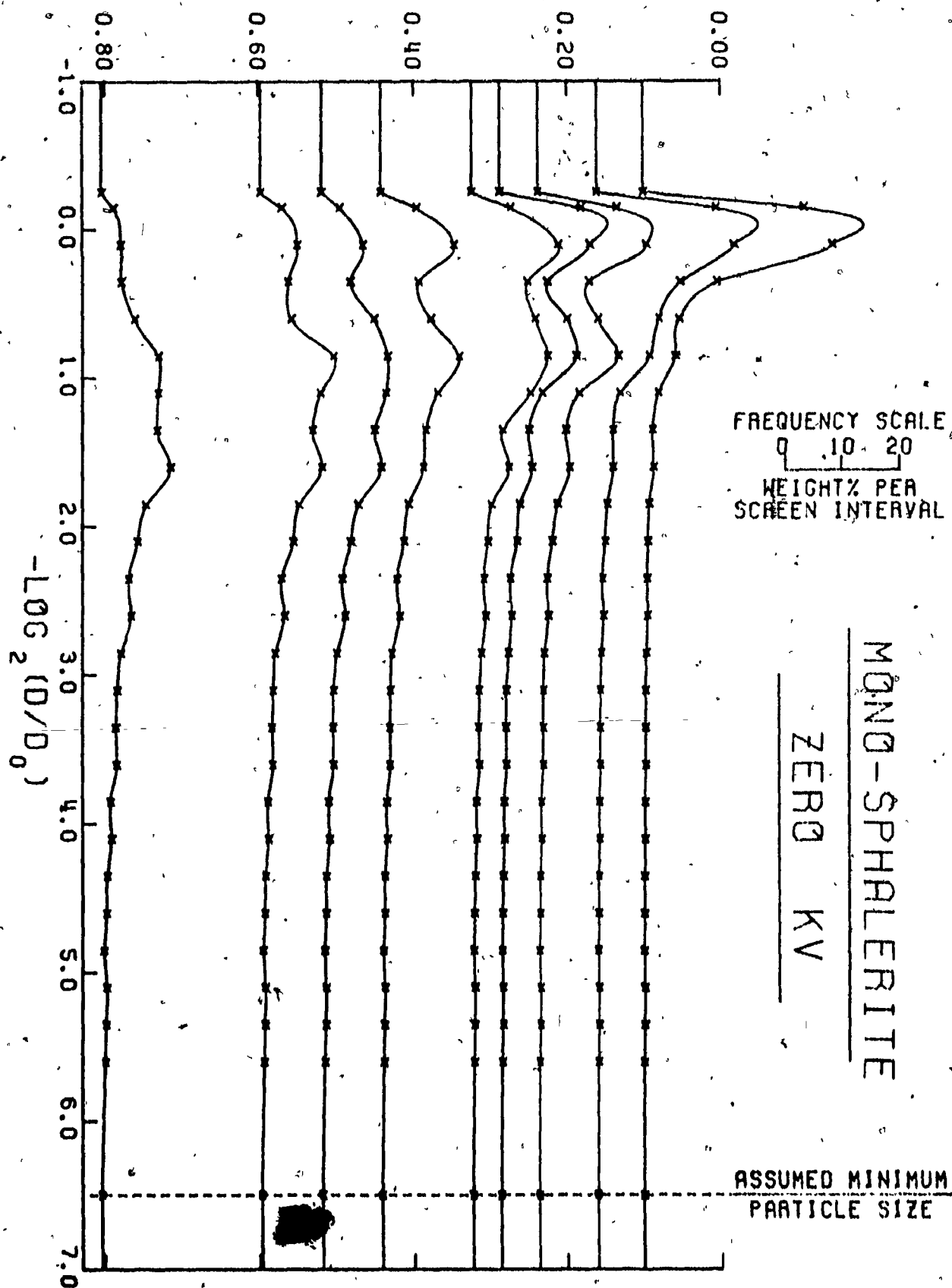
UNIT WORK, JOULES/GRAM



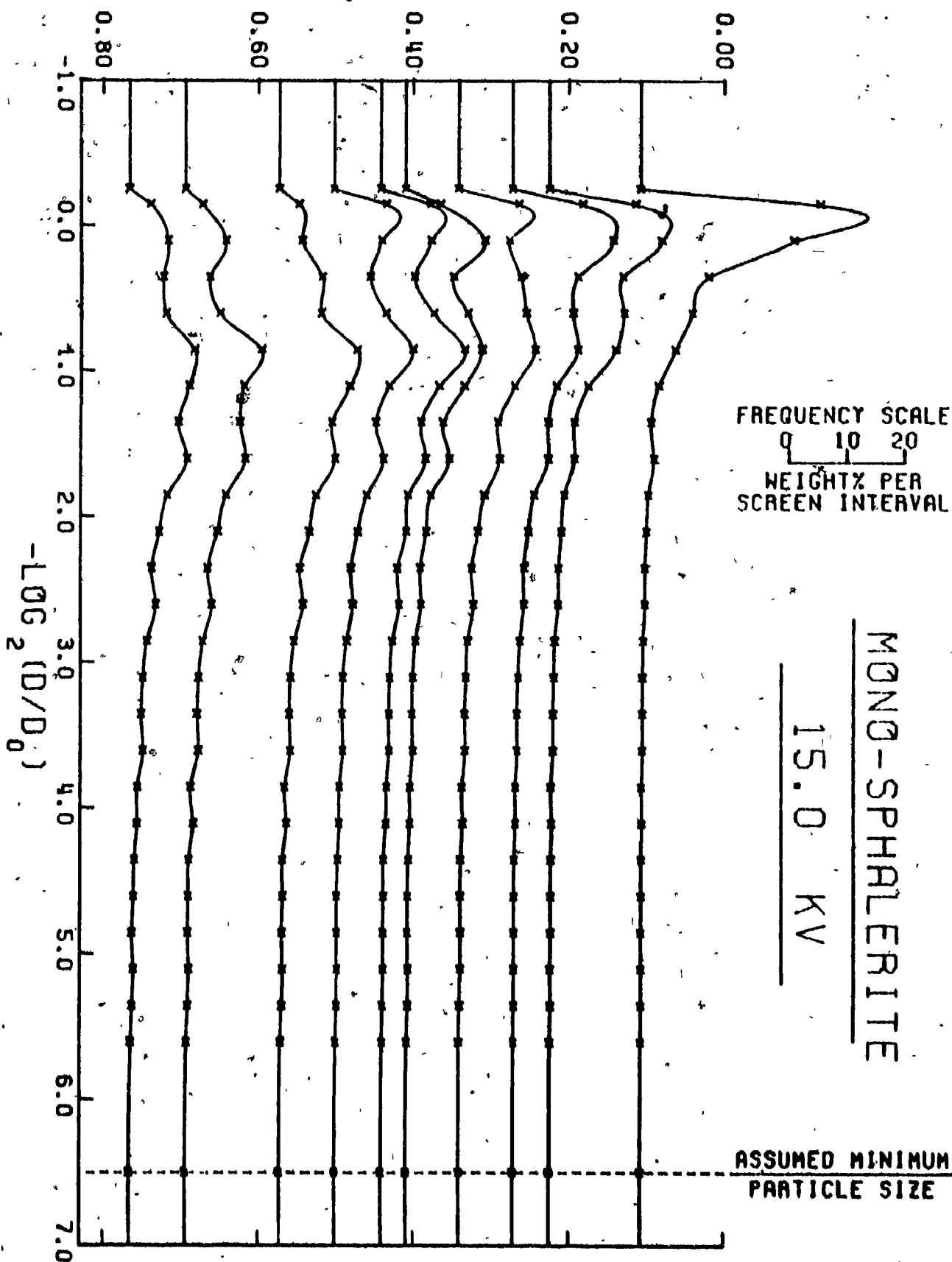
UNIT WORK, JOULES/GRAM



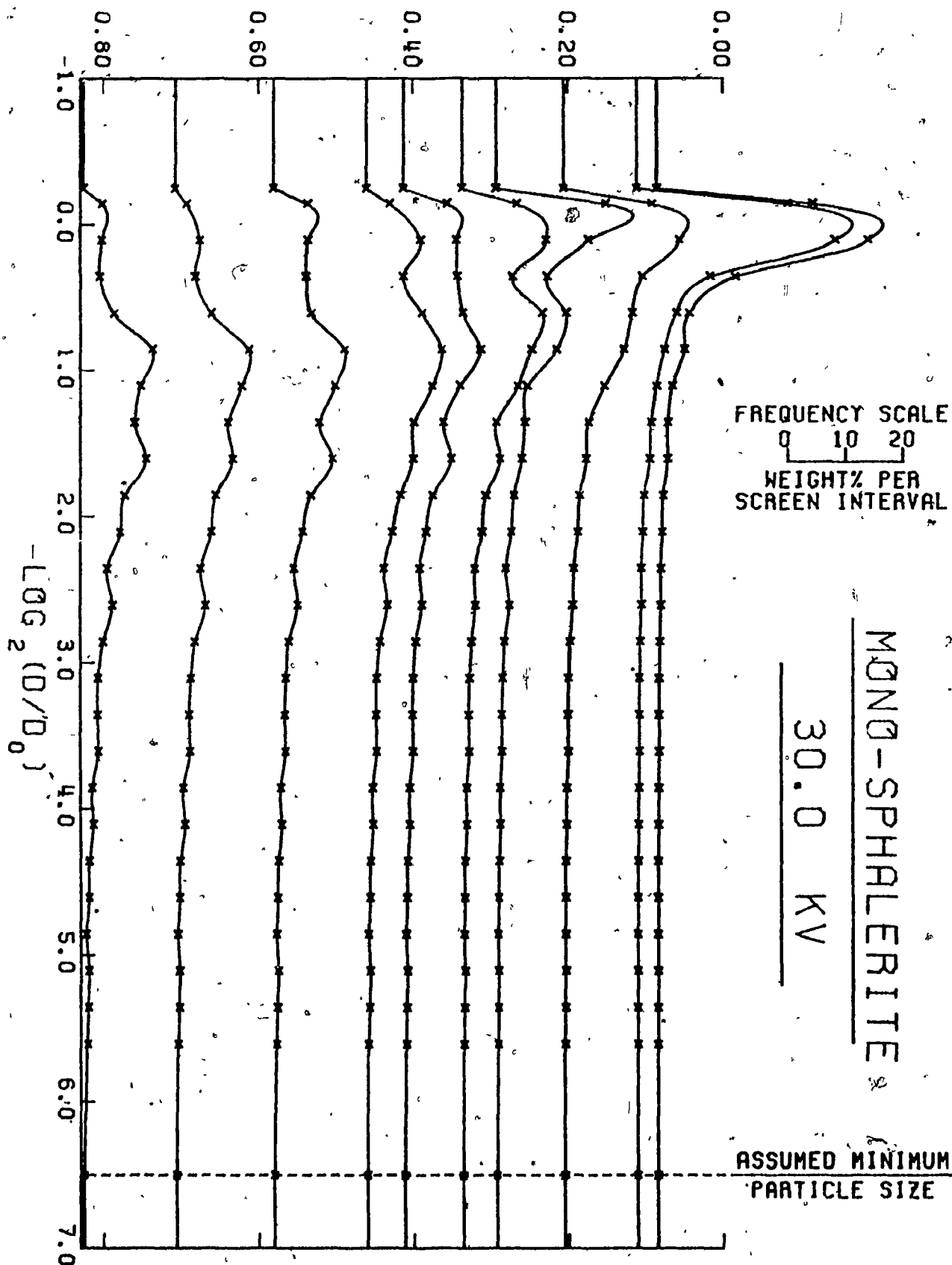
UNIT WORK, JOULES/GRAM



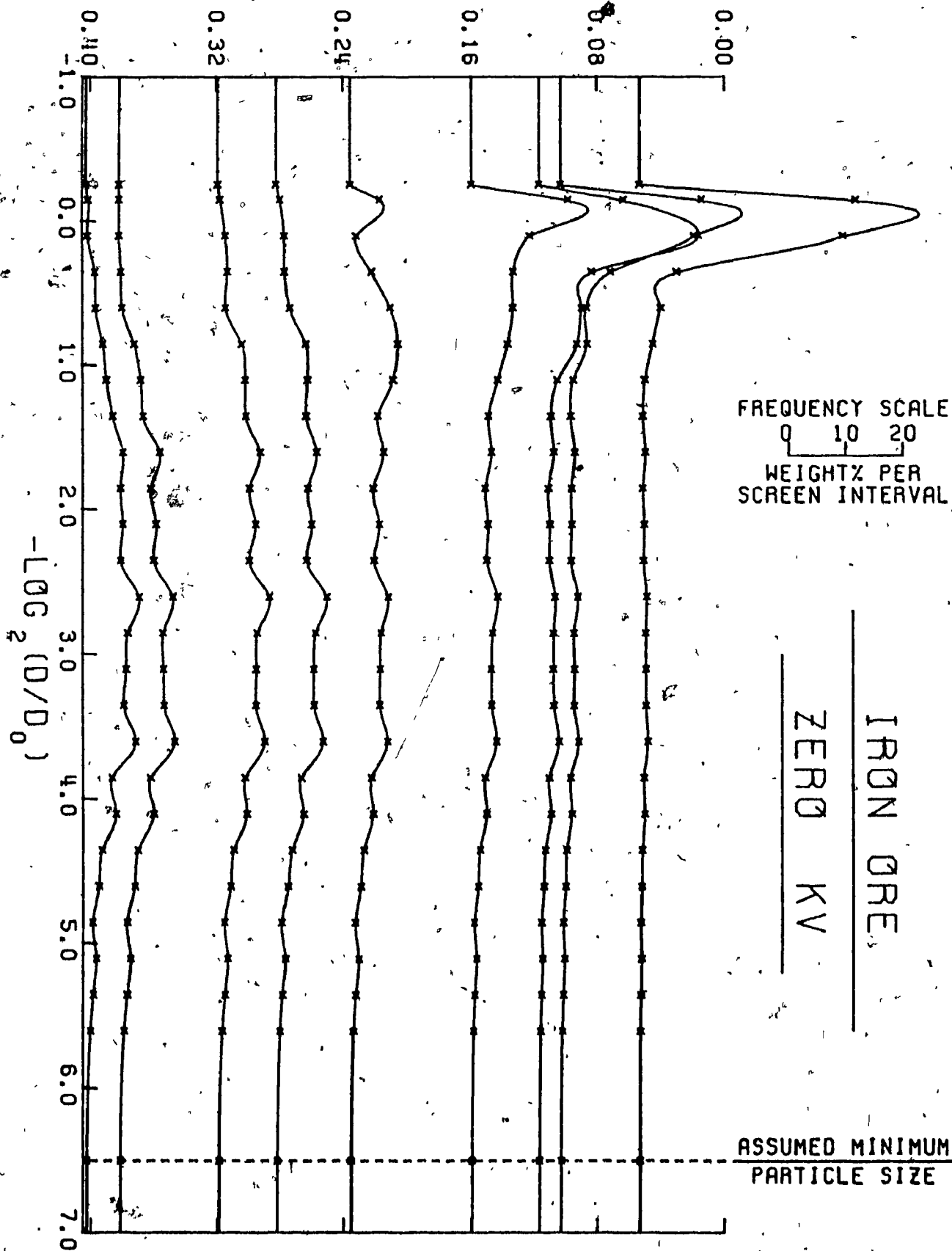
UNIT WORK, JOULES/GRAM



UNIT WORK, JOULES/GRAM



UNIT WORK, JOULES/GRAM

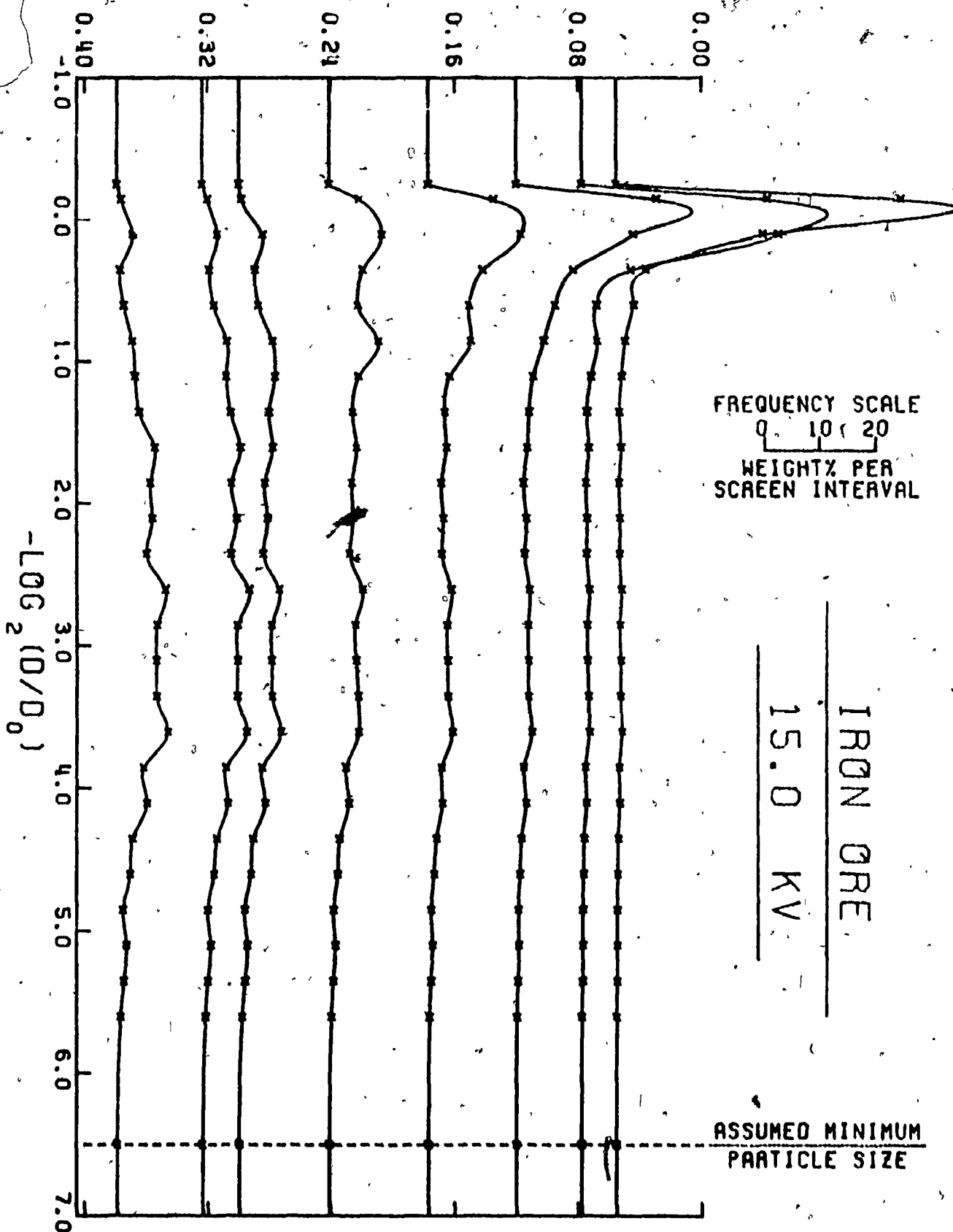


FREQUENCY SCALE
0 10 20
WEIGHT% PER
SCREEN INTERVAL

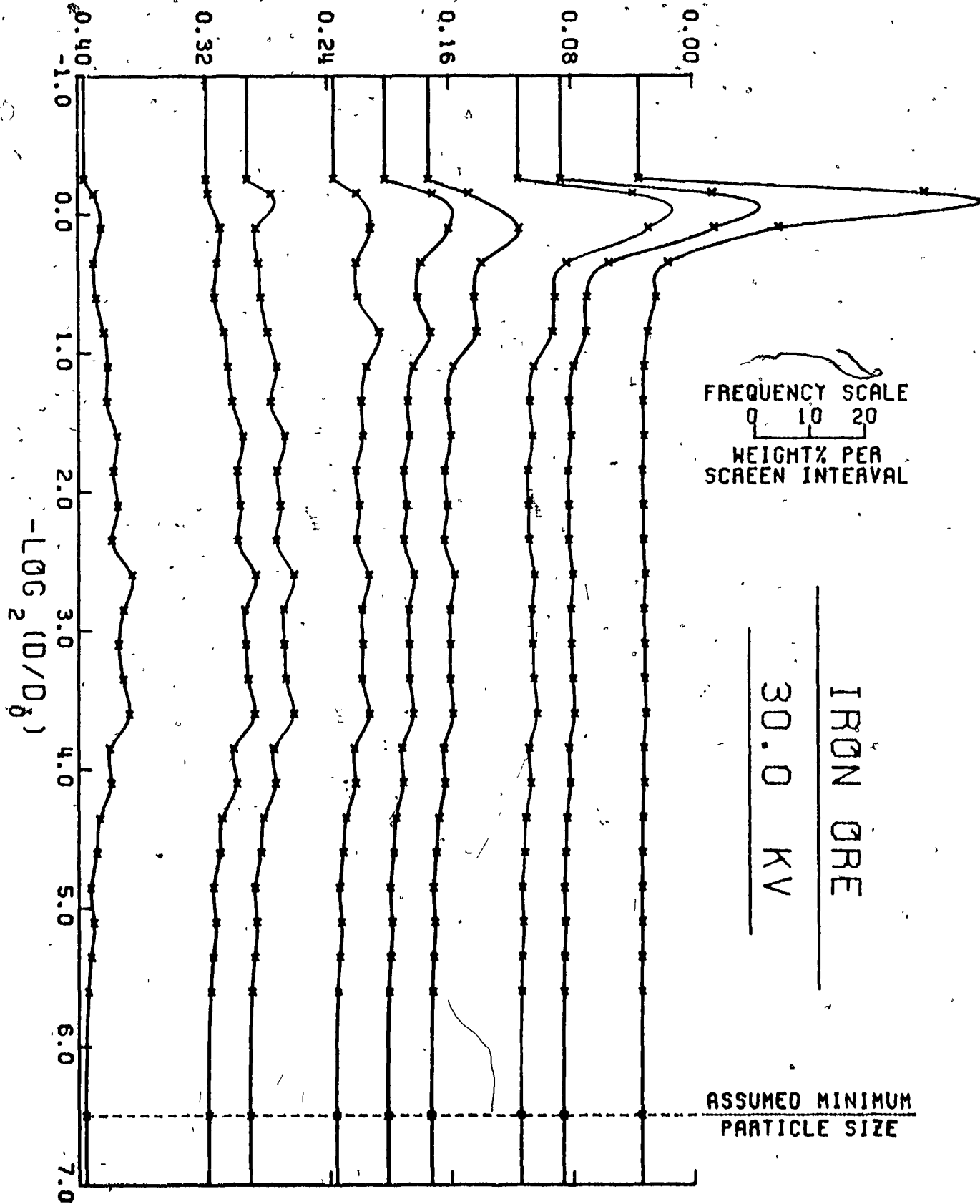
IRON ORE
ZERO KV

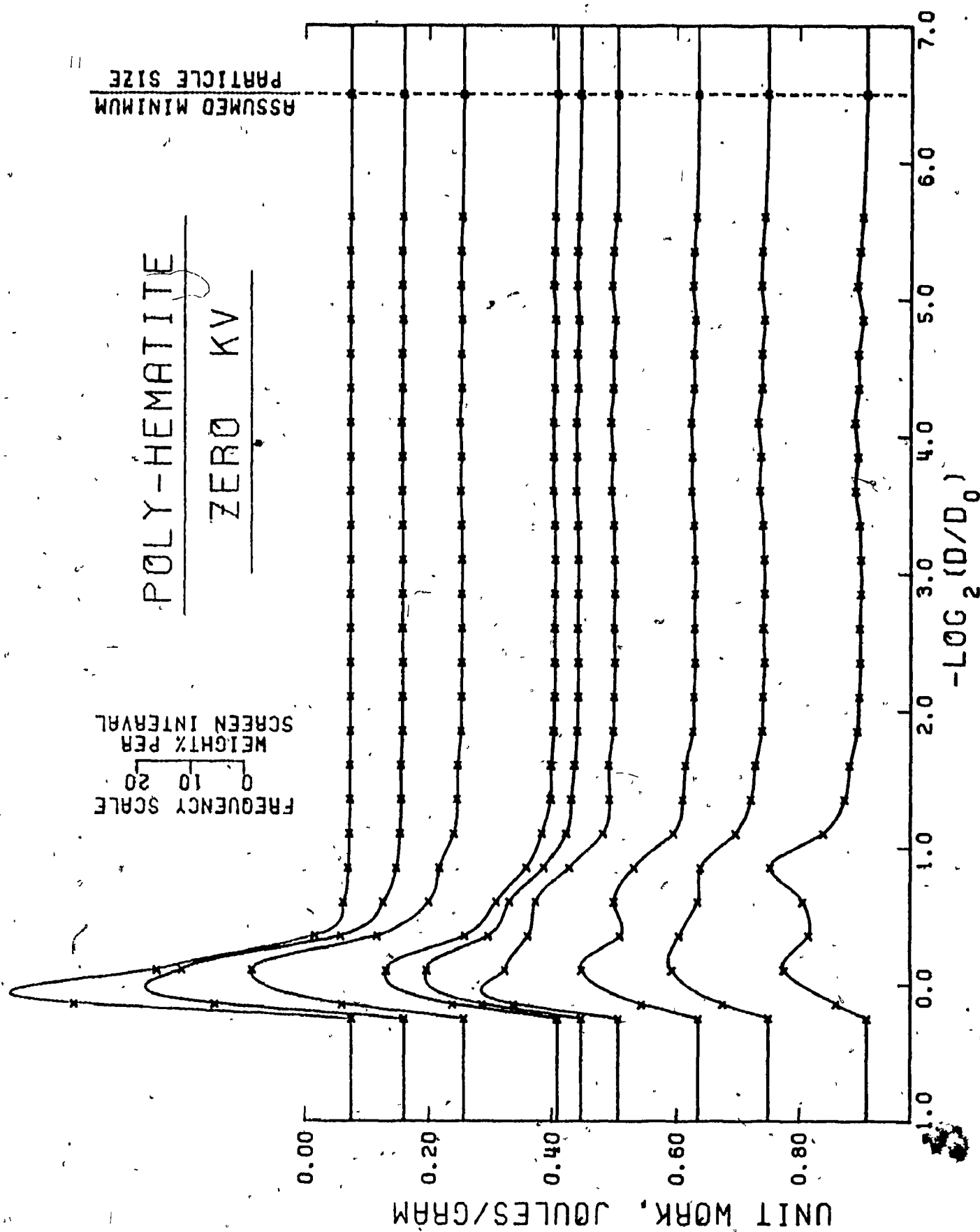
ASSUMED MINIMUM
PARTICLE SIZE

UNIT WORK, JOULES/GRAM

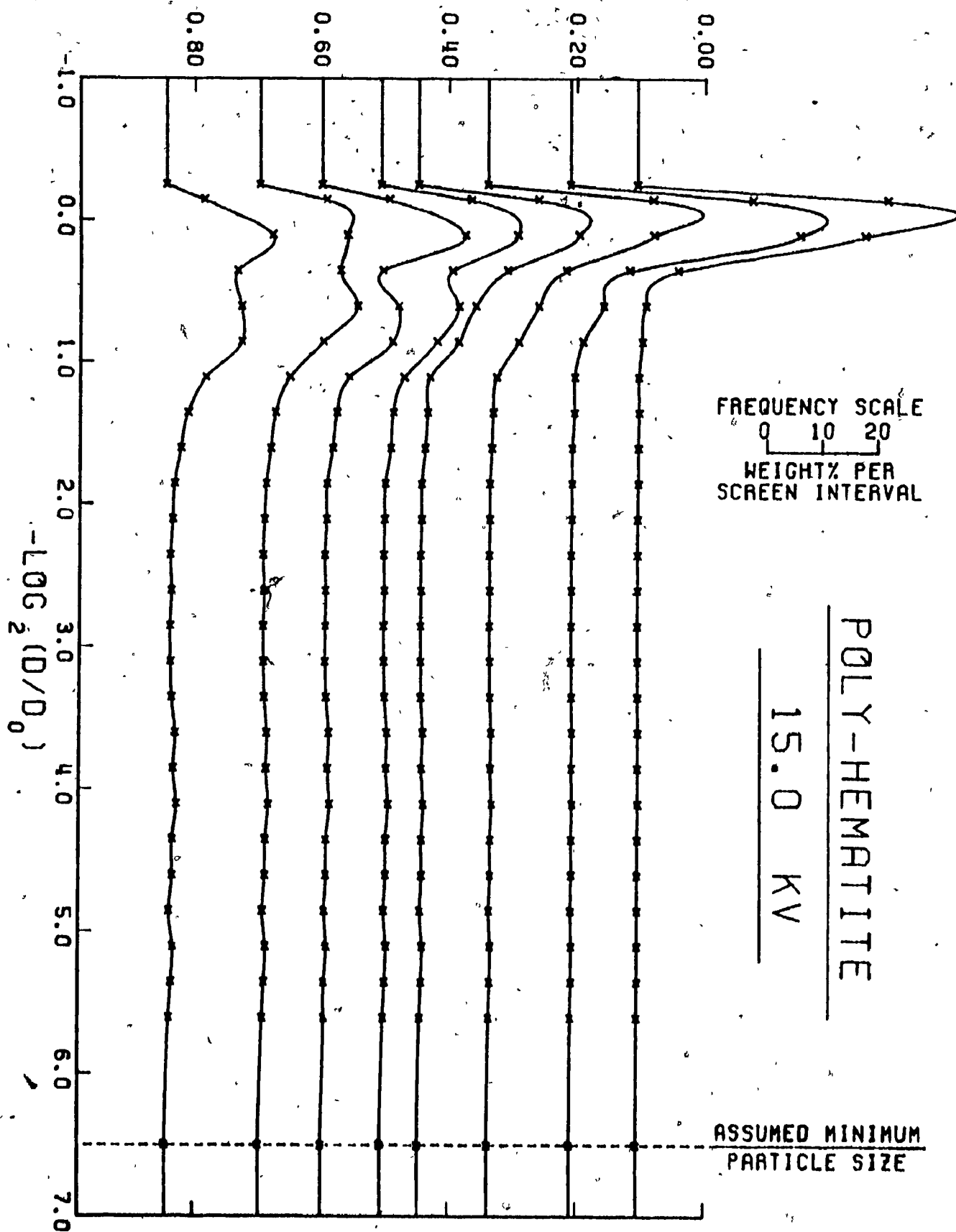


UNIT WORK, JOULES/GRAM





UNIT WORK, JOULES/GRAM

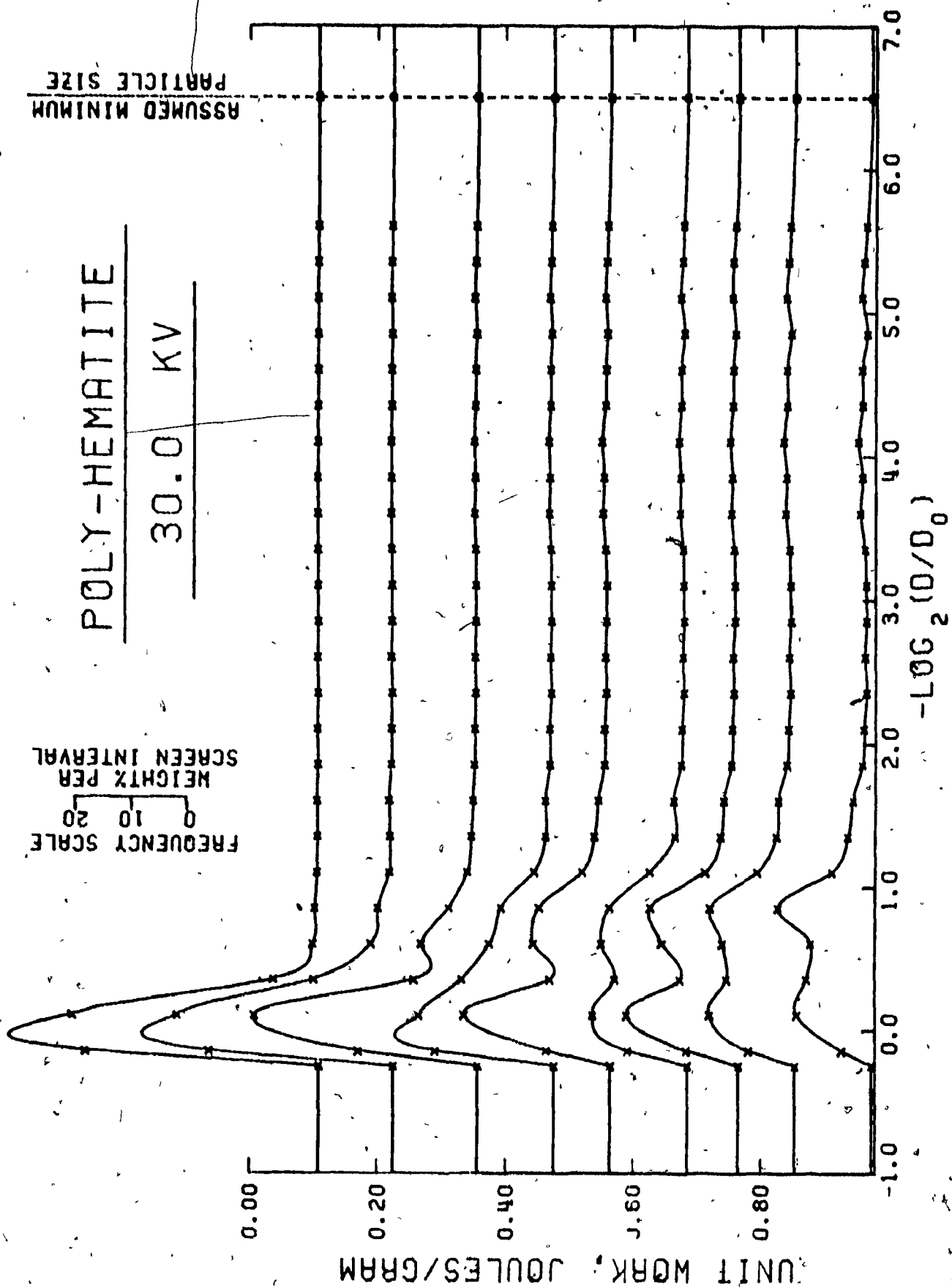


FREQUENCY SCALE
0 10 20
WEIGHT% PER
SCREEN INTERVAL

POLY-HEMATITE

15.0 KV

ASSUMED MINIMUM
PARTICLE SIZE



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