Development of an Approach to the Simulation of Size Reduction/Mineral Liberation for Magnetic Taconite Ore in Tumbling Mills and Its Implementation in a BASIC Computer Program

COLERAINE MINERALS RESEARCH LABORATORY

October 13, 2000

Sponsored by the Iron Ore Coop
and Permanent University Trust Fund

Project#5601107
CMRL/TR-00-16
NRRI/TR-2000/47

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Title: **Development of an Approach to the Simulation of Size Reduction/Mineral Liberation for Magnetic Taconite Ore in Tumbling Mills and Its Implementation in a BASIC Computer Program**

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Executive Summary

In late '98, the Iron Ore Cooperative Research Committee decided to fund a math modeling/simulation center for magnetic taconite concentrator applications at the Coleraine Minerals Research Laboratory of the University of Minnesota.

In a previous association with the iron ore industry, the writer was actively involved in early attempts at modeling and simulating the magnetic taconite beneficiation process. After returning to the University of Minnesota and the iron ore industry in 1997, I attempted to play "catch up" on developments over the past twenty years related to magnetic taconite process modeling and simulation. Based on that review, it was evident that two items that are of particular importance for magnetic taconite process simulation were still missing from the tools available in the software packages for mineral process modeling/simulation. These are: (1) a suitable technique for handling the description of mineral liberation as a function of changes in particle size resulting from size reduction steps in the process and (2) the prediction of the performance of rotating drum magnetic separators as a function of their design and their operating conditions. It was therefore decided that steps should be taken to begin to address these deficiencies very early in the life of the Taconite Concentrator Modeling Center.

The more complex of these two problem areas is the development of a technique for describing how mineral liberation, and the resultant possible early rejection of minerals to waste, can be related to particle size changes resulting from crushing and grinding size reduction. There have been numerous approaches to this subject,[10, 11] but none have taken it to a useful conclusion. Lacking a model of the simultaneous mineral liberation/size reduction operation, some investigators have resorted to the assumption of complete mineral liberation, that is, all mineral species are totally free of other mineral species. This is certainly not appropriate for magnetic taconite, where rejection is dependent on grinding.

The approach reported here begins with an early conceptual model of a binary mineral system's liberation by size reduction, as described by A. M. Gaudin in his 1939 text "Principles of Mineral Dressing." Relationships have previously been obtained to describe the amount of liberation of either component and the quantity/composition of unliberated or "locked" middlings as a function of the "effective" mineral grain size, particle size and the original ore's volumetric composition. The new developments described in this report make use of mathematically derived "directional coefficients" to follow the gradual transfer of material from locked assemblages of dissimilar mineral grains of one composition to other locked particle compositions and eventually to liberated particles of value or waste, as particle size is reduced.

Finally, a BASIC program has been developed and is presented, which permits one to calculate the simultaneous liberation/size reduction phenomena for multi-stage, perfectly mixed, tumbling mills in series. The liberation parameters of a particular crude magnetic taconite ore sample are obtained by collecting Davis tube data for individual particle size fractions and subjecting these to a "best fit" program described in an earlier report. Once the liberation parameters are defined, appropriate breakage rates of the liberated and locked middling particles can be used in combination with the geometric effects of the resultant size reduction on mineral liberation to simulate in a relatively simple and understandable way the complex operation of size reduction/liberation.

This BASIC program must now be translated into an appropriate FORTRAN program for use with the BRGM USIMPAC mineral processing simulation software. It can then be used in concert with other models to simulate the entire magnetic taconite beneficiation process.

This project was partially funded by Iron Ore cooperative Research (about 60%) and by Minerals Research funds derived as income from Permanent University Trust investments.

Size Reduction Mineral Liberation Model

An early visualization of mineral liberation effects due to particle size reduction was presented by A. M. Gaudin[1] in his 1939 textbook "Principles of Mineral Dressing." In the three-dimensional representation, there were two mineral components, value and waste, which occurred in an ore as randomly located, aligned cubic grains of uniform size, as shown in Figure 1. The volumetric fraction of values (head grade) determined the relative proportions of the two components. A cubic fracture lattice, aligned parallel to the grain lattice, breaks the ore into particles of uniform size, which, depending on the ratio of particle size to grain size can be made up of multiple mineral grain fragments or single grain fragments, as shown in Figure 2. The single grain fragment particles and the multiple grain fragment particle for which all grain fragments are the same mineral are the liberated particles of either values or waste, while the multiple grain fragment particles composed of dissimilar mineral grains are the "locked middlings" or unliberated portion of the broken ore.

Relationships were derived by Wiegel and Li[2] for this conceptual model, defining the amount of liberation of values and waste (PB, PA) as a function of mineral grain size (α), volumetric fraction of values in the ore (VB) and particle size (β), as shown in Figure 3. Several additional publications[3, 4, 5, 6, 7] demonstrated the quantitative use of this liberation model for magnetic iron formation ores. Two earlier CMRL reports also dealt with magnetic taconite liberation. One[8] described the expected composition distribution of locked particles as a function of grain size to particle size ratio, and the other[9] presented a computer program for determining the liberation parameters (effective mineral grain size, volumetric fraction of values in the mineralized ore[*] and barren waste dilution), which provide the best fit to Davis tube test and assay results for individual particle size fractions of magnetic concentrator feed material.

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[*] Mineralized ore in this report is visualized as that part of the mined material which was originally closely associated with magnetite mineralization.

Size Reduction Mineral Liberation Simulation Program

An overall assessment of the use of the Gaudin random liberation model (GRLM) for magnetic iron formations, subjective as it may be, is that despite all of the gross assumptions upon which the model is based, it does provide a framework approximating the relationship between important liberation parameters. For this reason, and lacking a better alternative, the GRLM was used as a basis for formulating a BASIC program to simulate size reduction/mineral liberation as achieved in single or multiple stage, fully mixed grinding mills. This program has been constructed in such a way that, in addition to simulating the geometric results of mineral liberation due to size reduction, the effects of different grinding rates for values and waste can be calculated.

The same composition ranges used by several other investigators have been used here, that is, 12 regions, which are defined in fraction by volume terms, as follows:

Index	Range	Midpt	Index	Range	Midpt
0	0 values	0	6	0.5-0.6	0.55
1	0-0.1	0.05	7	0.6-0.7	0.65
2	0.1-0.2	0.15	8	0.7-0.8	0.75
3	0.2-0.3	0.25	9	0.8-0.9	0.85
4	0.3-0.4	0.35	10	0.9-1.0	0.95
5	0.4-0.5	0.45	11	1.0	1.0

Upon consideration of how a size/composition matrix might be used throughout the entire concentration process to follow the progression of liberated and various locked species, it was concluded that one simplification that would be most useful would be to define the average composition of a narrowly bounded composition range as the midpoint of that range, i.e., 0.20 to 0.30 vol fraction values would have a 0.25 composition. The GRLM calculated values required very little shifting of quantities of material from one composition range to another to permit conforming to this simplification.

Conceptually, when carrying out the GRLM calculations, there is only one particle size into which the mineral grain aggregate is broken. In reality, there is an entire spectrum of sizes resulting from size reduction. The way the GRLM has been used is to calculate liberation results for the log mean particle size for each individual screen fraction defined by the normal square root of two Tyler screen size progression. One is then making the assumption that the particles in a resultant narrow size range have a composition spectrum similar to the uniform, cubic particles generated by the GRLM calculations.

Directional Coefficients

A size/composition matrix has been constructed from GRLM calculations using the square root of two size progressions, as shown in Table 1. It is obvious that as particle size becomes smaller, there are more liberated values and waste created and a corresponding decrease in the amount of each of the various locked particles. There is a requirement for conservation of overall volume and conservation of the two individual mineral components' volumes in passing from one particle size to the next smaller particle size. Despite these constraints, it is not possible to tell what portion of the volume in one composition range of a coarse particle size moves to another composition range of a finer size, except for the special case that, once particles are liberated, they remain liberated.

If one defines "directional coefficients" as the multipliers Q(I,II,J), which indicate the fraction of a coarser size (J) / composition (I) going to a next finer size (J+1) / composition (II), it is possible to convert this into a linear programming (LP) problem, which conceivably has numerous solutions, where the directional coefficients are the unknowns. When working with GRLM calculated results (adjusted to meet midpoint criteria described above) for particle sizes smaller than the mineral grain size, the general solution form had non-zero values for Q(I,I-3,J); Q(I,I,J); Q(I,I+3,J). The quantity of those particles going to higher and lower composition ranges were defined by the individual component material balances. The LP solution objective in this case was to maximize the directional coefficients that keep material in the same composition range as it passes from a coarser size to a finer size, Q(I,I,J).

When attempting to find simple LP solutions for particle sizes larger than grain size, it was necessary to look at fourth root of two size intervals (two size intervals per square root of two size change). For particle sizes in the range eight (8) times larger than grain size to two times larger than grain size, the non-zero directional coefficients were in general Q(I,I-1,J); Q(I,I,J); and Q(I,I+1,J); and for the particle size two times larger than grain size to particle size equal to grain size, the non-zero directional coefficients were Q(I,I-2,J); Q(I,I,J); Q(I,I+2,J). For particle sizes larger than eight (8) times grain size, there is no discernable liberation achieved [Q(I,I,J) = 1] and for particle sizes smaller than 1/22 grain size, directional coefficient Q(I,I,J) for the same composition reaches a constant value from size to size. The pictorial representation of non-zero directional coefficients for these three particle size regions is shown in Figure 4.

LP solutions were obtained for GRLM calculations with volumetric fractions of valuable mineral of 0.2, 0.5 and 0.8. The LP results for the same composition directional coefficients were then used to obtain regression equations for each composition range as a function of the ratio of effective mineral grain size to particle size. Since in all cases there were only two other composition ranges with non-zero directional coefficients (one higher and one lower in valuable mineral composition), these directional coefficients can be directly calculated from the same composition directional coefficient by material balance, using the midpoint compositions of the new ranges. The regression equation multipliers for these directional coefficient equations are given in Table 2. All of these calculations do provide a size/composition distribution, which is a reasonable approximation to that obtained from GRLM calculations, as shown in Table 3 for a 20% valuable mineral ore.

It should be pointed out that the equations for the directional coefficients are specific for each of the ten locked particle composition ranges, or, in essence, for their midpoint value. The amount of material changing composition to lower and higher values is dependent on the quantity in that composition range as well as the value of k, the effective mineral grain size to particle size ratio of the product particle size. The individual directional coefficients are, therefore, not dependent on an overall process stream composition, but the effect of the process stream composition is reflected by the amount of each composition interval that is changing. The use of this approach should permit one to simulate size reduction/liberation even when a part of the "natural" size/composition distribution is removed, i.e., by particle size/specific gravity classification or by magnetic separation. What is being suggested by this approach is that, to a reasonable approximation, the subsequent liberation of a specific values fraction middling interval, i.e., 0.2 – 0.3, is dependent on particle size and not original head grade.

Coarse Locked Middlings

As mentioned earlier, a previous report[8] provided information on the compositional distribution of locked middling particles for the GRLM when the particle size is smaller than or equal to the mineral grain size. Initially, in the development of this size reduction/mineral liberation simulation program, it was thought that there would be little need to be able to describe composition distributions for locked middlings when particle size is larger than mineral grain size. This was quickly found to be wrong. As an example, the particle sizes of interest for magnetic taconite concentrator simulation range from about 4 mesh (4700 μm) to passing 500 mesh (27 μm), while the GRLM's effective mineral grain size for magnetic taconite is in the 28 to 65 mesh region (200 to 500 μm).

It therefore became necessary to put together a BASIC program that would allow estimation of the compositional distribution of larger locked particles. This program, LRGRAND.BAS, was used to generate the composition distribution for some 80,000 particles for each fourth root of two size progression from a grain size to particle size ratio of 0.125 to 1.00. The larger of these particles corresponds to a containment of up to 729 mineral grains and fragments thereof. There is virtually no liberation with particle sizes larger than this.

These data were then used together with those presented in the previous report[8] to develop the directional coefficients appropriate for ores with volumetric feed grades of 20%, 50% and 80% of valuable mineral.

Program Calculation Sequencing

The size reduction mineral liberation simulation program was initially written with the size reduction calculation proceeding down from coarse to finer sizes (12 fractions plus a pan fraction) in a specific composition column, starting with liberated waste and ending up with liberated valuable mineral. After that program was made operational, it was realized that the alternative procedure of carrying out the calculations for a particular particle size row, going from composition to composition and then to the next finer row, etc., offered several advantages:

1. The calculation could be set up more as an iterative procedure rather than requiring program storage of numerous equations for each size fraction.

2. As coarse feed particles were broken, the resultant product could be immediately allocated to the appropriate finer composition range for subsequent further size reduction when the calculation reached that size/composition location.

3. This procedure would permit a rapid change in the number of size intervals handled by the program by just changing the upper limit of the size index counter.

4. The procedure provides the opportunity to apply different grinding rates for the two mineral species and the ten locked particle composition ranges. This is detailed in Figure 5. An example of the results of differences in grinding ratios (RAB) for the two minerals is presented in Table 4, where the effect on product size is minimal, because the overall grinding rate for a particular size stays the same, but the effect on size fraction composition is quite significant.

When working with size reduction/mineral liberation, the calculation of size/composition of the ground product necessitates keeping track of the quantity and composition of what reports to the pan/composition locations. This is different than with conventional size reduction simulation, where what ends up being attributed to the pan size fraction is the difference between the total quantity of feed and the product quantity for all other size intervals. In the existing program, the liberation results of the pan fraction are what would be calculated based on a particle size smaller by one squae root of two factor from the particle size of the next larger screen interval.

The current program is set up to simulate numerous (up to 20) perfectly mixed grinding stages with varying residence times and varying grinding rate ratios for waste to values* for each stage. Batch milling can be simulated by using numerous, short duration, perfectly mixed milling stages. The program results file provides a summary of directional coefficients for each particle size, and a size/composition distribution for the feed to and product from each perfectly mixed grinding stage.

Use of the Size Reduction/Liberation Program

Following are several demonstrations of the use of the size reduction/liberation (SL) simulation program. It should be remembered, however, that almost all of the results presented are in volumetric terms, since the liberation phenomena is geometry-based.

Demo 1 - A substantial amount of batch grinding and Davis tube testing of size fractions was presented in an earlier report on integrating size reduction and mineral liberation modeling.[4] A portion of these Davis tube data were used with an earlier reported[9] program (LIBFIT4.BAS) to obtain liberation parameters for use in the SL simulation program. These parameters were: effective mineral grain size 1200 μm, 30% Fe_3O_4 by volume in the ore (100%) and an additional 25% volume of barren waste dilution, yielding a head grade of 24% by volume. This sample came from the magnetic portion of the Benson Mine located in Star Lake, NY, which was closed in the early to mid- 1970's. A size/composition distribution was calculated for the batch grinding feed

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[*] Being able to vary grinding rate ratios from stage to stage is of questionable value in the program, but is currently available.

using another recently developed program ADDON.BAS, which uses the directional coefficients to simulate liberation for a wide range of particle sizes, encompassing the feed size distribution.

A set of volumetric breakage functions was obtained from another laboratory ground sample of crude taconite and was kept constant for all simulation runs described here. The overall volumetric grinding rates were determined for all particle sizes from several sets of taconite plant samples around the ball mill. Although none of these values were for the batch milled sample, they were considered typical for magnetic taconite and suitable for the purpose of demonstrating the program capabilities.

The batch grinding data for various grinding times indicated a tendency toward preferential grinding of magnetite over waste. This is demonstrated in Figures 6 through 8, where the actual volumetric concentrate grade, feed grade and the quantity of magnetic concentrate is plotted against the logarithm of an individual fraction's particle size.

Similar graphs of simulation results are presented for volumetric concentrate grade, feed grade and quantity of magnetic concentrate, for waste to magnetite grind rate ratios of 1.0 (Figures 9 through 11), 0.67 (Figures 12 through 14) and 1.5 (Figures 15 through 17). In this case, the totally liberated waste mineral would be considered magnetic tailing. Concentrate quantity and quality would therefore be based on what is left after that rejection, either size by size or for the entire distribution.

In the grind rate ratio of 1.0 data, the lack of individual points is due to the plotting of several points on top of each other. The data are for batch mill feed and the products after 1, 2, 3, 4 and 5 minutes of grinding. For the two sets of simulations for selective grinding, there is a gradual departure from the non-selective plots, with individual size concentrate grade getting lower, feed grade getting lower in coarse sizes and higher in fine sizes, and concentrate quantity getting lower when the grinding rate ratio of waste to magnetite is 0.67 and with individual size concentrate grade getting higher, feed grade getting higher in the coarser sizes and lower in the finer sizes and concentrate quantity getting higher for a grinding rate ratio of waste to magnetite of 1.5.

Demo 2 - A more recent set of data was collected when magnetic separators at the Minntac Mine were sampled to obtain commercial operating data. In this case, the Davis tube data was generated on individual size fraction samples of rod mill discharge. When these data were subjected to the liberation parameter fitting program, LIBFIT4.BAS, the best fit parameters were as follows: effective mineral grain size of 374 μm, 22.23% magnetite by volume in the mineralized ore (100%) and 26.09% of additional barren waste dilution volume. The results of this fitting procedure are shown in Table 5. These liberation parameters were then used with a program ADDON.BAS to generate the composition distribution appropriate for each size fraction in the feed to the size reduction process, as shown in Table 6. Simulations were made for a series of batch grinds from 0 to 7.5 min in 0.5 min intervals with a grind ratio of 1.0. These data have been used to indicate the total quantity and quality of magnetic concentrate which would be recovered given (1) a perfect separation of all magnetic particles from non-magnetic particles and, (2) a separation in which all particles containing less than 10% magnetite by volume were rejected as tailing. In the plots shown in Figures 18 through22 and summarized in Table 7, the results for the integrated size distribution are given, rather than for individual size fractions.

Figure 18 indicates how the amount of material passing 270 mesh (53 μm) increases with grinding time. Figure 19 compares the magnetic concentrate grade that would be obtained with either a perfect capture of all magnetite containing particles (CGO) or a capture of all particles containing more than 10% magnetite by volume (CG1), as a function of grind passing 270 mesh. Figure 20 presents the quantity of magnetic concentrate corresponding to the two situations depicted in Figure 19. Figure 21 indicates the calculated magnetite grade (%volFe_3O_4) of the tailing when all particles containing less than 10% by volume magnetite are rejected, while Figure 22 indicates the magnetite recovery loss corresponding to the tailing grades of Figure 21.

A series of graphs (Figures 23 through 27) are also presented for these same data, reflecting the conversion of the data used for Figures 18 through 22 into weight and assay terms. The specific gravities used were 5.2 for magnetite and 3.0 for waste; the waste minerals had an SiO_2 content of 65.36% and a non-magnetic iron content of 15.84%. The size distributions are the same in volume and weight terms because the ratio of waste to magnetite grinding rates is 1.0 (no selective grinding). In addition to simulation results indicating concentrate grades and weights, there are also indications of concentrate SiO_2 contents (Figure 25) and how it changes as particle size gets finer.

One set of computer simulation printouts are provided in Table 8A and B, which compare the volumetric and weight distributions for the same simulation test, a single stage perfectly mixed mill with a residence time of 4.0 minutes and a ratio of waste to magnetite grinding rates of 0.67.

Basic Computer Program – SL10.BAS

A copy of the size reduction/mineral liberation program described above, SL10.BAS, is listed as Table 8. A copy of both the BASIC program and an executable TurboBasic version is available on the enclosed floppy disk. Execution time for the TurboBasic version with a 3-stage tumbling mill and 13 size fractions is about one minute on a 133 Khz (~ 5 yr old) computer.

A copy of the ADDON.BAS program to generate the initial mineral composition distribution for a plant simulation is also included on this floppy disk.

References

1. Principles of Mineral Dressing, McGraw-Hill, by A. M. Gaudin, pp. 70-77, 1939.

2. A Random Model for Mineral Liberation by Size Reduction, by R. L. Wiegel and K. Li, SME Transactions, No. 238, pp. 179-189, 1967.

3. Liberation of Magnetite Iron Formations, by R. L. Wiegel, AIME Transactions, Vol. 258, No. 3, pp. 247-256, 1975.

4. Integrated Size Reduction-Mineral Liberation Model," by R. L. Wiegel, AIME Transactions, Vol. 260, No. 2, pp. 147-152, 1976.

5. Simulation of Magnetic Taconite Concentration Processes, by R. L. Wiegel, Ph.D. Thesis, Department of Mining and Metallurgical Engineering, University of Queensland, Brisbane, Australia, 1976.

6. Mathematical Model of Mineral Liberation, Chapter 9, (pp. 187-202) of Mineral Crushing and Grinding Circuits – Their Simulation, Optimisation, Design and Control, by A. J. Lynch, Elsevier Scientific Publishing Company, 1977.

7. Application of Process Modeling to Taconite, by R. L. Wiegel, Society of Mining Engineers of AIME Transactions, Vol. 266, pp. 1863-1876, 1979.

8. Magnetic Taconite Concentration Modeling, University of Minnesota-Duluth, Coleraine Minerals Research Laboratory Technical Report #CMRL/TR-99-12, by R. L. Wiegel, July 29, 1999.

9. Fitting of Liberation Model Parameters to Davis Tube Test Data, University of Minnesota-Duluth, Coleraine Minerals Research Laboratory Technical Report #CMRL/TR-99-13, by R. L. Wiegel, August 19, 1999.

10. Mineral Liberation, by G. Barbery, Quebec, GB, 1991.

11. Measurement and Calculation of Liberation in Continuous Milling Circuits, by C. L. Schneider, Ph D Thesis, Metallurgical Engineering Department, University of Utah, 1995.

Table 1

Effect of Ratio of Grain Size to Particle Size (K) on Quality of Liberated and Locked Particles for an Ore with 20% Valuable Mineral

Composition Index Range (%)	Percent by Volume for an Individual Size											
	0	1	2	3	4	5	6	7	8	9	10	11
	0	0/10	10/20	20/30	30/40	40/50	50/60	60/70	70/80	80/90	90/100	100
K=0.125			50.0	50.0								
0.177			50.0	50.0								
0.25		0.8	50.0	47.7	1.5							
0.354		6.6	45.6	39.4	8.0	0.4						
0.5	0.2	18.1	35.6	28.7	13.1	3.6	0.6	0.1				
0.707	6.9	26.8	23.7	17.5	12.5	7.1	3.7	1.4	0.3	0.1		
1	16.8	29.1	15.0	11.4	9.0	7.3	4.8	2.9	1.9	1.2	0.6	
1.41	37.6	17.2	10.0	7.7	6.5	5.6	4.5	3.2	2.5	2.1	1.8	1.3
2	51.5	10.2	6.6	5.2	4.7	4.2	3.7	2.9	2.5	2.3	2.1	4.1
2.83	60.6	6.2	4.4	3.6	3.3	3.1	2.9	2.4	2.2	2.1	2.0	7.2
4	66.8	3.7	2.9	2.5	2.4	2.3	2.2	1.9	1.8	1.7	1.6	10.2
5.66	70.9	2.4	2.0	1.8	1.7	1.6	1.6	1.4	1.4	1.3	1.3	12.6
8	73.7	1.6	1.3	1.2	1.2	1.2	1.1	1.1	1.0	1.0	1.0	14.6
11.31	75.6	1.0	0.9	0.9	0.8	0.8	0.8	0.8	0.8	0.8	0.8	16.0
16	76.8	0.7	0.6	0.6	0.6	0.6	0.6	0.6	0.6	0.6	0.6	17.1
22.63	77.8	0.5	0.5	0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.4	18.0
32	78.5	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	18.5

Table 2

Directional Coefficient Relationships for Same Composition Transfers When Breaking Particles of Size β(J) to Size β(J+1)

$$Q(I,I,J) = BO + B1 \log(KX) + B2(\log(KX))^2 + B3(\log(KX))^3 \quad \text{(with max = 1)}$$

$KX = \alpha / \beta(J+1)$ β(J+1) – particle size of product

	0.125>KX	0.125<KX≤0.5			0.5<KX<1			1≤KX≤22.63				KX>22.63
I	B0	B0	B1	B2	B0	B1	B2	B0	B1	B2	B3	B0
0	1	1			1			1				1
1	1	+.682	-.9604	-.6892	+.682	-.9604	-.6892	+.8001	-1.3522	+1.3902	-.4783	.3306
2	1	+.492	-1.035	-.4962	+.492	-1.035	-.4962	+.7142	-1.3403	+1.4446	-.5150	.2694
3	1	-.555	-4.149	-2.716	+.330	-2.426	0	+.4005	-.3536	+.4429	-.1871	.2812
4	1	-.680	-4.603	-3.074	+.390	-1.743	0	+.3347	-.3778	+.5053	-.2140	.2313
5	1	-.626	-4.105	-2.590	+.409	-1.570	0	+.5202	-.8675	+.7413	-.2246	.1470
6	1	-.626	-4.105	-2.590	+.409	-1.570	0	+.5202	-.8675	+.7413	-.2246	.1470
7	1	-.680	-4.603	-3.074	+.390	-1.743	0	+.3347	-.3778	+.5053	-.2140	.2313
8	1	-.555	-4.149	-2.716	+.330	-2.426	0	+.4005	-.3536	+.4429	-.1871	.2812
9	1	+.492	-1.035	-.4962	+.492	-1.035	-.4962	+.7142	-1.3403	+1.4446	-.5150	.2694
10	1	+.682	-.9604	-.6892	+.682	-.9604	-.6892	+.8001	-1.3522	+1.3902	-.4783	.3306
11	1	1			1			1				1
Particle Size Step		4th root of 2			4th root of 2			Square root of 2				

Table 3

Comparison of Gaudin Random Liberation Model Results with Size Reduction /Liberation Simulation Results for a 20% Valuable Mineral Ore

Composition Index Range		Percent by Volume for an Individual Size											
		0	1	2	3	4	5	6	7	8	9	10	11
		0	0/10	10/20	20/30	30/40	40/50	50/60	60/70	70/80	80/90	90/100	100
K = 0.125	M			50.0	50.0								
	S			50.0	50.0								
0.25	M		0.8	50.0	47.7	1.5							
	S		2.7	45.7	50.5	1.1							
0.5	M	0.2	18.1	35.6	28.7	13.1	3.6	0.6	0.1				
	S	1.1	15.8	41.2	22.4	14.4	4.5	0.6	0.0				
1	M	16.8	29.1	15.0	11.4	9.0	7.3	4.8	2.9	1.9	1.2	0.6	
	S	17.3	31.9	16.6	5.1	9.6	6.6	6.3	3.0	2.0	0.8	0.6	
2	M	51.5	10.2	6.6	5.2	4.7	4.2	3.7	2.9	2.5	2.3	2.1	4.1
	S	49.8	13.9	6.7	2.6	4.7	4.8	2.9	3.3	2.9	2.4	2.3	3.7
4	M	66.8	3.7	2.9	2.5	2.4	2.3	2.2	1.9	1.8	1.7	1.6	10.2
	S	67.1	4.3	2.7	1.4	2.6	2.6	1.5	2.2	2.2	1.4	1.9	10.0
8	M	73.7	1.6	1.3	1.2	1.2	1.2	1.1	1.1	1.0	1.0	1.0	14.6
	S	73.9	1.6	1.3	0.8	1.3	1.3	0.8	1.3	1.3	0.8	1.2	14.5
16	M	76.8	0.7	0.6	0.6	0.6	0.6	0.6	0.6	0.6	0.6	0.6	17.1
	S	77.0	0.7	0.7	0.4	0.7	0.7	0.4	0.7	0.7	0.4	0.7	17.1
32	M	78.5	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	18.5
	S	78.5	0.4	0.3	0.2	0.3	0.3	0.2	0.3	0.3	0.2	0.3	18.6

M – Gaudin random liberation model calculations

S – Size reduction/liberation simulation

Table 4

Effect of Variations in Grinding Rate Ratio (RAB) on Product Size and Composition (17.63% Values Head, 20.69% Barren Dilution)

RAB =		0.5		1.0		2.0	
	Size Fraction	Quan	Qual	Quan	Qual	Quan	Qual
0.5 min	1	1.01	16.87	1.00	17.63	1.00	18.07
	2	2.92	16.77	2.91	17.62	2.91	18.16
	3	5.94	16.60	5.90	17.63	5.92	18.32
	4	8.35	16.17	8.29	17.62	8.32	18.71
	5	8.52	15.73	8.46	17.63	8.49	19.16
	6	7.12	15.83	7.10	17.63	7.11	19.05
	7	7.28	16.05	7.27	17.63	7.28	18.80
	8	7.39	16.49	7.40	17.63	7.39	18.37
	9	7.41	17.03	7.43	17.63	7.42	17.90
	10	7.34	17.56	7.37	17.63	7.35	17.50
	11	7.20	18.02	7.23	17.62	7.22	17.20
	12	7.02	18.34	7.04	17.62	7.03	17.01
	13	22.52	20.61	22.60	17.63	22.56	15.59
1.0 min	1	0.20	16.08	0.20	17.63	0.20	18.50
	2	0.82	15.92	0.81	17.62	0.82	18.69
	3	2.20	15.62	2.16	17.63	2.18	19.01
	4	4.09	14.89	4.01	17.62	4.05	19.80
	5	5.59	14.13	5.47	17.63	5.54	20.72
	6	6.12	14.08	6.04	17.63	6.09	20.76
	7	7.04	14.31	6.99	17.63	7.02	20.37
	8	7.77	14.90	7.76	17.63	7.76	19.62
	9	8.26	15.74	8.29	17.63	8.27	18.75
	10	8.49	16.66	8.54	17.63	8.51	17.96
	11	8.51	17.52	8.57	17.63	8.54	17.34
	12	8.36	18.22	8.42	17.62	8.39	16.90
	13	32.54	21.40	32.74	17.63	32.65	14.95
1.5 min	1	0.04	15.25	0.04	17.63	0.04	18.91
	2	0.23	15.05	0.22	17.62	0.22	19.21
	3	0.78	14.66	0.76	17.63	0.77	19.71
	4	1.88	13.71	1.80	17.62	1.84	20.92
	5	3.28	12.69	3.14	17.63	3.22	22.41
	6	4.46	12.46	4.32	17.63	4.40	22.72
	7	5.86	12.62	5.74	17.63	5.80	22.25
	8	7.15	13.26	7.08	17.63	7.11	21.20
	9	8.17	14.25	8.17	17.63	8.16	19.94
	10	8.85	15.44	8.91	17.63	8.87	18.74
	11	9.19	16.63	9.27	17.63	9.22	17.76
	12	9.22	17.68	9.31	17.62	9.26	17.06
	13	40.90	21.68	41.24	17.63	41.08	14.63

Table 5

Results of Fitting GRLM Liberation Parameters to Minntac Mag Cobber Feed, Davis Tube Tests on Individual Size Fractions

Size Fract. Mesh	Part Size µm	DT Conc % Total Fe		DT Conc % Mag Fe		DT Conc % Weight		DT Feed % Total Fe		DT Feed % Mag Fe	
		Act	Calc	Act	Calc	Act	Calc	Act	Calc	Act	Calc
3/4	5603	34.2	34.6	23.5	24.0	91.0	81.7	32.6	31.1	21.4	19.6
4/8	3330	34.6	34.6	24.0	24.0	87.3	81.7	32.6	31.1	21.0	19.6
8/14	1655	34.0	34.6	23.3	24.0	85.1	81.7	31.8	31.1	19.8	19.6
14/28	830	36.3	34.6	26.2	24.0	70.7	81.6	30.7	31.1	18.5	19.6
28/48	417	38.0	36.5	28.4	26.4	63.3	74.2	29.7	31.1	18.0	19.6
48/100	208	44.1	46.0	36.2	38.6	51.8	50.7	30.4	31.1	18.7	19.6
100/150	124	51.7	53.6	45.9	48.4	44.2	40.5	31.6	31.1	20.3	19.6
150/200	88.8	57.4	57.8	53.2	53.8	40.1	36.4	32.4	31.1	21.3	19.6
200/270	62.6	61.8	61.5	58.8	58.4	36.5	33.5	32.0	31.1	21.5	19.6
270/400	44.3	67.2	64.3	65.8	62.0	33.8	31.6	32.2	31.1	22.2	19.6
400/500	30.4	68.5	66.6	67.4	65.0	31.4	30.1	30.9	31.1	21.2	19.6
-500	21.5	70.2	68.2	69.6	67.1	17.0	29.2	27.6	31.1	11.8	19.6

Sum of Squares Weighting $\left\{ \begin{array}{ll} 0.70 & \text{Conc Grade (MagFe)} \\ 0.20 & \text{Conc Weight} \\ 0.10 & \text{Feed Grade (MagFe)} \end{array} \right\}$ Min Sum Squares = 154.4

Specific Gravities 5.20 Fe_3O_4 3.00 Waste and Dilution

Parameters		
	Mineralized Ore	100% Vol @ 22.23% Fe_3O_4 by Vol
	Barren Dilution	26.09% Vol @15.84% Non Mag Fe by Wt
	Total Feed	126.09% @ 17.63% Fe_3O_4 by Vol

Effective Mineral Grain Size 374 µm (~ 35 mesh)

Table 7

Simulation Results – Effect of Batch Grinding Time on Product Size and Possible Magnetic Separation Results (Both Volumes and Weights)

Combined Size Distribution										
Min	+48	-270	No Values Loss				Less Than 10% by Vol Values Loss			
			Quantity		Quality		Quantity		Quality		Recovery
	295µ	53µ	Vol %	Wt %	% Fe_3O_4 by Vol	% Mag Fe by Wt	Vol %	Wt %	% Fe_3O_4 by Vol	% Mag Fe by Wt	Loss %
0	55.0	20.0	53.9	59.2	32.7	33.1	44.6	50.7	38.5	37.6	2.62
0.5	35.9	29.6	44.3	50.7	39.8	38.6	36.2	43.3	47.6	44.2	2.29
1.0	23.3	37.8	37.8	44.9	46.6	43.6	31.1	38.8	55.6	49.5	1.89
1.5	15.0	44.9	33.3	40.9	52.9	47.9	27.9	36.0	62.2	53.6	1.53
2.0	9.6	51.0	30.1	38.1	58.6	51.4	25.8	34.1	67.5	56.7	1.24
2.5	6.2	56.5	27.9	36.1	63.2	54.2	24.3	32.9	71.8	58.9	1.00
3.0	3.9	61.3	26.2	34.7	67.3	56.4	23.3	32.0	75.0	60.7	0.82
3.5	2.5	65.6	25.0	33.6	70.5	58.3	22.6	31.4	77.5	61.9	0.68
4.0	1.6	69.4	24.0	32.8	73.5	59.7	22.0	30.9	79.7	63.0	0.57
4.5	1.0	72.8	23.3	32.1	75.7	61.0	21.6	30.5	81.2	63.9	0.49
5.0	0.6	75.8	22.8	31.6	77.3	62.0	21.3	30.2	82.4	64.6	0.42
5.5	0.4	78.5	22.3	31.2	79.0	62.8	21.0	30.0	83.6	65.0	0.37
6.0	0.2	81.0	22.0	30.9	80.2	63.4	20.8	29.8	84.5	65.5	0.33
6.5	0.2	83.1	21.7	30.6	81.4	64.0	20.6	29.7	85.3	65.7	0.30
7.0	0.1	85.0	21.4	30.4	82.3	64.4	20.4	29.5	86.0	66.2	0.28
7.5	0.1	86.7	21.2	30.2	83.1	64.8	20.3	29.4	86.5	66.4	0.26

Table 8A

Simulation Output – Indicating Volumetric Size/Composition Results for a One Stage Tumbling Mill (GRIND.DAT)

```
NUMBER OF PERFECTLY MIXED GRINDING STAGES                1

 1           VALUE OF RESIDENCE TIME, TAU=            4          MIN.    VALUE OF GRIND RATE RATIO (WASTE/VALUE), RAB=    .67000

 COMPOSITION INTERVAL VALUES - % VOL FE304
    0.00    0.00    0.00    5.00   15.00   25.00   35.00   45.00   55.00   65.00   75.00   85.00   95.00  100.00

 FEED SIZE/COMPOSITION           VOL / % VOL FE304
    1.00    0.27    1.03    0.08    1.06    2.71    0.11    0.00    0.00    0.00    0.00    0.00    0.00    0.00    5.00   17.63
    2.00    0.38    2.08    0.45    2.63    3.62    1.13    0.10    0.00    0.00    0.00    0.00    0.00    0.00   10.00   17.62
    3.00    0.53    3.22    1.70    3.38    3.83    2.25    0.40    0.18    0.04    0.00    0.00    0.00    0.00   15.00   17.63
    4.00    0.76    3.75    3.28    2.22    2.10    1.66    1.00    0.67    0.18    0.10    0.02    0.01    0.00   15.00   17.62
    5.00    1.07    3.73    2.04    1.17    0.66    0.47    0.51    0.61    0.41    0.20    0.12    0.05    0.03   10.00   17.63
    6.00    1.51    2.52    0.70    0.38    0.21    0.20    0.22    0.23    0.14    0.11    0.13    0.09    0.08    5.00   17.63
    7.00    2.14    3.05    0.41    0.23    0.15    0.16    0.18    0.16    0.12    0.11    0.13    0.10    0.20    5.00   17.63
    8.00    3.02    3.42    0.23    0.15    0.10    0.12    0.13    0.11    0.10    0.10    0.10    0.09    0.35    5.00   17.63
    9.00    4.27    3.65    0.13    0.10    0.08    0.09    0.09    0.08    0.08    0.08    0.08    0.07    0.48    5.00   17.63
   10.00    6.04    3.79    0.08    0.07    0.06    0.06    0.07    0.06    0.06    0.06    0.06    0.05    0.59    5.00   17.63
   11.00    8.55    3.89    0.05    0.05    0.04    0.04    0.05    0.04    0.04    0.05    0.04    0.04    0.67    5.00   17.62
   12.00   12.09    3.96    0.04    0.03    0.03    0.03    0.03    0.03    0.03    0.03    0.03    0.03    0.73    5.00   17.62
   13.00   17.10    8.01    0.05    0.05    0.04    0.05    0.05    0.04    0.04    0.05    0.04    0.05    1.54   10.00   17.63
    0.00    0.00   46.11    9.24   11.50   13.62    6.37    2.83    2.21    1.24    0.90    0.75    0.56    4.66  100.00   17.63
    0.00    0.00    0.00    2.62    9.79   19.32   12.65    7.23    6.91    4.59    3.85    3.60    3.02   26.43  100.00

 PRODUCT SIZE/COMPOSITION           VOL / % VOL FE304
    1.00    0.27    0.07    0.00    0.06    0.15    0.01    0.00    0.00    0.00    0.00    0.00    0.00    0.00    0.29   17.16
    2.00    0.38    0.21    0.04    0.24    0.32    0.10    0.01    0.00    0.00    0.00    0.00    0.00    0.00    0.92   17.06
    3.00    0.53    0.47    0.24    0.46    0.50    0.28    0.05    0.02    0.00    0.00    0.00    0.00    0.00    2.03   16.88
    4.00    0.76    0.86    0.74    0.48    0.44    0.33    0.19    0.12    0.03    0.02    0.00    0.00    0.00    3.21   16.45
    5.00    1.07    1.54    0.83    0.46    0.25    0.17    0.18    0.21    0.14    0.06    0.04    0.01    0.01    3.90   15.86
    6.00    1.51    2.17    0.59    0.31    0.17    0.15    0.17    0.16    0.10    0.08    0.08    0.06    0.05    4.09   15.50
    7.00    2.14    3.14    0.42    0.23    0.14    0.15    0.16    0.14    0.10    0.09    0.11    0.08    0.16    4.92   15.33
    8.00    3.02    4.14    0.28    0.17    0.12    0.13    0.14    0.12    0.10    0.10    0.10    0.08    0.34    5.84   15.37
    9.00    4.27    5.07    0.19    0.13    0.10    0.11    0.12    0.10    0.09    0.10    0.09    0.08    0.56    6.75   15.62
   10.00    6.04    5.86    0.13    0.10    0.09    0.09    0.10    0.08    0.08    0.09    0.08    0.07    0.80    7.56   16.01
   11.00    8.55    6.47    0.09    0.08    0.07    0.07    0.08    0.07    0.07    0.07    0.06    0.06    1.02    8.20   16.51
   12.00   12.09    6.85    0.06    0.06    0.05    0.05    0.06    0.05    0.05    0.06    0.05    0.05    1.21    8.60   17.03
   13.00   17.10   34.08    0.22    0.22    0.19    0.21    0.22    0.20    0.20    0.22    0.20    0.21    7.53   43.69   19.59
    0.00    0.00   70.91    3.83    3.02    2.60    1.86    1.47    1.27    0.97    0.89    0.81    0.70   11.67  100.00   17.63
    0.00    0.00    0.00    1.09    2.57    3.68    3.69    3.75    3.98    3.57    3.78    3.90    3.78   66.20  100.00
```

Table 8B

Simulation Output – Indicating Weight and Assay Size/Composition Results for a One Stage Tumbling Mill (GRINDWT.DAT)

```
1            VALUE OF RESIDENCE TIME, TAU=            4            MIN.    VALUE OF GRIND RATE RATIO (WASTE/VALUE), RAB=    .67000

COMPOSITION INTERVAL VALUES - % VOL FE304/% WT FE304/% WT MAG FE/% WT TOT FE/% WT SIO2
    0.00     0.00     0.00     5.00    15.00    25.00    35.00    45.00    55.00    65.00    75.00    85.00    95.00   100.00
    0.00     0.00     0.00     8.36    23.42    36.62    48.28    58.65    67.93    76.30    83.87    90.76    97.05   100.00
    0.00     0.00     0.00     6.05    16.95    26.50    34.93    42.44    49.16    55.21    60.69    65.67    70.23    72.36
    0.00     0.00    15.84    20.57    29.08    36.54    43.13    48.99    54.24    58.96    63.24    67.14    70.69    72.36
    0.00     0.00    65.36    59.90    50.05    41.43    33.81    27.03    20.96    15.49    10.54     6.04     1.93     0.00

FEED SIZE/COMPOSITION         WT / % WT MAG FE
    1.00     0.27     0.92     0.07     1.04     2.84     0.13     0.00     0.00     0.00     0.00     0.00     0.00     0.00     5.00    19.58
    2.00     0.38     1.84     0.41     2.58     3.79     1.25     0.12     0.00     0.00     0.00     0.00     0.00     0.00    10.00    19.57
    3.00     0.53     2.85     1.56     3.32     4.01     2.51     0.47     0.23     0.05     0.00     0.00     0.00     0.00    15.00    19.58
    4.00     0.76     3.32     3.01     2.18     2.20     1.85     1.18     0.83     0.24     0.14     0.03     0.01     0.00    15.00    19.57
    5.00     1.07     3.30     1.87     1.15     0.69     0.53     0.60     0.76     0.54     0.27     0.18     0.07     0.04    10.00    19.58
    6.00     1.51     2.23     0.64     0.37     0.22     0.22     0.26     0.28     0.19     0.15     0.18     0.13     0.12     5.00    19.58
    7.00     2.14     2.70     0.38     0.23     0.15     0.17     0.21     0.20     0.15     0.16     0.19     0.14     0.31     5.00    19.58
    8.00     3.02     3.03     0.21     0.14     0.11     0.13     0.15     0.14     0.13     0.14     0.15     0.13     0.54     5.00    19.58
    9.00     4.27     3.23     0.12     0.10     0.08     0.10     0.11     0.10     0.10     0.11     0.11     0.10     0.74     5.00    19.58
   10.00     6.04     3.36     0.07     0.07     0.06     0.07     0.08     0.07     0.07     0.09     0.08     0.08     0.90     5.00    19.58
   11.00     8.55     3.45     0.05     0.05     0.04     0.05     0.06     0.05     0.05     0.06     0.06     0.06     1.02     5.00    19.57
   12.00    12.09     3.50     0.03     0.03     0.03     0.04     0.04     0.04     0.04     0.05     0.04     0.05     1.11     5.00    19.57
   13.00    17.10     7.09     0.04     0.05     0.04     0.05     0.06     0.05     0.06     0.07     0.06     0.07     2.36    10.00    19.58
    0.00     0.00    40.83     8.48    11.31    14.27     7.09     3.33     2.75     1.63     1.24     1.07     0.84     7.15   100.00    19.58
    0.00     0.00     0.00     2.62     9.79    19.32    12.65     7.23     6.91     4.59     3.85     3.60     3.02    26.43   100.00

PRODUCT SIZE/COMPOSITION         WT / % WT MAG FE
    1.00     0.27     0.06     0.00     0.06     0.16     0.01     0.00     0.00     0.00     0.00     0.00     0.00     0.00     0.29    19.12
    2.00     0.38     0.18     0.04     0.24     0.34     0.11     0.01     0.00     0.00     0.00     0.00     0.00     0.00     0.92    19.02
    3.00     0.53     0.41     0.22     0.45     0.53     0.32     0.06     0.03     0.01     0.00     0.00     0.00     0.00     2.02    18.84
    4.00     0.76     0.76     0.68     0.47     0.46     0.37     0.23     0.16     0.04     0.02     0.00     0.00     0.00     3.19    18.41
    5.00     1.07     1.36     0.76     0.45     0.26     0.19     0.21     0.26     0.18     0.09     0.05     0.02     0.01     3.85    17.82
    6.00     1.51     1.92     0.54     0.31     0.18     0.17     0.19     0.20     0.13     0.11     0.12     0.09     0.07     4.03    17.46
    7.00     2.14     2.78     0.39     0.23     0.15     0.16     0.19     0.17     0.13     0.13     0.15     0.12     0.25     4.85    17.28
    8.00     3.02     3.66     0.26     0.17     0.13     0.15     0.17     0.15     0.13     0.14     0.15     0.12     0.52     5.75    17.33
    9.00     4.27     4.49     0.17     0.13     0.11     0.12     0.14     0.13     0.12     0.14     0.13     0.12     0.86     6.66    17.57
   10.00     6.04     5.19     0.12     0.10     0.09     0.10     0.11     0.10     0.10     0.12     0.11     0.11     1.22     7.48    17.97
   11.00     8.55     5.73     0.08     0.08     0.07     0.08     0.09     0.08     0.09     0.10     0.09     0.09     1.56     8.14    18.47
   12.00    12.09     6.07     0.06     0.06     0.05     0.06     0.07     0.06     0.07     0.08     0.07     0.07     1.85     8.57    18.99
   13.00    17.10    30.18     0.20     0.22     0.20     0.23     0.26     0.24     0.27     0.30     0.28     0.31    11.55    44.25    21.49
    0.00     0.00    62.80     3.52     2.97     2.72     2.07     1.73     1.58     1.27     1.22     1.16     1.05    17.91   100.00    19.58
    0.00     0.00     0.00     1.09     2.57     3.68     3.69     3.75     3.98     3.57     3.78     3.90     3.78    66.20   100.00
```

Table 9

Size Reduction Mineral Liberation Simulation Program Text (SL10.BAS)

```
50 REM *************************************************************************
********************************************************************************
*******************************************************************************
55 REM THIS PROGRAM WRITTEN BY RON WIEGEL OF COLERAINE MINERALS RESEARCH LAB OF
UNIVERSITY OF MINNESOTA FOR USE IN DESCRIBING SIZE REDUCTION AND LIBERATION OF M
AGNETIC TACONITE ORES
60 REM THE SUPPORT FOR THIS PROGRAMS PREPARATION HAS COME FROM TWO SOURCES, THE
IRON ORE COOPERATIVE RESEARCH COMMITTEE, ADMINISTERED BY THE DNR-MINERALS DIV, A
ND THE UNIVERSITY OF MINNESOTA'S PERMANENT UNIVERSITY TRUST FUND MINERALS RESEAR
CH PROGRAM
81 REM *************************************************************************
********************************************************************************
*******************************************************************************
84 REM THIS IS VERSION OBTAINED ON 9/22/00, ENTITLED SL09B.BAS
85 REM THE SIZE/COMPOSITION DISTRIBUTION OF THE FEED TO THIS PROGRAM (SUBROUTINE
 6000) MUST BE IN VOLUMETRIC TERMS, SINCE LIBERATION IS A GEOMETRIC PHENOMENON
86 REM THIS CONTAINS PROVISION FOR OUTPUT FILES IN BOTH VOLUME (GRIND.DAT) AND W
EIGHT (GRINDWT.DAT) TERMS AND A TROUBLE SHOOTING FILE (DETAIL.DAT)
87 REM THIS PROGRAM CONTAINS INPUT REQUESTS THAT ACCEPT THE NUMBER OF PERFECTLY
MIXED STAGES (UP TO 20) AND DIFFERENT RESIDENCE TIMES (MIN) AND DIFFERENT RATIOS
 OF GRINDING RATES (WASTE/VALUE) FOR EACH PERFECTLY MIXED GRINDING STAGE
90 REM THIS IS NEWER VERSION OF SIZLIB STARTED ON 5/1/00
91 REM THIS VERSION IS BASED ON STARTING WITH LARGEST SIZE FRACTION OF LIBERATED
 WASTE AND CALCULATING RESULTS OF BREAKAGE EVENT ON THAT SIZE AND PLACING PRODUC
TS INTO APPROPRIATE SMALLER SIZES
92 REM THEN GOING ON TO LARGEST SIZE 0-10 % VALUES AND CALCULATING RESULTS OF A
BREAKAGE EVENT AND PLACING PRODUCTS IN SMALLER SIZES AND DIFFERENT COMPOSITIONS
93 REM AFTER COMPLETING CALCULATIONS FOR LARGEST SIZE LIBERATED VALUES THEN GO T
O NEXT LARGER SIZE LIBERATED WASTE, THEN 0-10 % VALUES ,ETC
94 REM BY PROCEEDING IN THIS FASHION, ONE SIZE AND ONE FEED COMPOSITION AT A TIM
E, AND PLACING RESULTANT PRODUCTS IN SMALLER SIZES AND CORRECT COMPOSITIONS, I B
ELIEVE ONE HAS A BETTER WAY OF SIMULATING THE EFFECT OF DIFFERENT GRINDING RATES
95 REM WHAT ONE ENDS UP WITH IS THE PRODUCT SIZE DISTRIBUTION AFTER USING APPROP
RIATE GRINDING RATES FOR THE VARIOUS SIZE/COMPOSITION INTERVALS
96 REM ONE COULD VIEW THIS AS THE COMBINATION OF MINERAL LIBERATION, RESULTING F
ROM GEOMETRIC EFFECTS, WITH SELECTIVE GRINDING DUE TO THE DIFFERENT RATES OF BRE
AKGE FOR VARIOUS MINERALS
99 DIM F(15,15),P(15,15),TS(15,15),V(15,15),B(20,20),CUM(15),CUMF(15),TC(15,15),
Q(15,15,15),BETA(15),VB(15),CPS(15),CVPS(15),CFS(15),CVFS(15),CPQ(15),CPR(15),CF
Q(15),CFR(15),CUMVB(15),CUMFF(15),GR(15,15),S(15),K(15)
100 DIM QQ(15,15,4),QT(15),KK(4),X(15,15),RRAB(20),TTAU(20),RO(15),WB(15),WBM(15
),WBT(15),WBS(15),XP(15,15),CUMW(15),WP(15,15),CWBM(15),CWB(15),CWBT(15),CWBS(15
),CUMWP(15)
101 REM ************************************************************************
********************************************************************************
********************************************************************************
102 INPUT "NUMBER OF PERFECTLY MIXED GRINDING STAGES   ";BMNN:FOR IBM=1 TO BMNN:
INPUT "VALUE OF RESIDENCE TIME (TAU) AND GRIND RATE RATIO WASTE TO VALUES (RAB)"
;TTAU(IBM),RRAB(IBM):NEXT IBM
103 ALPHA=374:BETA(0)=1980:FOR I=1 TO 15:BETA(I)=BETA(0)/(2^.5)^I:NEXT I
104 VB(0)=0:VB(1)=.05:VB(2)=.15:VB(3)=.25:VB(4)=.35:VB(5)=.45:VB(6)=.55:VB(7)=.6
5:VB(8)=.75:VB(9)=.85:VB(10)=.95:VB(11)=1:REM AVG COMP BY VOL OF 12 RANGES
220 OPEN "GRIND.DAT" FOR OUTPUT AS #1:PRINT#1,CHR$(15)
225 OPEN "DETAIL.DAT" FOR OUTPUT AS #2:PRINT #2,CHR$(15)
230 OPEN "GRINDWT.DAT" FOR OUTPUT AS #3:PRINT#3,CHR$(15)
233 GOSUB 3000
235 GOSUB 6000:FLAG=0
250 FOR I=0 TO 11:FOR J=1 TO 13:P(J,I)=F(J,I):CUMF(I)=CUMF(I)+F(J,I):NEXT J:NEXT
 I:REM NOTE THAT IN THIS PROGRAM F IS PRODUCT AND P IS FEED, A POSSIBLE CONFUSIN
G SITUATION
```

Table 9 (cont'd)

```
299 J=1:B(2,J)=.386:B(3,J)=.182:B(4,J)=.102:B(5,J)=.067:B(6,J)=.049:B(7,J)=.038:
B(8,J)=.031:B(9,J)=.025:B(10,J)=.021:B(11,J)=.017:B(12,J)=.014:B(13,J)=6.800001E
-02:REM DEFINING BREAKAGE PROPORTIONS TO EACH PARTICLE SIZE
300 NMAX=13:FOR J=2 TO (NMAX-1):B(NMAX,J)=1:FOR I=J+1 TO (NMAX-1):B(I,J)=B(I-1,J
-1):B(NMAX,J)=B(NMAX,J)-B(I,J):NEXT I:NEXT J
325 S(1)=4!:S(2)=2.97:S(3)=2.23:S(4)=1.66:S(5)=1.23:S(6)=.921:S(7)=.688:S(8)=.51
4:S(9)=.384:S(10)=.287:S(11)=.214:S(12)=.16:S(13)=.12:REM DEFINING GRINDING RATE
S FOR EACH PARTICLE SIZE
997 REM *************************************************************************
*********************************************************************************
*********************************************************************************
998 REM IMPORTANT PART OF PROGRAM BEGINS HERE
999 PRINT #1, "NUMBER OF PERFECTLY MIXED GRINDING STAGES     ",BMNN
1000 FOR BMN=1 TO BMNN:FOR JJ=1 TO 12:REM JJ IS FEED SIZE INDEX
1004 REM CALC OF DIFFERENT GRIND RATES BASED ON SIZE AND COMPOSITION
1005 FOR J=1 TO 13:CUMVB(J)=0:CUMFF(J)=0:FOR I=0 TO 11:CUMVB(J)=CUMVB(J)+F(J,I)*
VB(I):CUMFF(J)=CUMFF(J)+F(J,I):NEXT I:CUMVB(J)=CUMVB(J)/(CUMFF(J)+.0000001):NEXT
 J
1006 TAU=TTAU(BMN):RAB=RRAB(BMN):FOR J=1 TO 13:FOR I=0 TO 11:GR(J,I)=(VB(I)*1+(1
-VB(I))*RAB)/(CUMVB(J)*1+(1-CUMVB(J))*RAB+.0000001):TS(J,I)=TAU*S(J)*GR(J,I):PRI
NT #2,USING " ###.###";J,I,VB(I),CUMVB(J),GR(J,I),TS(J,I),TAU,RAB,BMN:NEXT I:NEX
T J
1010 FOR I=0 TO 11:REM I IS FEED COMPOSITION INDEX
1030 FOR J=JJ TO 13:IF (J=JJ) THEN FF=F(JJ,I):REM J PRODUCT SIZE INDEX FOR BREAK
AGE EVENT ON SIZE JJ
1040 IF (J=JJ) THEN V(J,JJ)=F(JJ,I)/(1+TS(JJ,I)) ELSE V(J,JJ)=(FF-V(JJ,JJ))*B(J,
JJ)
1055 IF(J=JJ) THEN F(JJ,I)=V(J,JJ) ELSE GOSUB 2000
1056 IF (J=JJ) THEN CUM(I)=CUM(I)+F(J,I)
1060 NEXT J
1070 NEXT I
1080 IF (JJ<12) GOTO 1180
1090 GOSUB 5000
1101 PRINT #1, " "
1105 PRINT #1, BMN," VALUE OF RESIDENCE TIME, TAU=  ",TAU,"MIN.    VALUE OF GRIN
D RATE RATIO (WASTE/VALUE), RAB=  ",RAB
1106 PRINT #1, " ":PRINT #1, " COMPOSITION INTERVAL VALUES - % VOL FE304"
1107 PRINT #1, USING " ####.##";0,0,100*VB(0),100*VB(1),100*VB(2),100*VB(3),100*
VB(4),100*VB(5),100*VB(6),100*VB(7),100*VB(8),100*VB(9),100*VB(10),100*VB(11)
1108 PRINT #1, " "
1109 PRINT #1, " FEED SIZE/COMPOSITION         VOL / % VOL FE304"
1110 FOR J=1 TO 13:PRINT #1, USING " ####.##";J,(ALPHA/BETA(J)),P(J,0),P(J,1),P(
J,2),P(J,3),P(J,4),P(J,5),P(J,6),P(J,7),P(J,8),P(J,9),P(J,10),P(J,11),CPS(J),100
*CVPS(J)
1120 NEXT J
1125 PRINT #1, USING " ####.##";0,0,CPQ(0),CPQ(1),CPQ(2),CPQ(3),CPQ(4),CPQ(5),CP
Q(6),CPQ(7),CPQ(8),CPQ(9),CPQ(10),CPQ(11),PQ,100*(PR/PQ)
1127 PRINT #1, USING " ####.##";0,0,CPR(0),CPR(1),CPR(2),CPR(3),CPR(4),CPR(5),CP
R(6),CPR(7),CPR(8),CPR(9),CPR(10),CPR(11),(100*PR/PR)
1129 PRINT #1, " ":PRINT #1, " PRODUCT SIZE/COMPOSITION          VOL / % VOL FE30
4"
1130 FOR J=1 TO 13:PRINT #1, USING " ####.##";J,(ALPHA/BETA(J)),F(J,0),F(J,1),F(
J,2),F(J,3),F(J,4),F(J,5),F(J,6),F(J,7),F(J,8),F(J,9),F(J,10),F(J,11),CFS(J),100
*CVFS(J)
1140 NEXT J
1160 PRINT #1, USING " ####.##";0,0,CFQ(0),CFQ(1),CFQ(2),CFQ(3),CFQ(4),CFQ(5),CF
Q(6),CFQ(7),CFQ(8),CFQ(9),CFQ(10),CFQ(11),FQ,100*(FR/FQ)
1165 PRINT #1, USING " ####.##";0,0,CFR(0),CFR(1),CFR(2),CFR(3),CFR(4),CFR(5),CF
R(6),CFR(7),CFR(8),CFR(9),CFR(10),CFR(11),(100*FR/FR)
1170 GOSUB 9500
```

Table 9 (cont'd)

```
1180 NEXT JJ
1185 FOR I=0 TO 11:CUMF(I)=0:CUM(I)=0:NEXT I
1190 FOR I=0 TO 11:FOR J=1 TO 13:P(J,I)=F(J,I):CUMF(I)=CUMF(I)+F(J,I):NEXT J:NEX
T I:REM NOTE THAT IN THIS PROGRAM F IS PRODUCT AND P IS FEED
1200 NEXT BMN
1998 CLOSE:END
1999 REM ***********************************************************************
********************************************************************************

********************************************************************************
2000 REM SUBROUTINE FOR DISTRIBUTING PRODUCT TO APPROPRIATE COMPOSITIONS
2010 GOSUB 4000:FOR II=0 TO 11:F(J,II)=F(J,II)+TC(NS,II):CUMF(II)=CUMF(II)+TC(NS
,II):NEXT II:CUMF(I)=CUMF(I)-V(J,JJ):RETURN:REM II PRODUCT COMPOSITION INDEX
2011 REM ***********************************************************************
********************************************************************************

********************************************************************************
3000 REM SUBROUTINE TO CALCULATE DIRECTIONAL COEFFICIENTS FOR VARIOUS SIZE FRACT
         IONS AND COMPOSITION RANGES
3001 REM BASED ON SIMPLEST LINEAR PROGRAM SOLUTION WHICH IN GENERAL GIVES VALUES
         FOR Q(I,I,J),Q(I,I-3,J),Q(I,I+3,J) VALUES FOR Q(I,I,J) ARE AVG FOR 0.2,
         0.5 AND 0.8 VOL FRACTION HEAD FOR SIZE J-1 GOING TO J
3002 KL=2.30259:FOR NNK=1 TO 13:K(NNK)=ALPHA/BETA(NNK+1):FOR IN=0 TO 11:FOR JN=0
 TO 11:Q(IN,JN,NNK)=0:NEXT JN:NEXT IN:Q(0,0,NNK)=1:Q(11,11,NNK)=1
3003 IF(K(NNK)>=1) THEN GOTO 3100 ELSE GOTO 3150:REM ALPHA-EFFECTIVE MINERAL GRA
IN SIZE, BETA(N)-LOG MEAN PARTICLE SIZE FOR FRACTION N, K-RATIO OF THE TWO LINEA
R DIMENSIONS
3100 GOSUB 7900:GOSUB 7520:GOTO 3212
3150 KK(1)=K(NNK)/2^.25:KK(2)=K(NNK)
3155 FOR JX=1 TO 2:IF(KK(JX)<=.5) THEN GOTO 3170
3160 IF(KK(JX)>.5) THEN GOTO 3200
3170 GOSUB 7600:GOSUB 7140:GOTO 3205
3200 GOSUB 7800:GOSUB 7400
3205 PRINT #1,USING " ####.###";JX,0,KK(JX),QQ(0,0,JX),QQ(1,1,JX),QQ(2,2,JX),QQ(
3,3,JX),QQ(4,4,JX),QQ(5,5,JX),QQ(6,6,JX),QQ(7,7,JX),QQ(8,8,JX),QQ(9,9,JX),QQ(10,
10,JX),QQ(11,11,JX)
3210 NEXT JX:GOSUB 9100
3212 PRINT #1,USING " ####.###";NNK,BETA(NNK),K(NNK),Q(0,0,NNK),Q(1,1,NNK),Q(2,2
,NNK),Q(3,3,NNK),Q(4,4,NNK),Q(5,5,NNK),Q(6,6,NNK),Q(7,7,NNK),Q(8,8,NNK),Q(9,9,NN
K),Q(10,10,NNK),Q(11,11,NNK)
3220 NEXT NNK:RETURN
3300 REM ***********************************************************************
********************************************************************************

********************************************************************************
4000 REM SUBROUTINE TO DISTRIBUTE BREAKAGE PRODUCT FOR V(J,JJ) OVER APPROPRIATE
COMPOSITIONS
4001 FOR JN=0 TO 13:FOR IN=0 TO 11:TC(JN,IN)=0:NEXT IN:NEXT JN
4010 NS=J-JJ:REM NS IS NUMBER OF BREAKAGE STEPS OR SIZE FRACTIONS OF 2^.5 RATIO
4020 FOR IN=0 TO 11:TC(0,IN)=0:IF (IN=I) THEN TC(0,IN)=V(J,JJ)*1
4021 NEXT IN
4030 IF (NS=0) THEN GOTO 4080
4040 FOR N=1 TO NS:NK=JJ+N-1
4050 FOR IN=0 TO 11
4055 FOR IIN=0 TO 11
4060 TC(N,IIN)=TC(N,IIN)+TC(N-1,IN)*Q(IN,IIN,NK)
4070 NEXT IIN: NEXT IN
4072 IF (FLAG=0) THEN PRINT #2,USING " ####.####";72,JJ,I,J,II,NS,N,TC(N,0),TC(N
,1),TC(N,2):PRINT #2,USING " ####.####";TC(N,3),TC(N,4),TC(N,5),TC(N,6),TC(N,7),
TC(N,8),TC(N,9),TC(N,10),TC(N,11)
4074 NEXT N
4075 IF(N=20) THEN FLAG=1
4080 RETURN
```

```
4090 REM *********************************************************************
*****************************************************************************
*****************************************************************************
5000 REM SUBROUTINE TO CUMULATE FEED AND PRODUCT SIZE AND COMPOSITION
5005 PR=0:FR=0:PQ=0:FQ=0:FOR JN=1 TO 13:CPS(JN)=0:CVPS(JN)=0:CFS(JN)=0:CVFS(JN)=
0:NEXT JN
5010 FOR JN=1 TO 13:FOR IN=0 TO 11
5015 CPS(JN)=CPS(JN)+P(JN,IN):CVPS(JN)=CVPS(JN)+P(JN,IN)*VB(IN)
5020 CFS(JN)=CFS(JN)+F(JN,IN):CVFS(JN)=CVFS(JN)+F(JN,IN)*VB(IN)
5025 NEXT IN
5030 CVPS(JN)=CVPS(JN)/(CPS(JN)+.0000001):CVFS(JN)=CVFS(JN)/(CFS(JN)+.0000001)
5035 NEXT JN
5055 FOR IN=0 TO 11:CPQ(IN)=0:CPR(IN)=0:CFQ(IN)=0:CFR(IN)=0:NEXT IN
5060 FOR IN=0 TO 11:FOR JN=1 TO 13
5065 CPQ(IN)=CPQ(IN)+P(JN,IN):CPR(IN)=CPR(IN)+P(JN,IN)*VB(IN)
5070 CFQ(IN)=CFQ(IN)+F(JN,IN):CFR(IN)=CFR(IN)+F(JN,IN)*VB(IN)
5075 NEXT JN
5080 PR=PR+CPR(IN):FR=FR+CFR(IN):PQ=PQ+CPQ(IN):FQ=FQ+CFQ(IN)
5085 NEXT IN
5090 FOR IN=0 TO 11:CPR(IN)=100*CPR(IN)/(PR+.0000001):CFR(IN)=100*CFR(IN)/(FR+.0
000001):NEXT IN
5100 RETURN
5110 REM *********************************************************************
*****************************************************************************
*****************************************************************************
6000 GOTO 6180:REM F(1,2)=50:F(1,3)=50:RETURN
6001 F(1,0)=.66:F(1,1)=0:F(1,2)=.45:F(1,3)=.87:F(1,4)=.87:F(1,5)=.45:REM FEED/CO
MPOSITION DISTRIBUTION
6005 F(2,0)=1.71:F(2,1)=.48:F(2,2)=.76:F(2,3)=1.13:F(2,4)=1.1:F(2,5)=.68:F(2,6)=
.19:F(2,7)=.14:F(2,8)=.11:F(2,9)=9.000001E-02:F(2,10)=.08:F(2,11)=.03
6010 F(3,0)=3.14:F(3,1)=1.42:F(3,2)=.94:F(3,3)=.8:F(3,4)=.73:F(3,5)=.7:F(3,6)=.5
7:F(3,7)=.4:F(3,8)=.32:F(3,9)=.26:F(3,10)=.23:F(3,11)=9.000001E-02
6015 F(4,0)=5.18:F(4,1)=1.13:F(4,2)=.79:F(4,3)=.67:F(4,4)=.63:F(4,5)=.61:F(4,6)=
.55:F(4,7)=.42:F(4,8)=.37:F(4,9)=.34:F(4,10)=.33:F(4,11)=.48
6020 F(5,0)=6.46:F(5,1)=.76:F(5,2)=.56:F(5,3)=.49:F(5,4)=.47:F(5,5)=.46:F(5,6)=.
4:F(5,7)=.36:F(5,8)=.33:F(5,9)=.32:F(5,10)=.32:F(5,11)=.97
6025 F(6,0)=6.5:F(6,1)=.44:F(6,2)=.35:F(6,3)=.31:F(6,4)=.3:F(6,5)=.3:F(6,6)=.29:
F(6,7)=.25:F(6,8)=.24:F(6,9)=.23:F(6,10)=.23:F(6,11)=1.26
6030 F(7,0)=6.53:F(7,1)=.27:F(7,2)=.22:F(7,3)=.21:F(7,4)=.2:F(7,5)=.2:F(7,6)=.2:
F(7,7)=.17:F(7,8)=.17:F(7,9)=.17:F(7,10)=.17:F(7,11)=1.49
6035 F(8,0)=5.83:F(8,1)=.15:F(8,2)=.13:F(8,3)=.12:F(8,4)=.12:F(8,5)=.12:F(8,6)=.
12:F(8,7)=.11:F(8,8)=.11:F(8,9)=.11:F(8,10)=.11:F(8,11)=1.47
6040 F(9,0)=4.53:F(9,1)=.08:F(9,2)=.07:F(9,3)=.07:F(9,4)=.07:F(9,5)=.07:F(9,6)=.
06:F(9,7)=.06:F(9,8)=.06:F(9,9)=.06:F(9,10)=.05:F(9,11)=1.22
6045 F(10,0)=3.04:F(10,1)=.04:F(10,2)=.03:F(10,3)=.03:F(10,4)=.03:F(10,5)=.03:F(
10,6)=.03:F(10,7)=.03:F(10,8)=.03:F(10,9)=.03:F(10,10)=.02:F(10,11)=.86
6050 F(11,0)=2.79:F(11,1)=.02:F(11,2)=.02:F(11,3)=.02:F(11,4)=.02:F(11,5)=.02:F(
11,6)=.02:F(11,7)=.02:F(11,8)=.02:F(11,9)=.02:F(11,10)=.01:F(11,11)=.82
6055 F(12,0)=2.67:F(12,1)=.01:F(12,2)=.02:F(12,3)=.01:F(12,4)=.01:F(12,5)=.02:F(
12,6)=.01:F(12,7)=.01:F(12,8)=.02:F(12,9)=.01:F(12,10)=.01:F(12,11)=.8
6060 F(13,0)=7.47:F(13,1)=.03:F(13,2)=.03:F(13,3)=.03:F(13,4)=.03:F(13,5)=.03:F(
13,6)=.03:F(13,7)=.02:F(13,8)=.02:F(13,9)=.02:F(13,10)=.02:F(13,11)=2.27
6065 RETURN
6066 F(1,0)=.41:F(1,1)=.01:F(1,2)=.62:F(1,3)=1.94:F(1,4)=.32:F(1,5)=0!:REM FEED/
COMPOSITION DISTRIBUTION
6067 F(2,0)=.81:F(2,1)=.15:F(2,2)=1.67:F(2,3)=2.64:F(2,4)=1.07:F(2,5)=.15:F(2,6)
=.01
6068 F(3,0)=1.21:F(3,1)=.98:F(3,2)=2.39:F(3,3)=2.58:F(3,4)=1.62:F(3.5)=.63:F(3.6
)=.16:F(3,7)=.03:F(3,8)=0!
6069 F(4,0)=1.93:F(4,1)=2.15:F(4,2)=2.18:F(4,3)=1.83:F(4,4)=1.47:F(4,5)=1.01:F(4
```

Table 9 (cont'd)

```
,6)=.54:F(4,7)=.28:F(4,8)=9.000001E-02:F(4,9)=.02:F(4,10)=0!:F(4,11)=0!
6070 F(5,0)=2.9:F(5,1)=2.69:F(5,2)=1.53:F(5,3)=1.23:F(5,4)=1.02:F(5,5)=.89:F(5,6
)=.63:F(5,7)=.4:F(5,8)=.29:F(5,9)=.19:F(5,10)=.12:F(5,11)=.01
6071 F(6,0)=4.41:F(6,1)=1.5:F(6,2)=.94:F(6,3)=.75:F(6,4)=.66:F(6,5)=.6:F(6,6)=.5
:F(6,7)=.36:F(6,8)=.3:F(6,9)=.25:F(6,10)=.23:F(6,11)=.2
6072 F(7,0)=5.29:F(7,1)=.87:F(7,2)=.59:F(7,3)=.48:F(7,4)=.44:F(7,5)=.42:F(7,6)=.
38:F(7,7)=.3:F(7,8)=.26:F(7,9)=.24:F(7,10)=.23:F(7,11)=.5
6073 F(8,0)=5.19:F(8,1)=.46:F(8,2)=.34:F(8,3)=.29:F(8,4)=.27:F(8,5)=.26:F(8,6)=.
24:F(8,7)=.2:F(8,8)=.19:F(8,9)=.18:F(8,10)=.18:F(8,11)=.7
6074 F(9,0)=4.28:F(9,1)=.22:F(9,2)=.17:F(9,3)=.15:F(9,4)=.14:F(9,5)=.14:F(9,6)=.
13:F(9,7)=.12:F(9,8)=.11:F(9,9)=.11:F(9,10)=.11:F(9,11)=.72
6075 F(10,0)=2.94:F(10,1)=9.000001E-02:F(10,2)=.08:F(10,3)=.07:F(10,4)=.07:F(10,
5)=.07:F(10,6)=.06:F(10,7)=.06:F(10,8)=.06:F(10,9)=.06:F(10,10)=.06:F(10,11)=.58
6076 F(11,0)=2.78:F(11,1)=.05:F(11,2)=.05:F(11,3)=.04:F(11,4)=.04:F(11,5)=.04:F(
11,6)=.04:F(11,7)=.04:F(11,8)=.04:F(11,9)=.04:F(11,10)=.04:F(11,11)=.6
6077 F(12,0)=2.69:F(12,1)=.03:F(12,2)=.03:F(12,3)=.03:F(12,4)=.03:F(12,5)=.03:F(
12,6)=.03:F(12,7)=.02:F(12,8)=.03:F(12,9)=.03:F(12,10)=.03:F(12,11)=.62
6078 F(13,0)=7.61:F(13,1)=.06:F(13,2)=.06:F(13,3)=.06:F(13,4)=.06:F(13,5)=.06:F(
13,6)=.06:F(13,7)=.06:F(13,8)=.05:F(13,9)=.05:F(13,10)=.05:F(13,11)=1.82
6079 RETURN
6080 F(2,0)=(.2+.8*.0412)*6.5:F(2,1)=.8*.2092*6.5:F(2,2)=.8*.1389*6.5:F(2,3)=.8*
.1415*6.5:F(2,4)=.8*.1436*6.5:F(2,5)=.8*.1292*6.5
6081 F(2,6)=.8*.1002*6.5:F(2,7)=.8*.048*6.5:F(2,8)=.8*.0301*6.5:F(2,9)=.8*.0112*
6.5:F(2,10)=.8*.0065*6.5:F(2,11)=.8*.0003*6.5:REM FEED/COMPOSITION DISTRIBUTION
6082 F(3,0)=(.2+.8*.1798)*9.600001:F(3,1)=.8*.1955*9.600001:F(3,2)=.8*.1204*9.60
0001:F(3,3)=.8*.0804*9.600001:F(3,4)=.8*.0697*9.600001:F(3,5)=.8*.085*9.600001
6083 F(3,6)=.8*.0871*9.600001:F(3,7)=.8*.0648*9.600001:F(3,8)=.8*.0466*9.600001:
F(3,9)=.8*.0343*9.600001:F(3,10)=.8*.0212*9.600001:F(3,11)=.8*.0151*9.600001
6084 F(4,0)=(.2+.8*.3258)*11.5:F(4,1)=.8*.1337*11.5:F(4,2)=.8*.0844*11.5:F(4,3)=
.8*.0554*11.5:F(4,4)=.8*.055*11.5:F(4,5)=.8*.0653*11.5
6085 F(4,6)=.8*.0611*11.5:F(4,7)=.8*.0443*11.5:F(4,8)=.8*.0433*11.5:F(4,9)=.8*.0
443*11.5:F(4,10)=.8*.0353*11.5:F(4,11)=.8*.0521*11.5
6086 F(5,0)=(.2+.8*.4431)*11.9:F(5,1)=.8*.0819*11.9:F(5,2)=.8*.0557*11.9:F(5,3)=
.8*.0396*11.9:F(5,4)=.8*.0408*11.9:F(5,5)=.8*.0492*11.9
6087 F(5,6)=.8*.0436*11.9:F(5,7)=.8*.0345*11.9:F(5,8)=.8*.0372*11.9:F(5,9)=.8*.0
389*11.9:F(5,10)=.8*.0328*11.9:F(5,11)=.8*.1028*11.9
6088 F(6,0)=(.2+.8*.5249)*10.7:F(6,1)=.8*.0483*10.7:F(6,2)=.8*.0374*10.7:F(6,3)=
.8*.0289*10.7:F(6,4)=.8*.03*10.7:F(6,5)=.8*.0356*10.7
6089 F(6,6)=.8*.0313*10.7:F(6,7)=.8*.0266*10.7:F(6,8)=.8*.0304*10.7:F(6,9)=.8*.0
296*10.7:F(6,10)=.8*.0262*10.7:F(6,11)=.8*.1509*10.7
6090 F(7,0)=(.2+.8*.579)*10:F(7,1)=.8*.0293*10:F(7,2)=.8*.0257*10:F(7,3)=.8*.021
3*10:F(7,4)=.8*.0217*10:F(7,5)=.8*.0254*10
6091 F(7,6)=.8*.0222*10:F(7,7)=.8*.0202*10:F(7,8)=.8*.0235*10:F(7,9)=.8*.0216*10
:F(7,10)=.8*.0198*10:F(7,11)=.8*.1901*10
6092 F(8,0)=(.2+.8*.6151)*8.5:F(8,1)=.8*.0188*8.5:F(8,2)=.8*.0182*8.5:F(8,3)=.8*
.0156*8.5:F(8,4)=.8*.0156*8.5:F(8,5)=.8*.018*8.5
6093 F(8,6)=.8*.0158*8.5:F(8,7)=.8*.015*8.5:F(8,8)=.8*.0175*8.5:F(8,9)=.8*.0156*
8.5:F(8,10)=.8*.0148*8.5:F(8,11)=.8*.2199*8.5
6094 F(9,0)=(.2+.8*.6397)*6.4:F(9,1)=.8*.0126*6.4:F(9,2)=.8*.013*6.4:F(9,3)=.8*.
0113*6.4:F(9,4)=.8*.0112*6.4:F(9,5)=.8*.0128*6.4
6095 F(9,6)=.8*.0113*6.4:F(9,7)=.8*.0109*6.4:F(9,8)=.8*.0128*6.4:F(9,9)=.8*.0113
*6.4:F(9,10)=.8*.0109*6.4:F(9,11)=.8*.2419*6.4
6096 F(10,0)=(.2+.8*.6571)*4.2:F(10,1)=.8*.0088*4.2:F(10,2)=.8*.0093*4.2:F(10,3)
=.8*.0081*4.2:F(10,4)=.8*8.000001E-03*4.2:F(10,5)=.8*.0092*4.2
6097 F(10,6)=.8*.0081*4.2:F(10,7)=.8*.0079*4.2:F(10,8)=.8*.0092*4.2:F(10,9)=.8*.
0081*4.2:F(10,10)=.8*8.000001E-03*4.2:F(10,11)=.8*.2582*4.2
6098 F(11,0)=(.2+.8*.6696)*3.8:F(11,1)=.8*.0061*3.8:F(11,2)=.8*.0065*3.8:F(11,3)
=.8*.0057*3.8:F(11,4)=.8*.0057*3.8:F(11,5)=.8*.0066*3.8
6099 F(11,6)=.8*.0058*3.8:F(11,7)=.8*.0057*3.8:F(11,8)=.8*.0065*3.8:F(11,9)=.8*.
0057*3.8:F(11,10)=.8*.0058*3.8:F(11,11)=.8*.2702*3.8
```

Table 9 (cont'd)

```
6100 F(12,0)=(.2+.8*.6785)*3.6:F(12,1)=.8*.0042*3.6:F(12,2)=.8*.0046*3.6:F(12,3)
=.8*.0041*3.6:F(12,4)=.8*.0041*3.6:F(12,5)=.8*.0047*3.6
6101 F(12,6)=.8*.0041*3.6:F(12,7)=.8*.0041*3.6:F(12,8)=.8*.0046*3.6:F(12,9)=.8*.
004*3.6:F(12,10)=.8*.0041*3.6:F(12,11)=.8*.2788*3.6
6102 F(13,0)=(.2+.8*.6848)*10:F(13,1)=.8*.003*10:F(13,2)=.8*.0032*10:F(13,3)=.8*
.0029*10:F(13,4)=.8*.0029*10:F(13,5)=.8*.0033*10
6103 F(13,6)=.8*.0029*10:F(13,7)=.8*.0029*10:F(13,8)=.8*.0033*10:F(13,9)=.8*.002
8*10:F(13,10)=.8*.0029*10:F(13,11)=.8*.2849*10
6104 F(1,0)=(.2+.8*.0046)*3.3:F(1,1)=.8*.0839*3.3:F(1,2)=.8*.1324*3.3:F(1,3)=.8*
.3055*3.3:F(1,4)=.8*.2685*3.3:F(1,5)=.8*.1099*3.3
6105 F(1,6)=.8*6.580001E-02*3.3:F(1,7)=.8*.0219*3.3:F(1,8)=.8*.006*3.3:F(1,9)=.8
*.0012*3.3:F(1,10)=.8*.0001*3.3:F(1,11)=.8*0!*3.3
6107 REM ***********************************************************************
********************************************************************************
********************************************************************************
6180 F(1,0)=.207*5!:F(1,1)=.0151*5!:F(1,2)=.2125*5!:F(1,3)=.5427*5!:F(1,4)=.0226
*5!:F(1,5)=.0001*5!
6181 F(1,6)=0:F(1,7)=0:F(1,8)=0:F(1,9)=0:F(1,10)=0:F(1,11)=0:REM FEED/COMPOSITIO
N DISTRIBUTION
6182 F(2,0)=.2077*10!:F(2,1)=.0448*10!:F(2,2)=.2625*10!:F(2,3)=.3618*10!:F(2,4)=
.1127*10!:F(2,5)=.0101*10!
6183 F(2,6)=.0003*10!:F(2,7)=0:F(2,8)=0:F(2,9)=0:F(2,10)=0:F(2,11)=0
6184 F(3,0)=.2147*15!:F(3,1)=.1135*15!:F(3,2)=.225*15!:F(3,3)=.2551*15!:F(3,4)=.
1502*15!:F(3,5)=.0267*15!
6185 F(3,6)=.0121*15!:F(3,7)=.0026*15!:F(3,8)=.0002*15!:F(3,9)=0:F(3,10)=0:F(3,1
1)=0
6186 F(5,0)=.3732*10!:F(5,1)=.2042*10!:F(5,2)=.1169*10!:F(5,3)=.066*10!:F(5,4)=.
0475*10!:F(5,5)=.051*10!
6187 F(5,6)=.0611*10!:F(5,7)=.0414*10!:F(5,8)=.0196*10!:F(5,9)=.0122*10!:F(5,10)
=.0045*10!:F(5,11)=.0027*10!
6188 F(6,0)=.5042*5!:F(6,1)=.1395*5!:F(6,2)=.0761*5!:F(6,3)=.0418*5!:F(6,4)=.039
9*5!:F(6,5)=.0443*5!
6189 F(6,6)=.0451*5!:F(6,7)=.029*5!:F(6,8)=.0225*5!:F(6,9)=.025*5!:F(6,10)=.0176
*5!:F(6,11)=.0151*5!
6190 F(7,0)=.6107*5!:F(7,1)=.0829*5!:F(7,2)=.0466*5!:F(7,3)=.0292*5!:F(7,4)=.031
2*5!:F(7,5)=.0354*5!
6191 F(7,6)=.0316*5!:F(7,7)=.0236*5!:F(7,8)=.0227*5!:F(7,9)=.0259*5!:F(7,10)=.01
93*5!:F(7,11)=.0409*5!
6192 F(8,0)=.6833*5!:F(8,1)=.0465*5!:F(8,2)=.0294*5!:F(8,3)=.021*5!:F(8,4)=.0235
*5!:F(8,5)=.0261*5!
6193 F(8,6)=.0227*5!:F(8,7)=.0192*5!:F(8,8)=.0204*5!:F(8,9)=.0208*5!:F(8,10)=.01
7*5!:F(8,11)=.0703*5!
6194 F(9,0)=.7294*5!:F(9,1)=.0265*5!:F(9,2)=.0195*5!:F(9,3)=.0154*5!:F(9,4)=.017
1*5!:F(9,5)=.0187*5!
6195 F(9,6)=.0162*5!:F(9,7)=.0151*5!:F(9,8)=.0165*5!:F(9,9)=.0155*5!:F(9,10)=.01
37*5!:F(9,11)=.0965*5!
6196 F(10,0)=.7587*5!:F(10,1)=.0161*5!:F(10,2)=.0135*5!:F(10,3)=.0113*5!:F(10,4)
=.0123*5!:F(10,5)=.0133*5!
6197 F(10,6)=.0115*5!:F(10,7)=.0114*5!:F(10,8)=.0126*5!:F(10,9)=.0113*5!:F(10,10
)=.0107*5!:F(10,11)=.1174*5!
6198 F(11,0)=.7781*5!:F(11,1)=.0104*5!:F(11,2)=9.600001E-03*5!:F(11,3)=.0082*5!:
F(11,4)=.0088*5!:F(11,5)=.0094*5!
6199 F(11,6)=.0082*5!:F(11,7)=.0084*5!:F(11,8)=.0093*5!:F(11,9)=.0082*5!:F(11,10
)=.0081*5!:F(11,11)=.1333*5!
6200 F(12,0)=.7914*5!:F(12,1)=.0071*5!:F(12,2)=.0068*5!:F(12,3)=.0059*5!:F(12,4)
=.0063*5!:F(12,5)=.0067*5!
6201 F(12,6)=.0058*5!:F(12,7)=.0061*5!:F(12,8)=.0067*5!:F(12,9)=.0059*5!:F(12,10
)=.0061*5!:F(12,11)=.1451*5!
6202 F(13,0)=.8008*10:F(13,1)=.0049*10:F(13,2)=.0048*10:F(13,3)=.0041*10:F(13,4)
=.0045*10:F(13,5)=.0048*10
```

```
6203 F(13,6)=.0042*10:F(13,7)=.0044*10:F(13,8)=.0048*10:F(13,9)=.0042*10:F(13,10
)=.0045*10:F(13,11)=.1539*10
6204 F(4,0)=.2503*15!:F(4,1)=.2187*15!:F(4,2)=.1477*15!:F(4,3)=.14*15!:F(4,4)=.1
108*15!:F(4,5)=.0668*15!
6205 F(4,6)=.0447*15!:F(4,7)=.0122*15!:F(4,8)=.0069*15!:F(4,9)=.0013*15!:F(4,10)
=.0005*15!:F(4,11)=0
6306 RETURN
7140 QQ(1,2,JX)=(1-QQ(1,1,JX))*(VB(1)-VB(0))/(VB(2)-VB(0)):QQ(1,0,JX)=1-QQ(1,1,J
X)-QQ(1,2,JX):REM THIS IS +-1 DISTRIBUTION  OF COMP FOR K<=0.5
7145 QQ(2,3,JX)=(1-QQ(2,2,JX))*(VB(2)-VB(1))/(VB(3)-VB(1)):QQ(2,1,JX)=1-QQ(2,2,J
X)-QQ(2,3,JX)
7150 QQ(3,4,JX)=(1-QQ(3,3,JX))*(VB(3)-VB(2))/(VB(4)-VB(2)):QQ(3,2,JX)=1-QQ(3,3,J
X)-QQ(3,4,JX)
7155 QQ(4,5,JX)=(1-QQ(4,4,JX))*(VB(4)-VB(3))/(VB(5)-VB(3)):QQ(4,3,JX)=1-QQ(4,4,J
X)-QQ(4,5,JX)
7160 QQ(5,6,JX)=(1-QQ(5,5,JX))*(VB(5)-VB(4))/(VB(6)-VB(4)):QQ(5,4,JX)=1-QQ(5,5,J
X)-QQ(5,6,JX)
7165 QQ(6,7,JX)=(1-QQ(6,6,JX))*(VB(6)-VB(5))/(VB(7)-VB(5)):QQ(6,5,JX)=1-QQ(6,6,J
X)-QQ(6,7,JX)
7170 QQ(7,8,JX)=(1-QQ(7,7,JX))*(VB(7)-VB(6))/(VB(8)-VB(6)):QQ(7,6,JX)=1-QQ(7,7,J
X)-QQ(7,8,JX)
7175 QQ(8,9,JX)=(1-QQ(8,8,JX))*(VB(8)-VB(7))/(VB(9)-VB(7)):QQ(8,7,JX)=1-QQ(8,8,J
X)-QQ(8,9,JX)
7180 QQ(9,10,JX)=(1-QQ(9,9,JX))*(VB(9)-VB(8))/(VB(10)-VB(8)):QQ(9,8,JX)=1-QQ(9,9
,JX)-QQ(9,10,JX)
7185 QQ(10,11,JX)=(1-QQ(10,10,JX))*(VB(10)-VB(9))/(VB(11)-VB(9)):QQ(10,9,JX)=1-Q
Q(10,10,JX)-QQ(10,11,JX)
7190 RETURN
7195 REM ***********************************************************************
********************************************************************************
********************************************************************************
7400 QQ(1,2,JX)=(1-QQ(1,1,JX))*(VB(1)-VB(0))/(VB(2)-VB(0)):QQ(1,0,JX)=1-QQ(1,1,J
X)-QQ(1,2,JX):REM THIS IS +-2 DISTRIBUTION OF COMP FOR 0<K<=1
7405 QQ(2,4,JX)=(1-QQ(2,2,JX))*(VB(2)-VB(1))/(VB(4)-VB(1)):QQ(2,1,JX)=1-QQ(2,2,J
X)-QQ(2,4,JX)
7410 QQ(3,5,JX)=(1-QQ(3,3,JX))*(VB(3)-VB(1))/(VB(5)-VB(1)):QQ(3,1,JX)=1-QQ(3,3,J
X)-QQ(3,5,JX)
7415 QQ(4,6,JX)=(1-QQ(4,4,JX))*(VB(4)-VB(2))/(VB(6)-VB(2)):QQ(4,2,JX)=1-QQ(4,4,J
X)-QQ(4,6,JX)
7420 QQ(5,7,JX)=(1-QQ(5,5,JX))*(VB(5)-VB(3))/(VB(7)-VB(3)):QQ(5,3,JX)=1-QQ(5,5,J
X)-QQ(5,7,JX)
7425 QQ(6,8,JX)=(1-QQ(6,6,JX))*(VB(6)-VB(4))/(VB(8)-VB(4)):QQ(6,4,JX)=1-QQ(6,6,J
X)-QQ(6,8,JX)
7430 QQ(7,9,JX)=(1-QQ(7,7,JX))*(VB(7)-VB(5))/(VB(9)-VB(5)):QQ(7,5,JX)=1-QQ(7,7,J
X)-QQ(7,9,JX)
7435 QQ(8,10,JX)=(1-QQ(8,8,JX))*(VB(8)-VB(6))/(VB(10)-VB(6)):QQ(8,6,JX)=1-QQ(8,8
,JX)-QQ(8,10,JX)
7440 QQ(9,10,JX)=(1-QQ(9,9,JX))*(VB(9)-VB(7))/(VB(10)-VB(7)):QQ(9,7,JX)=1-QQ(9,9
,JX)-QQ(9,10,JX)
7445 QQ(10,11,JX)=(1-QQ(10,10,JX))*(VB(10)-VB(9))/(VB(11)-VB(9)):QQ(10,9,JX)=1-Q
Q(10,10,JX)-QQ(10,11,JX)
7450 RETURN
7455 REM ***********************************************************************
********************************************************************************
********************************************************************************
7520 Q(1,4,NNK)=(1-Q(1,1,NNK))*(VB(1)-VB(0))/(VB(4)-VB(0)):Q(1,0,NNK)=1-Q(1,1,NN
K)-Q(1,4,NNK):REM THIS IS +-3 DISTRIBUTION OF COMP FOR K>1
7525 Q(2,5,NNK)=(1-Q(2,2,NNK))*(VB(2)-VB(0))/(VB(5)-VB(0)):Q(2,0,NNK)=1-Q(2,2,NN
K)-Q(2,5,NNK)
7530 Q(3,6,NNK)=(1-Q(3,3,NNK))*(VB(3)-VB(0))/(VB(6)-VB(0)):Q(3,0,NNK)=1-Q(3,3,NN
```

```
K)-Q(3,6,NNK)
7535 Q(4,7,NNK)=(1-Q(4,4,NNK))*(VB(4)-VB(1))/(VB(7)-VB(1)):Q(4,1,NNK)=1-Q(4,4,NN
K)-Q(4,7,NNK)
7540 Q(5,8,NNK)=(1-Q(5,5,NNK))*(VB(5)-VB(2))/(VB(8)-VB(2)):Q(5,2,NNK)=1-Q(5,5,NN
K)-Q(5,8,NNK)
7545 Q(6,9,NNK)=(1-Q(6,6,NNK))*(VB(6)-VB(3))/(VB(9)-VB(3)):Q(6,3,NNK)=1-Q(6,6,NN
K)-Q(6,9,NNK)
7550 Q(7,10,NNK)=(1-Q(7,7,NNK))*(VB(7)-VB(4))/(VB(10)-VB(4)):Q(7,4,NNK)=1-Q(7,7,
NNK)-Q(7,10,NNK)
7555 Q(8,11,NNK)=(1-Q(8,8,NNK))*(VB(8)-VB(5))/(VB(11)-VB(5)):Q(8,5,NNK)=1-Q(8,8,
NNK)-Q(8,11,NNK)
7560 Q(9,11,NNK)=(1-Q(9,9,NNK))*(VB(9)-VB(6))/(VB(11)-VB(6)):Q(9,6,NNK)=1-Q(9,9,
NNK)-Q(9,11,NNK)
7565 Q(10,11,NNK)=(1-Q(10,10,NNK))*(VB(10)-VB(7))/(VB(11)-VB(7)):Q(10,7,NNK)=1-Q
(10,10,NNK)-Q(10,11,NNK)
7570 RETURN
7575 REM ***********************************************************************
*****************************************************************************
*****************************************************************************
7600 REM SUBROUTINE TO CALCULATE QQ(I,I,J) WHEN K<0.5
7605 FOR IJ=0 TO 11:FOR JI=0 TO 11:QQ(IJ,JI,JX)=0:NEXT JI:NEXT IJ
7610 LK=LOG(KK(JX))/KL:LK2=LK^2:QQ(0,0,JX)=1:QQ(11,11,JX)=1:QQ(1,1,JX)=.682-.960
4*LK-.6892*LK2:IF (QQ(1,1,JX)>1) THEN QQ(1,1,JX)=1
7620 IF (KK(JX)<=.125) THEN GOTO 7675
7625 QQ(2,2,JX)=.492-1.035*LK-.4962*LK2:IF(QQ(2,2,JX)>1) THEN QQ(2,2,JX)=1
7630 QQ(3,3,JX)=-.555-4.149*LK-2.716*LK2:IF(QQ(3,3,JX)>1) THEN QQ(3,3,JX)=1
7635 QQ(4,4,JX)=-.68-4.603*LK-3.074*LK2:IF(QQ(4,4,JX)>1) THEN QQ(4,4,JX)=1
7640 QQ(5,5,JX)=-.626-4.105*LK-2.59*LK2:IF(QQ(5,5,JX)>1) THEN QQ(5,5,JX)=1
7645 QQ(6,6,JX)=-.626-4.105*LK-2.59*LK2:IF(QQ(6,6,JX)>1) THEN QQ(6,6,JX)=1
7650 QQ(7,7,JX)=-.68-4.603*LK-3.074*LK2:IF(QQ(7,7,JX)>1) THEN QQ(7,7,JX)=1
7655 QQ(8,8,JX)=-.555-4.149*LK-2.716*LK2:IF(QQ(8,8,JX)>1) THEN QQ(8,8,JX)=1
7660 QQ(9,9,JX)=.492-1.035*LK-.4962*LK2:IF(QQ(9,9,JX)>1) THEN QQ(9,9,JX)=1
7665 QQ(10,10,JX)=.682-.9604*LK-.6892*LK2:IF(QQ(10,10,JX)>1) THEN QQ(10,10,JX)=1
7670 RETURN
7675 QQ(1,1,JX)=1:QQ(2,2,JX)=1:QQ(3,3,JX)=1:QQ(4,4,JX)=1:QQ(5,5,JX)=1:QQ(6,6,JX)
=1:QQ(7,7,JX)=1:QQ(8,8,JX)=1:QQ(9,9,JX)=1:QQ(10,10,JX)=1
7680 RETURN
7685 REM ***********************************************************************
*****************************************************************************
*****************************************************************************
7800 REM SUBROUTINE TO CALCULATE QQ(I,I,J) WHEN .5<K<=1
7805 FOR IJ=0 TO 11:FOR JI=0 TO 11:QQ(IJ,JI,JX)=0:NEXT JI:NEXT IJ
7810 LK=LOG(KK(JX))/KL:LK2=LK^2:QQ(0,0,JX)=1:QQ(11,11,JX)=1:QQ(1,1,JX)=.682-.960
4*LK-.6892*LK2:IF (QQ(1,1,JX)>1) THEN QQ(1,1,JX)=1
7815 QQ(2,2,JX)=.492-1.035*LK-.4962*LK2:IF(QQ(2,2,JX)>1) THEN QQ(2,2,JX)=1
7820 QQ(3,3,JX)=.33-2.426*LK:IF(QQ(3,3,JX)>1) THEN QQ(3,3,JX)=1
7825 QQ(4,4,JX)=.39-1.743*LK:IF(QQ(4,4,JX)>1) THEN QQ(4,4,JX)=1
7830 QQ(5,5,JX)=.409-1.57*LK:IF(QQ(5,5,JX)>1) THEN QQ(5,5,JX)=1
7835 QQ(6,6,JX)=.409-1.57*LK:IF(QQ(6,6,JX)>1) THEN QQ(6,6,JX)=1
7840 QQ(7,7,JX)=.39-1.743*LK:IF(QQ(7,7,JX)>1) THEN QQ(7,7,JX)=1
7845 QQ(8,8,JX)=.33-2.426*LK:IF(QQ(8,8,JX)>1) THEN QQ(8,8,JX)=1
7850 QQ(9,9,JX)=.492-1.035*LK-.4962*LK2:IF(QQ(9,9,JX)>1) THEN QQ(9,9,JX)=1
7855 QQ(10,10,JX)=.682-.9604*LK-.6892*LK2:IF(QQ(10,10,JX)>1) THEN QQ(10,10,JX)=1
7860 RETURN
7865 REM ***********************************************************************
*****************************************************************************
*****************************************************************************
7900 REM SUBROUTINE TO CALCULATE Q(I,I,J)
7905 FOR IJ=0 TO 11:FOR JI=0 TO 11:Q(IJ,JI,NNK)=0:NEXT JI:NEXT IJ
7910 LK=LOG(K(NNK))/KL:LK2=LK^2:LK3=LK^3:Q(0,0,NNK)=1:Q(11,11,NNK)=1
```

```
7915 IF(K(NNK)>22.6274) THEN GOTO 7975
7920 Q(1,1,NNK)=.80006-1.35224*LK+1.39025*LK2-.47826*LK3:IF (Q(1,1,NNK)>1) THEN
Q(1,1,NNK)=1
7925 Q(2,2,NNK)=.71424-1.34034*LK+1.44463*LK2-.51497*LK3:IF(Q(2,2,NNK)>1) THEN Q
(2,2,NNK)=1
7930 Q(3,3,NNK)=.40049-.35359*LK+.44286*LK2-.18713*LK3:IF(Q(3,3,NNK)>1) THEN Q(3
,3,NNK)=1
7935 Q(4,4,NNK)=.3347-.37783*LK+.5052801*LK2-.21405*LK3:IF(Q(4,4,NNK)>1) THEN Q(
4,4,NNK)=1
7940 Q(5,5,NNK)=.5202-.86754*LK+.74131*LK2-.2246*LK3:IF(Q(5,5,NNK)>1) THEN Q(5,5
,NNK)=1
7945 Q(6,6,NNK)=.5202-.86754*LK+.74131*LK2-.2246*LK3:IF(Q(6,6,NNK)>1) THEN Q(6,6
,NNK)=1
7950 Q(7,7,NNK)=.3347-.37783*LK+.5052801*LK2-.21405*LK3:IF(Q(7,7,NNK)>1) THEN Q(
7,7,NNK)=1
7955 Q(8,8,NNK)=.40049-.35359*LK+.44286*LK2-.18713*LK3:IF(Q(8,8,NNK)>1) THEN Q(8
,8,NNK)=1
7960 Q(9,9,NNK)=.71424-1.34034*LK+1.44463*LK2-.51497*LK3:IF(Q(9,9,NNK)>1) THEN Q
(9,9,NNK)=1
7965 Q(10,10,NNK)=.80006-1.35224*LK+1.39025*LK2-.47826*LK3:IF(Q(10,10,NNK)>1) TH
EN Q(10,10,NNK)=1
7970 RETURN
7975 Q(1,1,NNK)=.33057:Q(2,2,NNK)=.26941:Q(3,3,NNK)=.28121:Q(4,4,NNK)=.23126:Q(5
,5,NNK)=.14703:Q(6,6,NNK)=.14703:Q(7,7,NNK)=.23126:Q(8,8,NNK)=.28121:Q(9,9,NNK)=
.26941:Q(10,10,NNK)=.33057:RETURN
7980 REM ***********************************************************************
********************************************************************************
********************************************************************************
9100 REM SUBROUTINE TO HANDLE COMBINATION OF TWO FACTORS OF 2^.25 TO GET EQUVALE
NT OF A 2^.5 FACTOR FOR USE WITH NORMAL 2^.5 SCREEN SIVES (IORI-ORIGINAL SIZE, I
INT-INTERMEDIATE SIZE, IFIN-FINAL SIZE)
9110 FOR IORI=0 TO 11:FOR IFIN=0 TO 11:QQ(IORI,IFIN,3)=0:NEXT IFIN:NEXT IORI
9120 FOR IFIN=0 TO 11
9130 FOR IINT=0 TO 11
9140 FOR IORI=0 TO 11
9150 QQ(IORI,IFIN,3)=QQ(IORI,IFIN,3)+QQ(IORI,IINT,1)*QQ(IINT,IFIN,2)
9160 NEXT IORI:NEXT IINT:NEXT IFIN
9170 FOR IORI=0 TO 11:FOR IFIN=0 TO 11:Q(IORI,IFIN,NNK)=QQ(IORI,IFIN,3):NEXT IFI
N:NEXT IORI:RETURN
9175 REM ***********************************************************************
********************************************************************************
********************************************************************************
9180 FOR J=2 TO 13
9190 FOR I=0 TO 11:QT(I)=0:NEXT I
9200 FOR I=0 TO 11:FOR II=0 TO 11:QT(I)=QT(I)+Q(I,II,JX):NEXT II:NEXT I
9210 PRINT #1," "
9220 PRINT #1,USING " ###.##";K(JX),Q(0,0,JX),Q(1,1,JX),Q(2,2,JX),Q(3,3,JX),Q(4,
4,JX),Q(5,5,JX),Q(6,6,JX),Q(7,7,JX),Q(8,8,JX),Q(9,9,JX),Q(10,10,JX),Q(11,11,JX)
9230 PRINT #1,USING " ###.##";K(J),QT(0),QT(1),QT(2),QT(3),QT(4),QT(5),QT(6),QT(
7),QT(8),QT(9),QT(10),QT(11)
9240 NEXT J
9250 RETURN
9260 REM ***********************************************************************
********************************************************************************
********************************************************************************
9500 REM SUB TO CONVERT VOL RESULTS TO WT RESULTS-SIWAST IS % WT SIO2 IN WASTE,
FEWAST IS % WT NONMAG FE IN WASTE, ROA AND ROB ARE RESPECTIVELY THE SPECIFIC GRA
VITIES OF WASTE AND MAGNETITE, 72.36 IS % FE BY WT IN FE3O4
9505 SIWAST=65.36:FEWAST=15.84:ROA=3!:ROB=5.2:FOR IW=0 TO 11:RO(IW)=VB(IW)*ROB+(
1-VB(IW))*ROA:WB(IW)=VB(IW)*ROB/RO(IW):WBM(IW)=WB(IW)*72.36:WBT(IW)=WB(IW)*72.36
```

Table 9 (cont'd)

```
+(1-WB(IW))*FEWAST:WBS(IW)=(1-WB(IW))*SIWAST:NEXT IW
9507 FOR J=1 TO 13:FOR IW=0 TO 11:XP(J,IW)=P(J,IW):NEXT IW:NEXT J
9508 REM FOR J=1 TO 13:PRINT #3, USING " ####.##";J,(ALPHA/BETA(J)),XP(J,0),XP(J
,1),XP(J,2),XP(J,3),XP(J,4),XP(J,5),XP(J,6),XP(J,7),XP(J,8),XP(J,9),XP(J,10),XP(
J,11):NEXT J
9509 REM FOR J=1 TO 13:PRINT #3, USING " ####.##";J,(ALPHA/BETA(J)),P(J,0),P(J,1
),P(J,2),P(J,3),P(J,4),P(J,5),P(J,6),P(J,7),P(J,8),P(J,9),P(J,10),P(J,11):NEXT J
9510 CUMWT=0:FOR J=1 TO 13:CUMW(J)=0:FOR IW=0 TO 11:WP(J,IW)=XP(J,IW)*RO(IW):CUM
W(J)=CUMW(J)+WP(J,IW):NEXT IW:CUMWT=CUMWT+CUMW(J):NEXT J
9515 FOR J=1 TO 13:FOR IW=0 TO 11:WP(J,IW)=WP(J,IW)*100/CUMWT:NEXT IW:CUMW(J)=CU
MW(J)*100/CUMWT:NEXT J
9520 FOR J=1 TO 13:CWBM(J)=0:FOR IW=0 TO 11:CWBM(J)=CWBM(J)+WP(J,IW)*WBM(IW):NEX
T IW:CWBM(J)=CWBM(J)/CUMW(J):NEXT J
9525 FOR J=1 TO 13:CWBT(J)=0:FOR IW=0 TO 11:CWBT(J)=CWBT(J)+WP(J,IW)*WBT(IW):NEX
T IW:CWBT(J)=CWBT(J)/CUMW(J):NEXT J
9530 FOR J=1 TO 13:CWBS(J)=0:FOR IW=0 TO 11:CWBS(J)=CWBS(J)+WP(J,IW)*WBS(IW):NEX
T IW:CWBS(J)=CWBS(J)/CUMW(J):NEXT J
9551 PRINT #3, " "
9555 PRINT #3, BMN," VALUE OF RESIDENCE TIME, TAU=  ",TAU,"MIN.    VALUE OF GRIN
D RATE RATIO (WASTE/VALUE), RAB=  ",RAB
9556 PRINT #3, " "
9560 PRINT #3, " COMPOSITION INTERVAL VALUES - % VOL FE304/% WT FE304/% WT MAG F
E/% WT TOT FE/% WT SIO2 "
9599 PRINT #3, USING " ####.##";0,0,100*VB(0),100*VB(1),100*VB(2),100*VB(3),100*
VB(4),100*VB(5),100*VB(6),100*VB(7),100*VB(8),100*VB(9),100*VB(10),100*VB(11)
9600 PRINT #3, USING " ####.##";0,0,100*WB(0),100*WB(1),100*WB(2),100*WB(3),100*
WB(4),100*WB(5),100*WB(6),100*WB(7),100*WB(8),100*WB(9),100*WB(10),100*WB(11)
9601 PRINT #3, USING " ####.##";0,0,WBM(0),WBM(1),WBM(2),WBM(3),WBM(4),WBM(5),WB
M(6),WBM(7),WBM(8),WBM(9),WBM(10),WBM(11)
9602 PRINT #3, USING " ####.##";0,0,WBT(0),WBT(1),WBT(2),WBT(3),WBT(4),WBT(5),WB
T(6),WBT(7),WBT(8),WBT(9),WBT(10),WBT(11)
9603 PRINT #3, USING " ####.##";0,0,WBS(0),WBS(1),WBS(2),WBS(3),WBS(4),WBS(5),WB
S(6),WBS(7),WBS(8),WBS(9),WBS(10),WBS(11)
9604 PRINT #3, " "
9605 PRINT #3, " FEED SIZE/COMPOSITION          WT / % WT MAG FE"
9610 FOR J=1 TO 13:PRINT #3, USING " ####.##";J,(ALPHA/BETA(J)),WP(J,0),WP(J,1),
WP(J,2),WP(J,3),WP(J,4),WP(J,5),WP(J,6),WP(J,7),WP(J,8),WP(J,9),WP(J,10),WP(J,11
),CUMW(J),CWBM(J)
9620 NEXT J
9622 CUM=0:CUMG=0:FOR IW=0 TO 11:CUMWP(IW)=0:FOR J=1 TO 13:CUMWP(IW)=CUMWP(IW)+W
P(J,IW):NEXT J:CUMG=CUMG+CUMWP(IW)*WBM(IW):CUM=CUM+CUMWP(IW):NEXT IW:CUMG=CUMG/C
UM
9625 PRINT #3, USING " ####.##";0,0,CUMWP(0),CUMWP(1),CUMWP(2),CUMWP(3),CUMWP(4)
,CUMWP(5),CUMWP(6),CUMWP(7),CUMWP(8),CUMWP(9),CUMWP(10),CUMWP(11),CUM,CUMG
9627 PRINT #3, USING " ####.##";0,0,CPR(0),CPR(1),CPR(2),CPR(3),CPR(4),CPR(5),CP
R(6),CPR(7),CPR(8),CPR(9),CPR(10),CPR(11),(100*PR/PR)
9628 FOR J=1 TO 13:FOR IW=0 TO 11:XP(J,IW)=P(J,IW):NEXT IW:NEXT J
9629 PRINT #3, " ":PRINT #3, " PRODUCT SIZE/COMPOSITION          WT / % WT MAG FE
"
9630 CUMWT=0:FOR J=1 TO 13:CUMW(J)=0:FOR IW=0 TO 11:WP(J,IW)=XP(J,IW)*RO(IW):CUM
W(J)=CUMW(J)+WP(J,IW):NEXT IW:CUMWT=CUMWT+CUMW(J):NEXT J
9635 FOR J=1 TO 13:FOR IW=0 TO 11:WP(J,IW)=WP(J,IW)*100/CUMWT:NEXT IW:CUMW(J)=CU
MW(J)*100/CUMWT:NEXT J
9640 FOR J=1 TO 13:CWBM(J)=0:FOR IW=0 TO 11:CWBM(J)=CWBM(J)+WP(J,IW)*WBM(IW):NEX
T IW:CWBM(J)=CWBM(J)/CUMW(J):NEXT J
9645 FOR J=1 TO 13:CWBT(J)=0:FOR IW=0 TO 11:CWBT(J)=CWBT(J)+WP(J,IW)*WBT(IW):NEX
T IW:CWBT(J)=CWBT(J)/CUMW(J):NEXT J
9650 FOR J=1 TO 13:CWBS(J)=0:FOR IW=0 TO 11:CWBS(J)=CWBS(J)+WP(J.IW)*WBS(IW):NEX
T IW:CWBS(J)=CWBS(J)/CUMW(J):NEXT J
9700 REM PRINT #3, USING " ####.##";0,0,100*WB(0),100*WB(1),100*WB(2),100*WB(3),
```

Table 9 (cont'd)

```
100*WB(4),100*WB(5),100*WB(6),100*WB(7),100*WB(8),100*WB(9),100*WB(10),100*WB(11
)
9710 FOR J=1 TO 13:PRINT #3, USING " ####.##";J,(ALPHA/BETA(J)),WP(J,0),WP(J,1),
WP(J,2),WP(J,3),WP(J,4),WP(J,5),WP(J,6),WP(J,7),WP(J,8),WP(J,9),WP(J,10),WP(J,11
),CUMW(J),CWBM(J):NEXT J
9712 CUM=0:CUMG=0:FOR IW=0 TO 11:CUMWP(IW)=0:FOR J=1 TO 13:CUMWP(IW)=CUMWP(IW)+W
P(J,IW):NEXT J:CUMG=CUMG+CUMWP(IW)*WBM(IW):CUM=CUM+CUMWP(IW):NEXT IW:CUMG=CUMG/C
UM
9715 PRINT #3, USING " ####.##";0,0,CUMWP(0),CUMWP(1),CUMWP(2),CUMWP(3),CUMWP(4)
,CUMWP(5),CUMWP(6),CUMWP(7),CUMWP(8),CUMWP(9),CUMWP(10),CUMWP(11),CUM,CUMG
9717 PRINT #3, USING " ####.##";0,0,CFR(0),CFR(1),CFR(2),CFR(3),CFR(4),CFR(5),CF
R(6),CFR(7),CFR(8),CFR(9),CFR(10),CFR(11),(100*FR/FR)
9799 RETURN
9800 REM ***********************************************************************
********************************************************************************
********************************************************************************
```

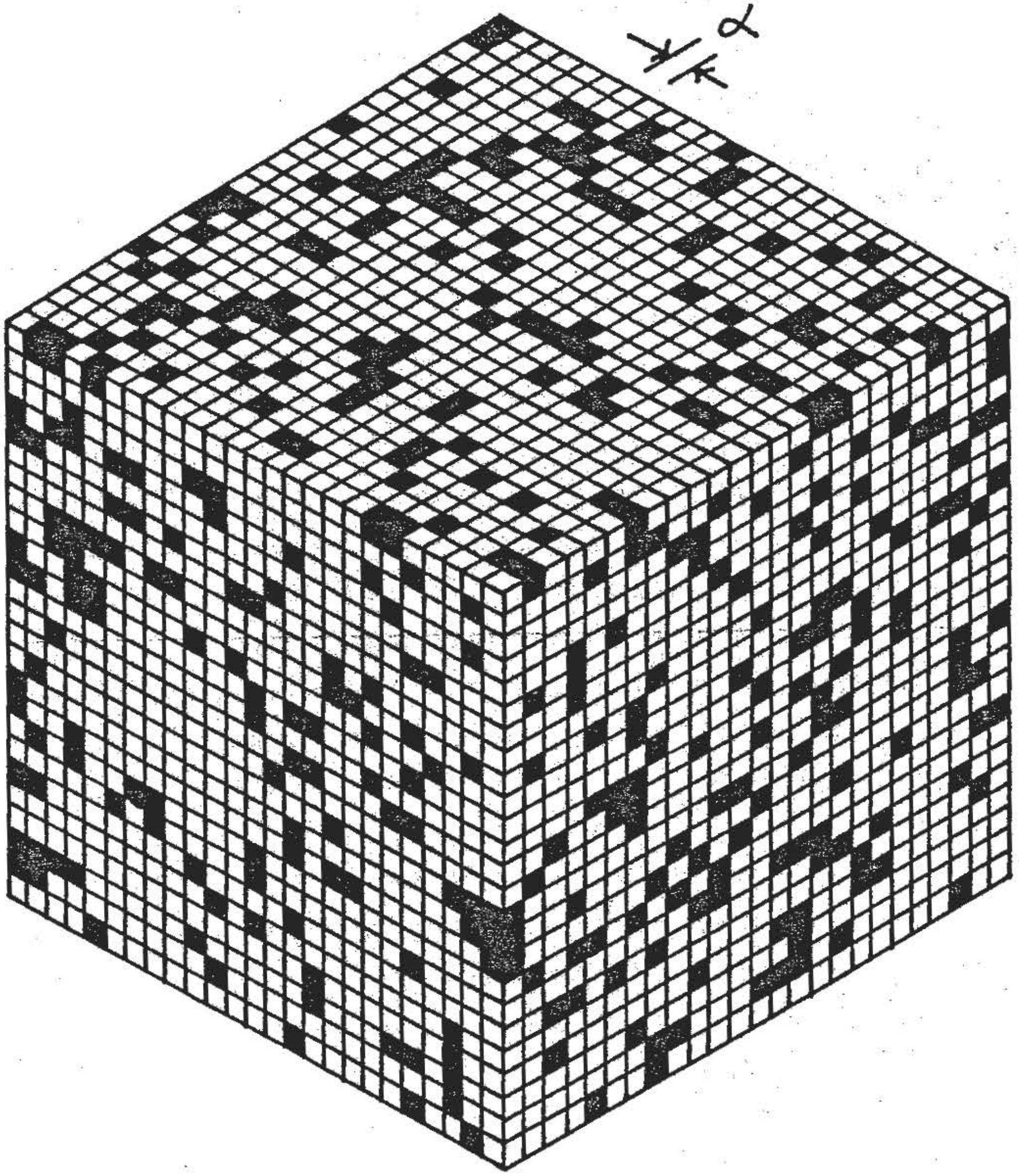


FIGURE 1 – VISUALIZATON OF A THEORETICAL BINARY MINERAL SYSTEM

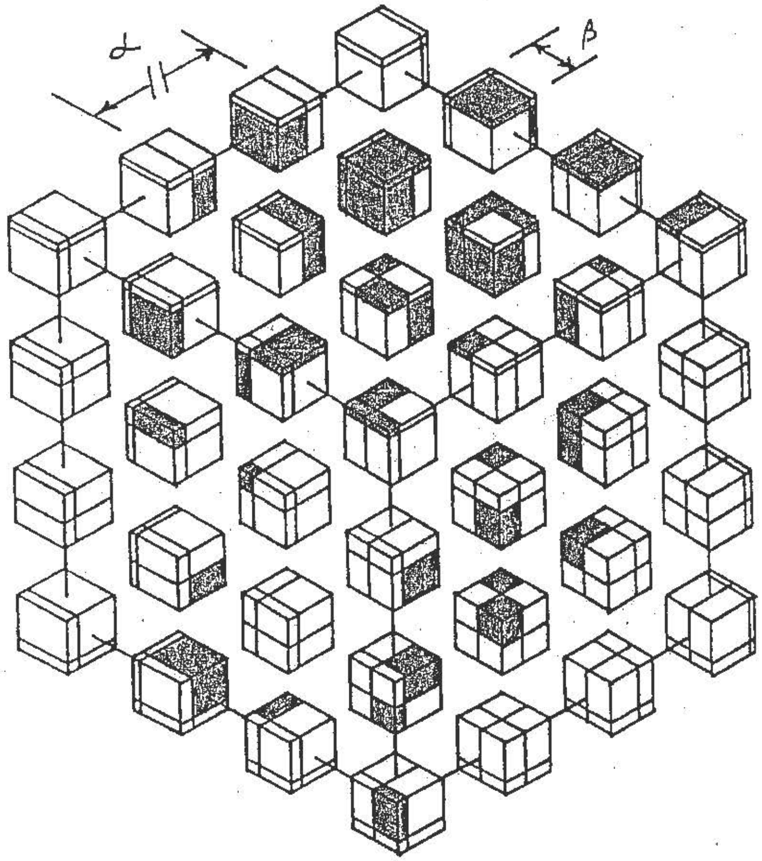


FIGURE 2A – VISUALIZATION OF BREAKAGE - PARTICLE SIZE APPROXIMATING GRAIN SIZE

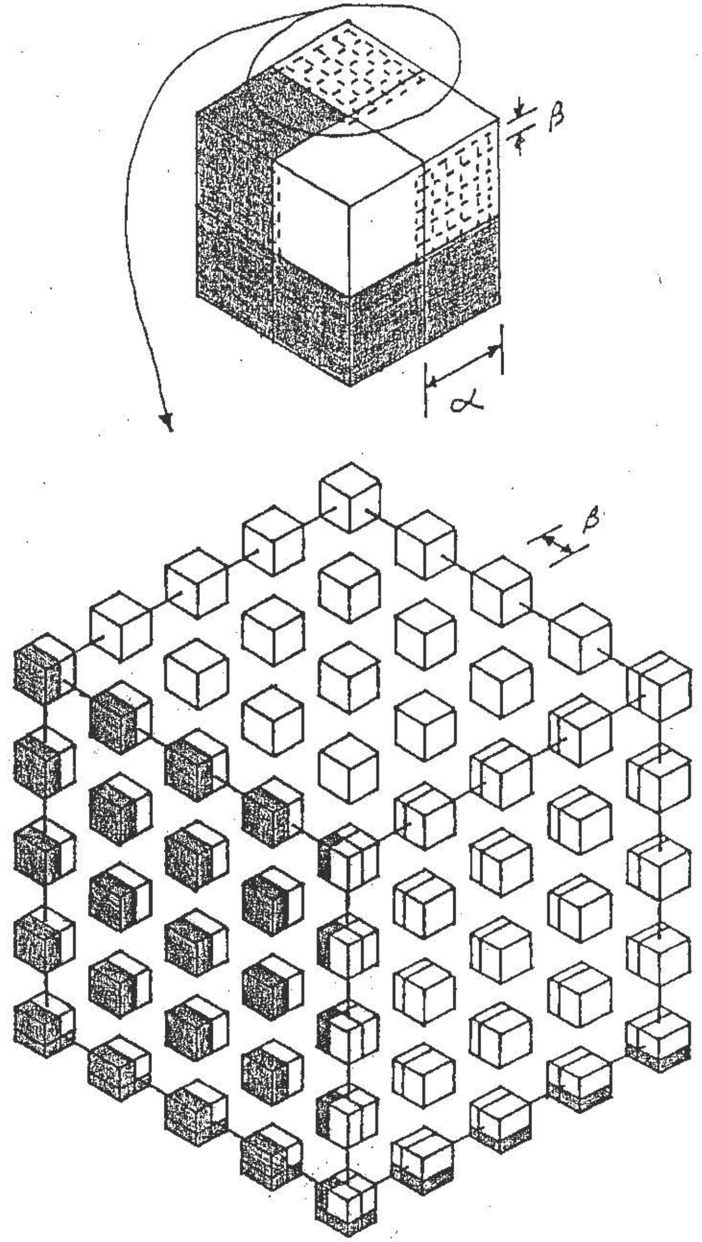


FIGURE 2B – VISUALIZATION OF BREAKAGE - PARTICLE SIZE SMALLER THAN GRAIN SIZE

FIGURE 3 – RELATIONSHIPS DERIVED FOR THE GAUDIN RANDOM LIBERATION MODEL

$VA + VB = 1$

VA	volume fraction waste mineral
VB	volume fraction valuable mineral

$k = \alpha / \beta$

α	mineral grain size
β	particle size

$1 / k = t + \in$

t	largest integer
$\in$	fractional remainder

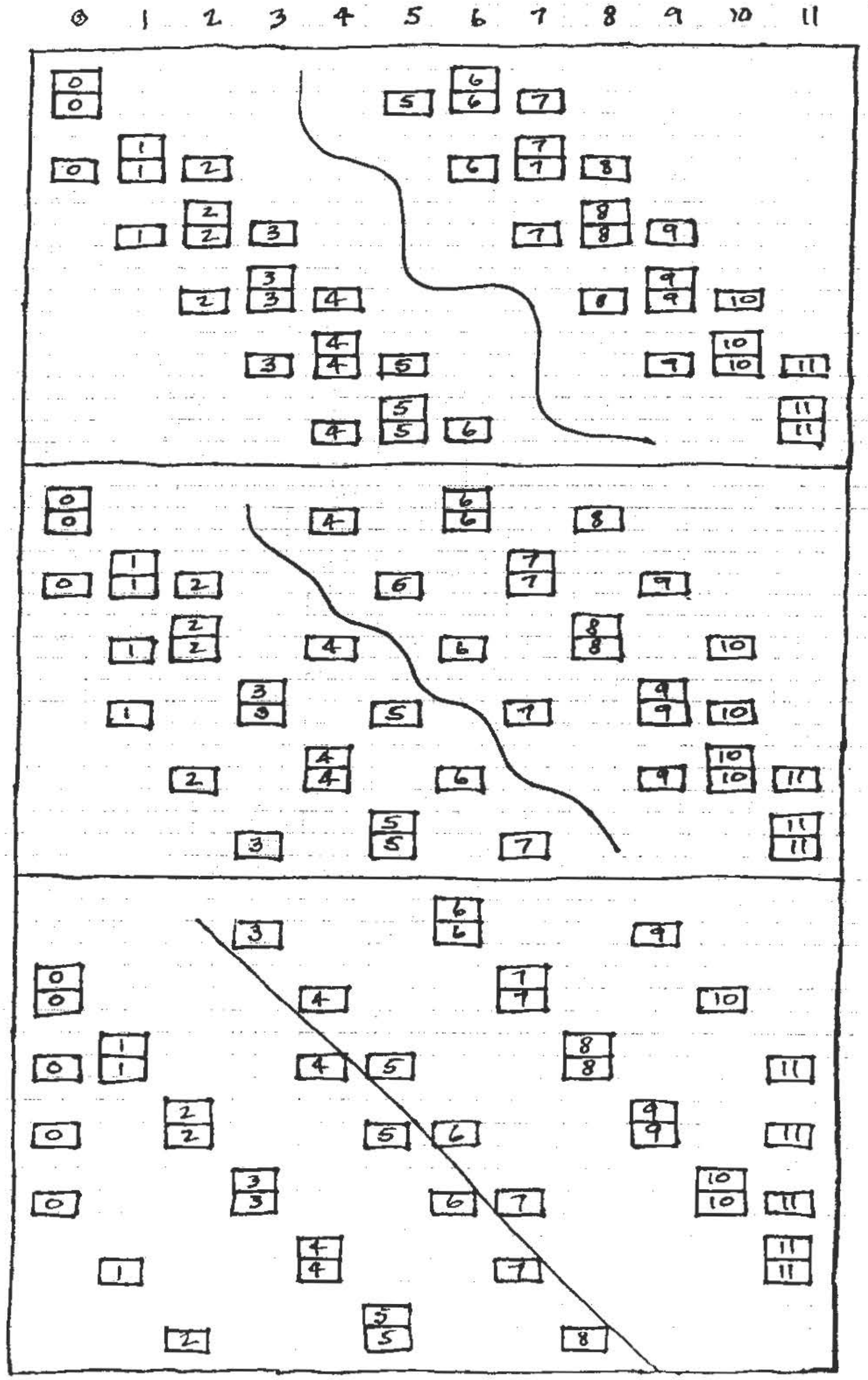
PA	fraction of particles which are liberated waste mineral
PB	fraction of particles which are liberated valuable mineral
PAB	fraction of particles which are locked waste/valuable minerals

$$PA = (1-\in)^3\, VA^{(t+1)^3} + 3\in(1-\in)^2\, VA^{(t+1)^2(t+2)} + 3\in^2(1-\in)\, VA^{(t+1)(t+2)^2} + \in^3\, VA^{(t+2)^3}$$

$$PB = (1-\in)^3\, VB^{(t+1)^3} + 3\in(1-\in)^2\, VB^{(t+1)^2(t+2)} + 3\in^2(1-\in)\, VB^{(t+1)(t+2)^2} + \in^3\, VB^{(t+2)^3}$$

$PAB = 1 - PA - PB$

FIGURE 4 – PICTORIAL REPRESENTATION OF NON-ZERO DIRECTIONAL COEFFICIENTS FOR THE THREE LIBERATION AREAS



$0.125 < KX \leq 0.5$

4th root of 2 particle size step

$0.5 < KX < 1$

4th root of 2 particle size step

$1 \leq KX \leq 22.63$

square root of 2 particle size step

FIGURE 5 – COMPOSITION SELECTIVE GRINDING RATE ADJUSTMENT

The following procedure is followed for modifying grinding rates as a linear function of particle values composition, VB(I),

$$\mathrm{AVGVB}(J) = \frac{\sum^{I} F(J,I)*VB(I)}{\sum^{I} F(J,I)}$$

I	composition index
J	particle size index
RAB	grind ratio, waste to value
TAU	residence time
S(J)	size dependent grind rate

$$\mathrm{GR}(J,I) = \frac{(VB(I) * 1 + (1-VB(I)) * RAB)}{(AVGVB(J) * 1 + (1-AVGVB(J)) * RAB)}$$

$$\mathrm{TS}(J,I) = S(J) * TAU * GR(J,I)$$

FIGURE 6 – DAVIS TUBE CONCENTRATE GRADE VERSUS PARTICLE SIZE

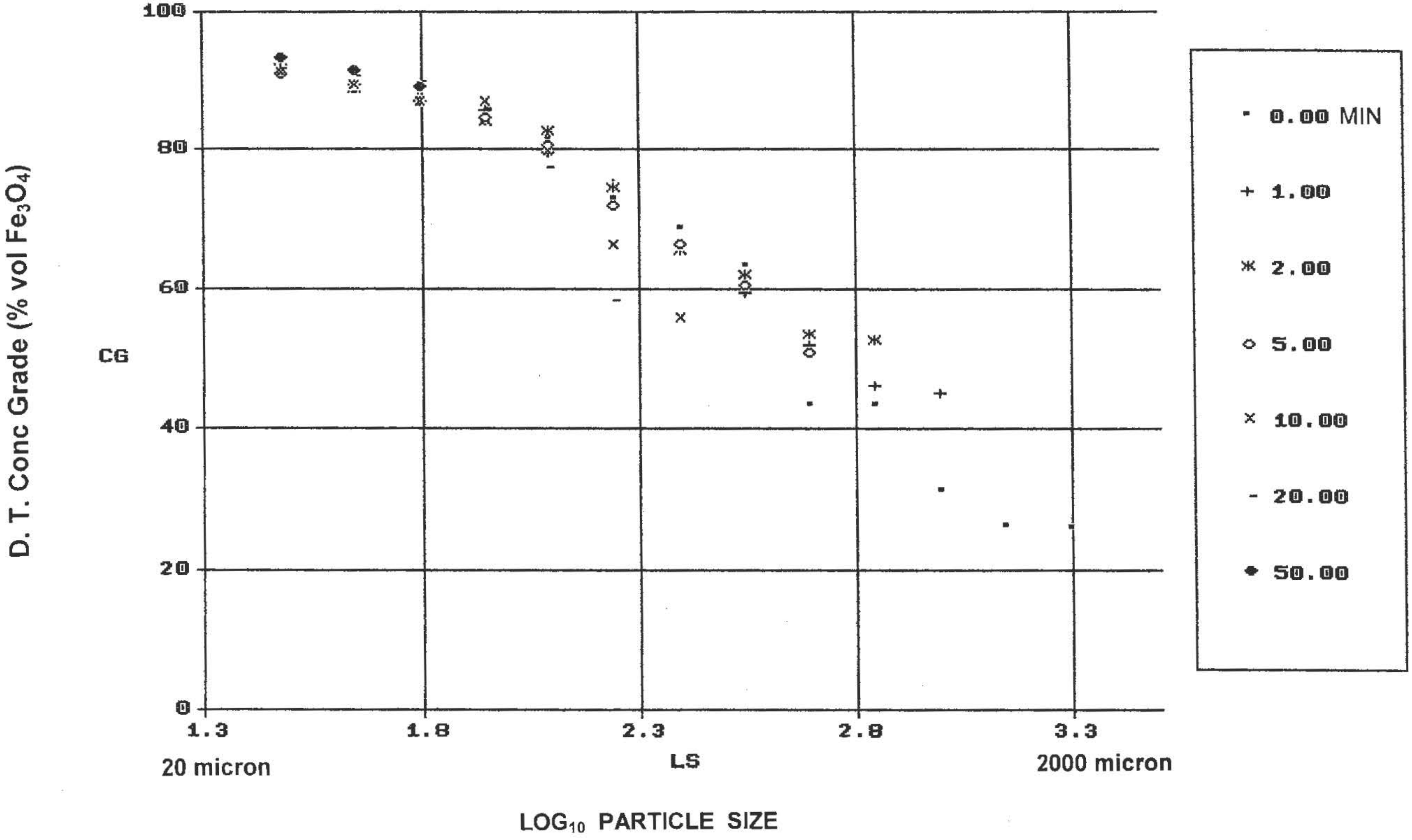


FIGURE 7 – DAVIS TUBE FEED GRADE VERSUS PARTICLE SIZE

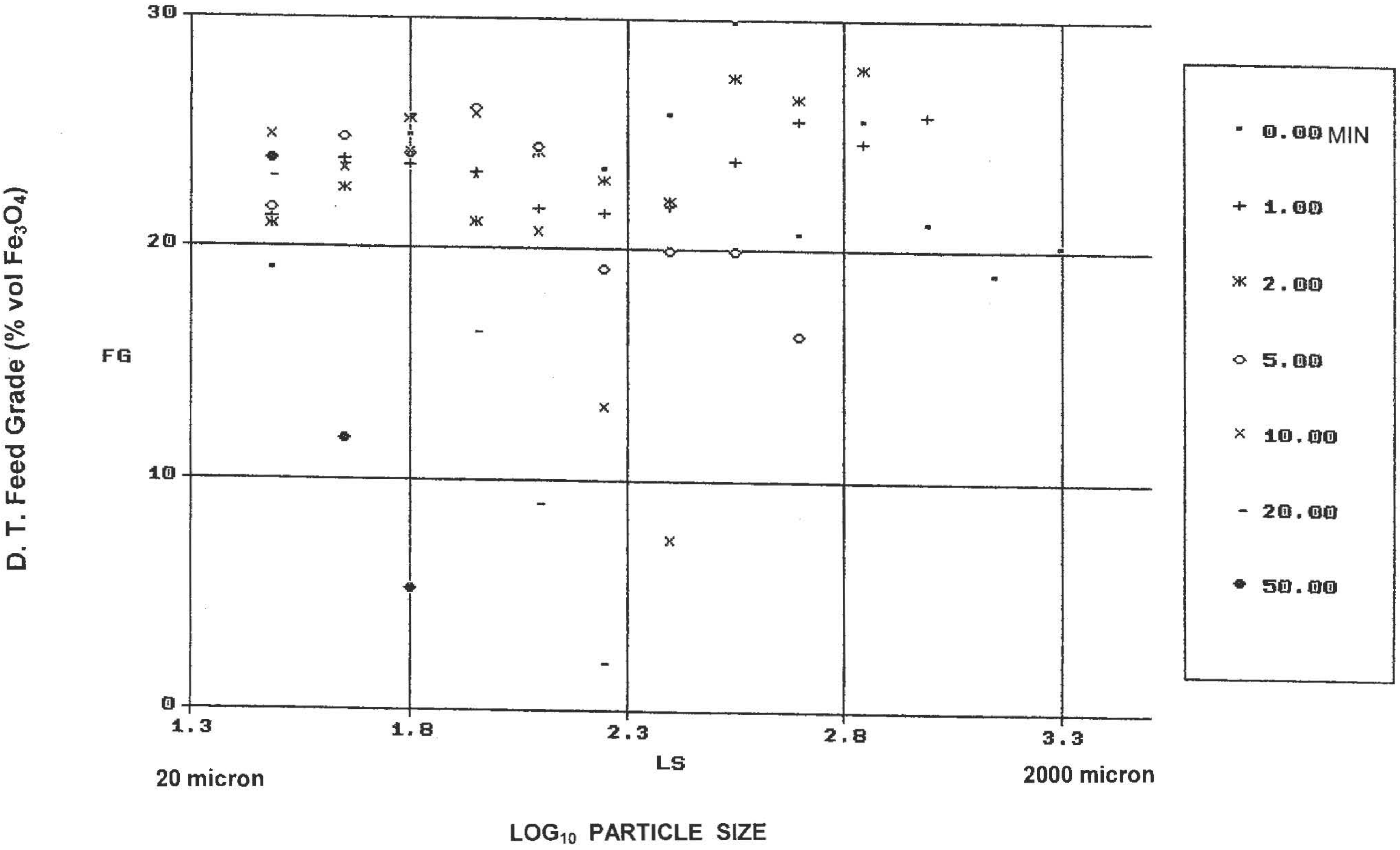


FIGURE 8 – DAVIS TUBE CONCENTRATE QUANTITY VERSUS PARTICLE SIZE

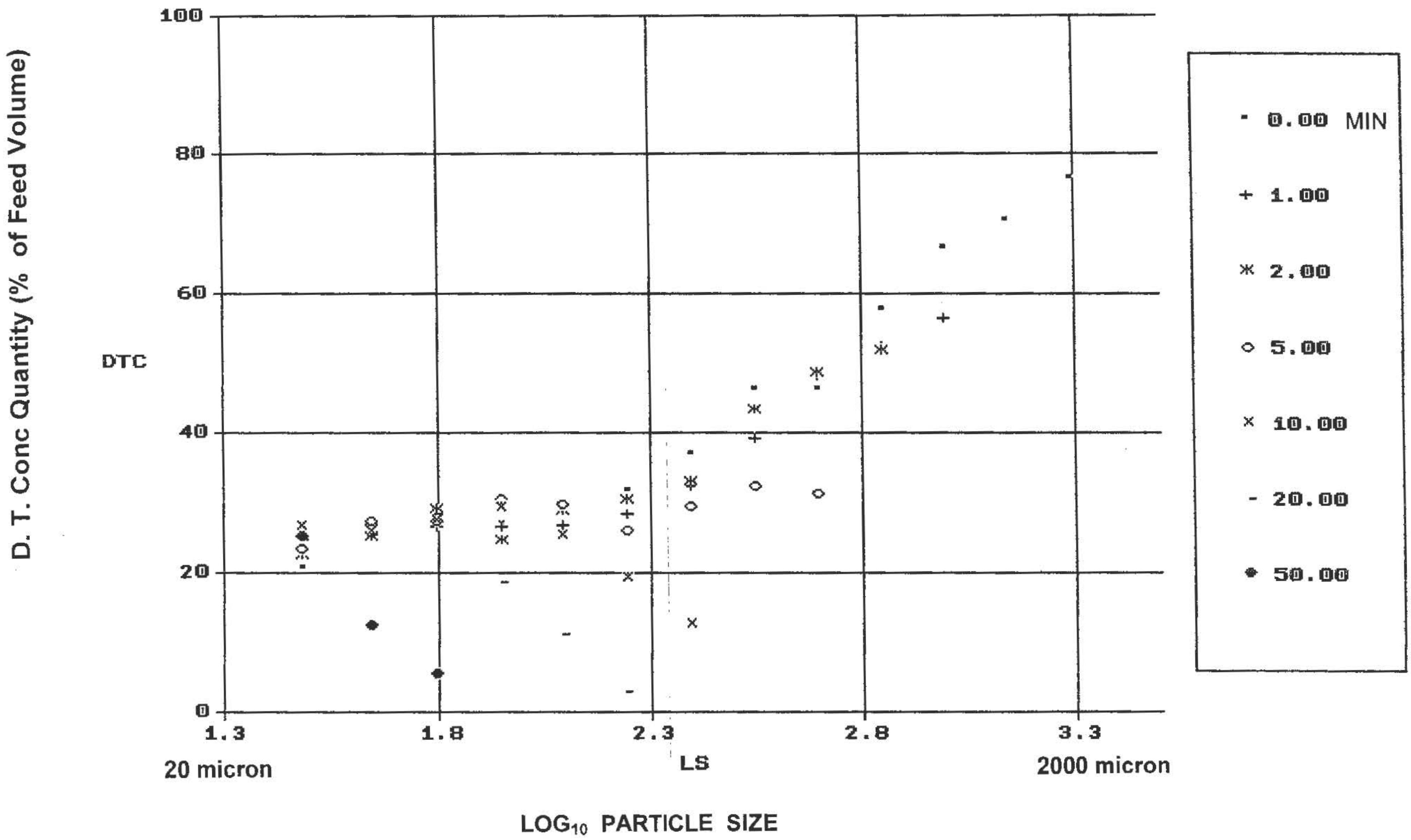


FIGURE 9 – SIMULATION RESULTS - CONCENTRATE GRADE VERSUS PARTICLE SIZE FOR GRIND RATIO OF 1.0

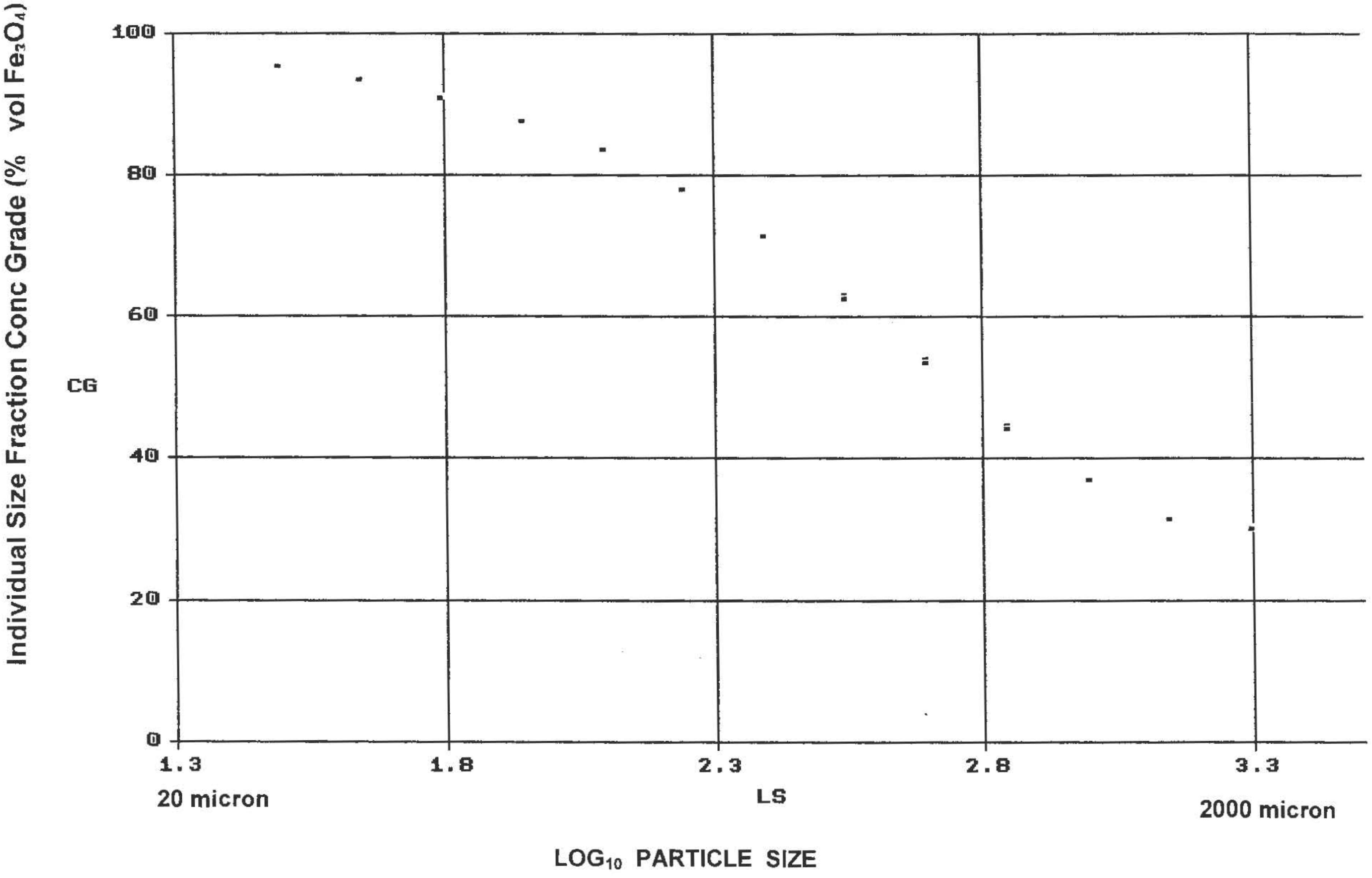


FIGURE 10 – SIMULATION RESULTS - FEED GRADE VERSUS PARTICLE SIZE
FOR GRIND RATIO OF 1.0

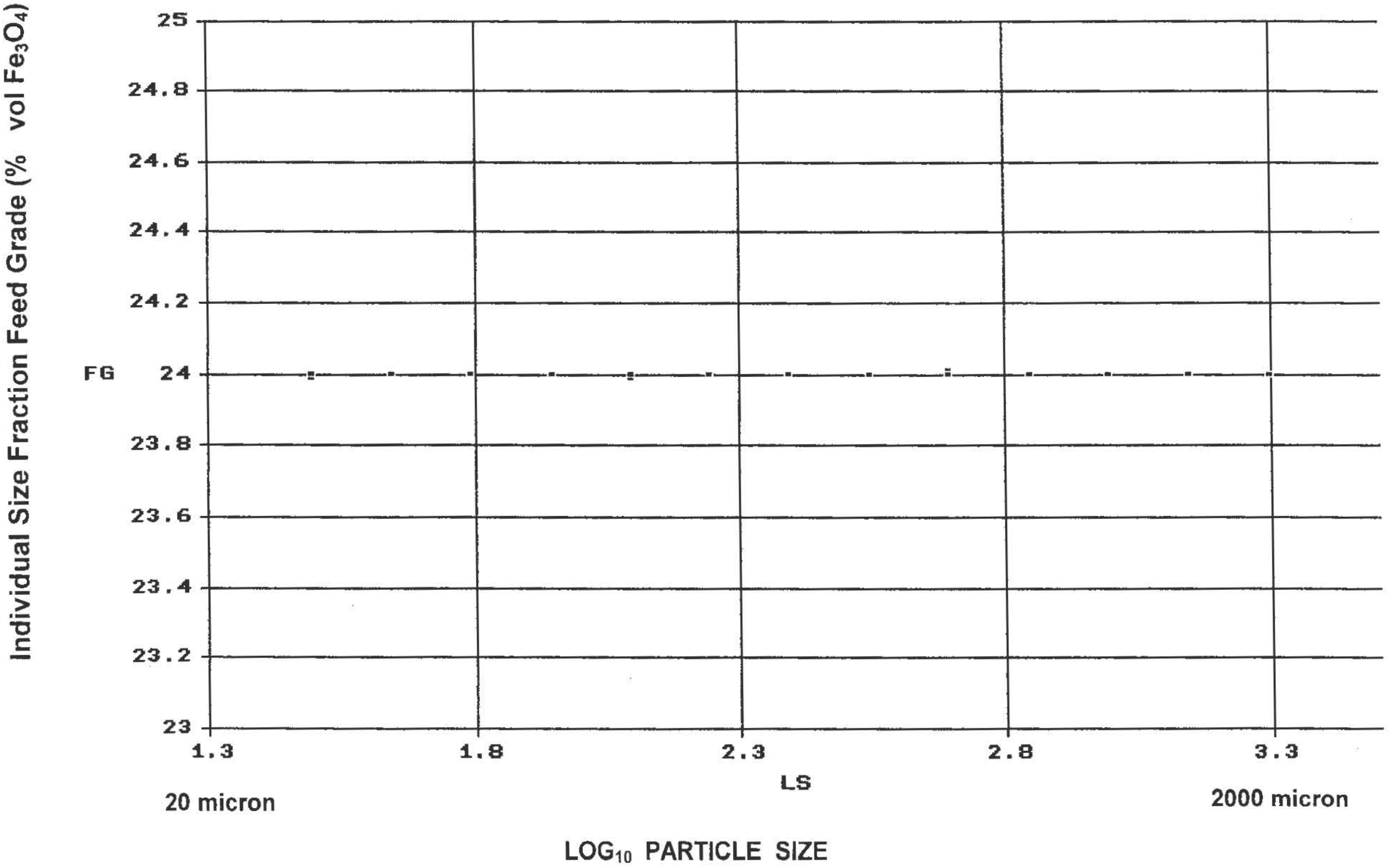


FIGURE 11 – SIMULATION RESULTS – CONCENTRATE QUANTITY VERSUS PARTICLE SIZE
FOR GRIND RATIO OF 1.0

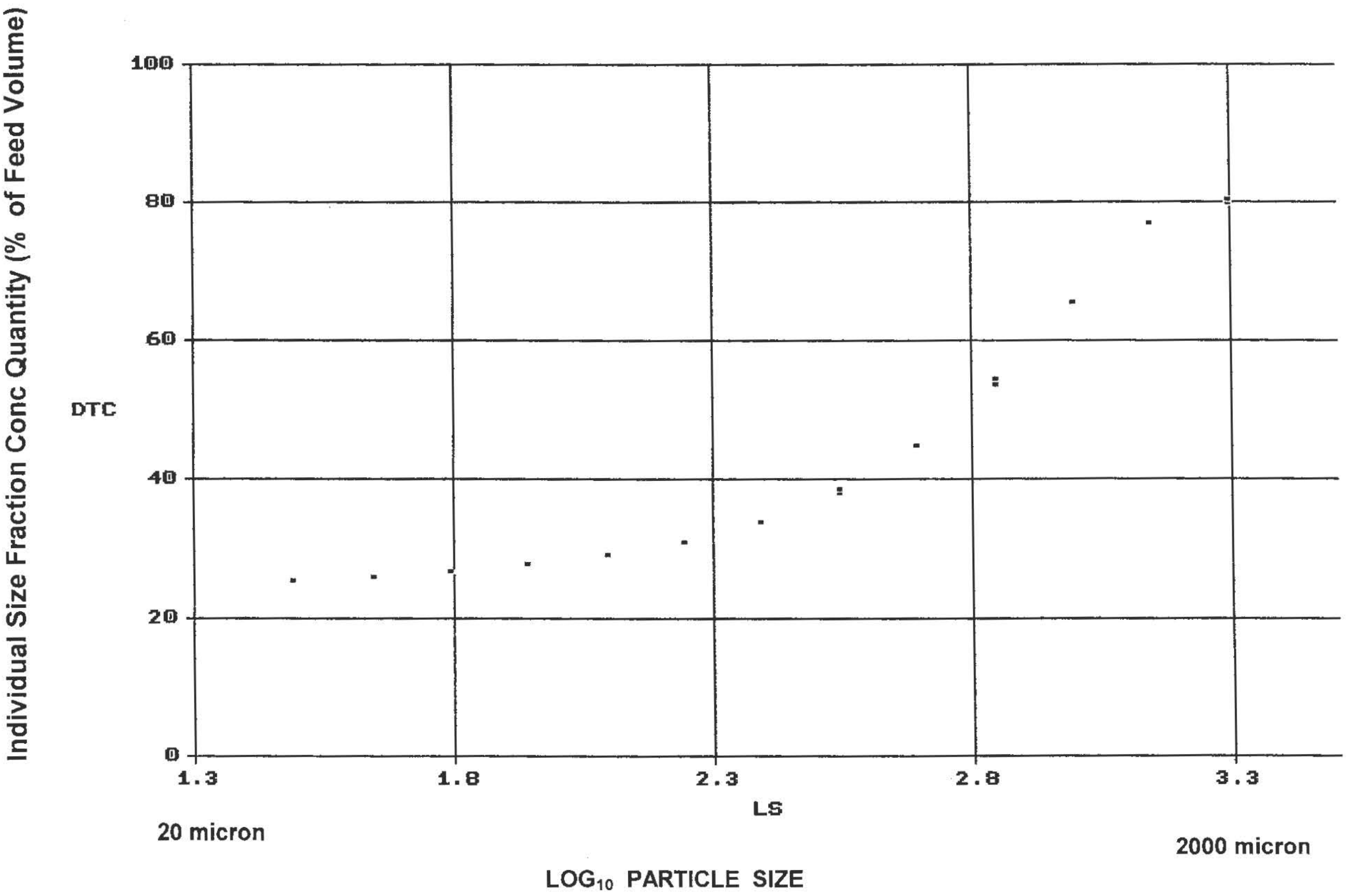


FIGURE 12 – SIMULATION RESULTS – CONCENTRATE GRADE VERSUS PARTICLE SIZE
FOR GRIND RATIO OF 0.67

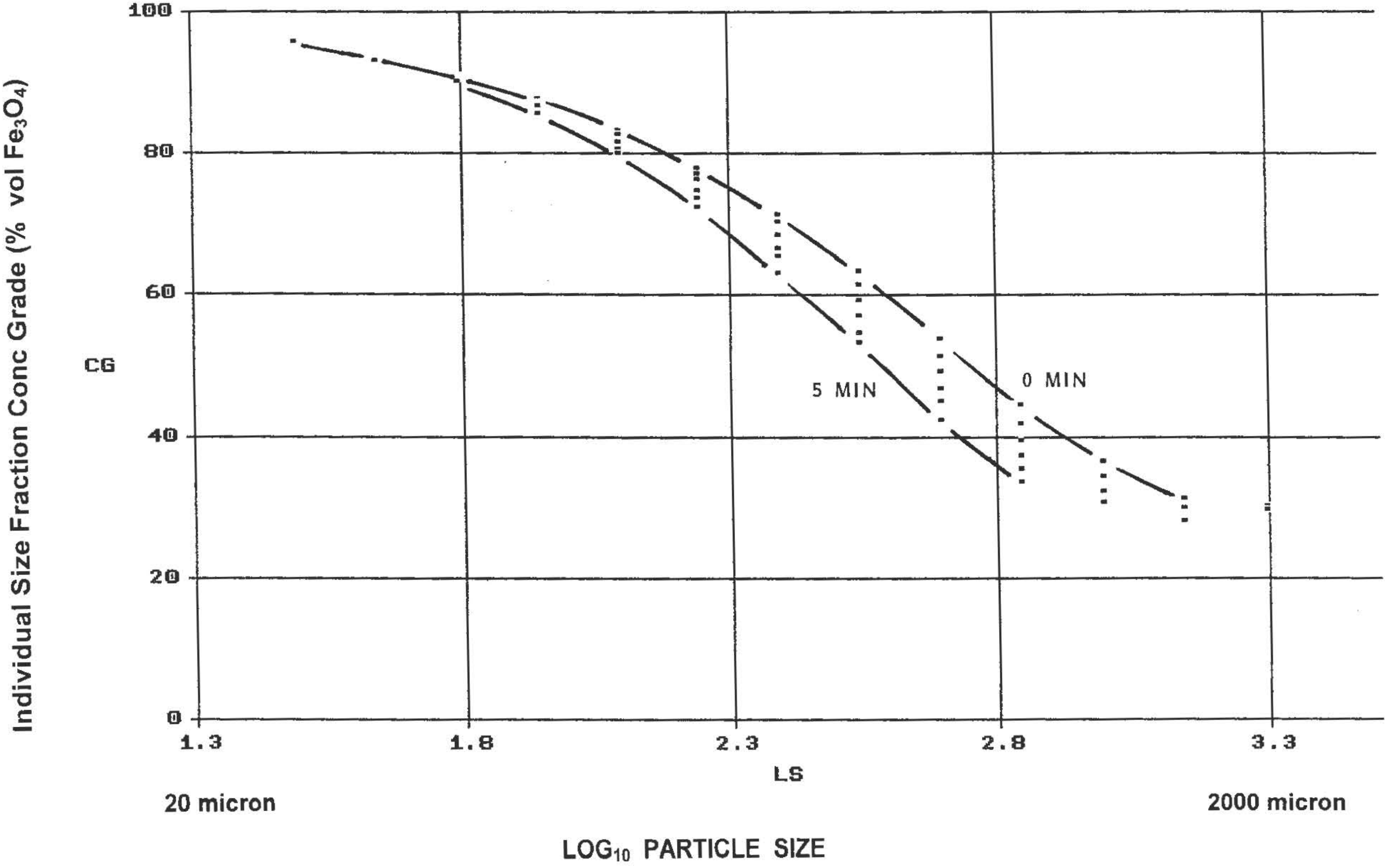


FIGURE 13 – SIMULATION RESULTS – FEED GRADE VERSUS PARTICLE SIZE
FOR GRIND RATIO OF 0.67

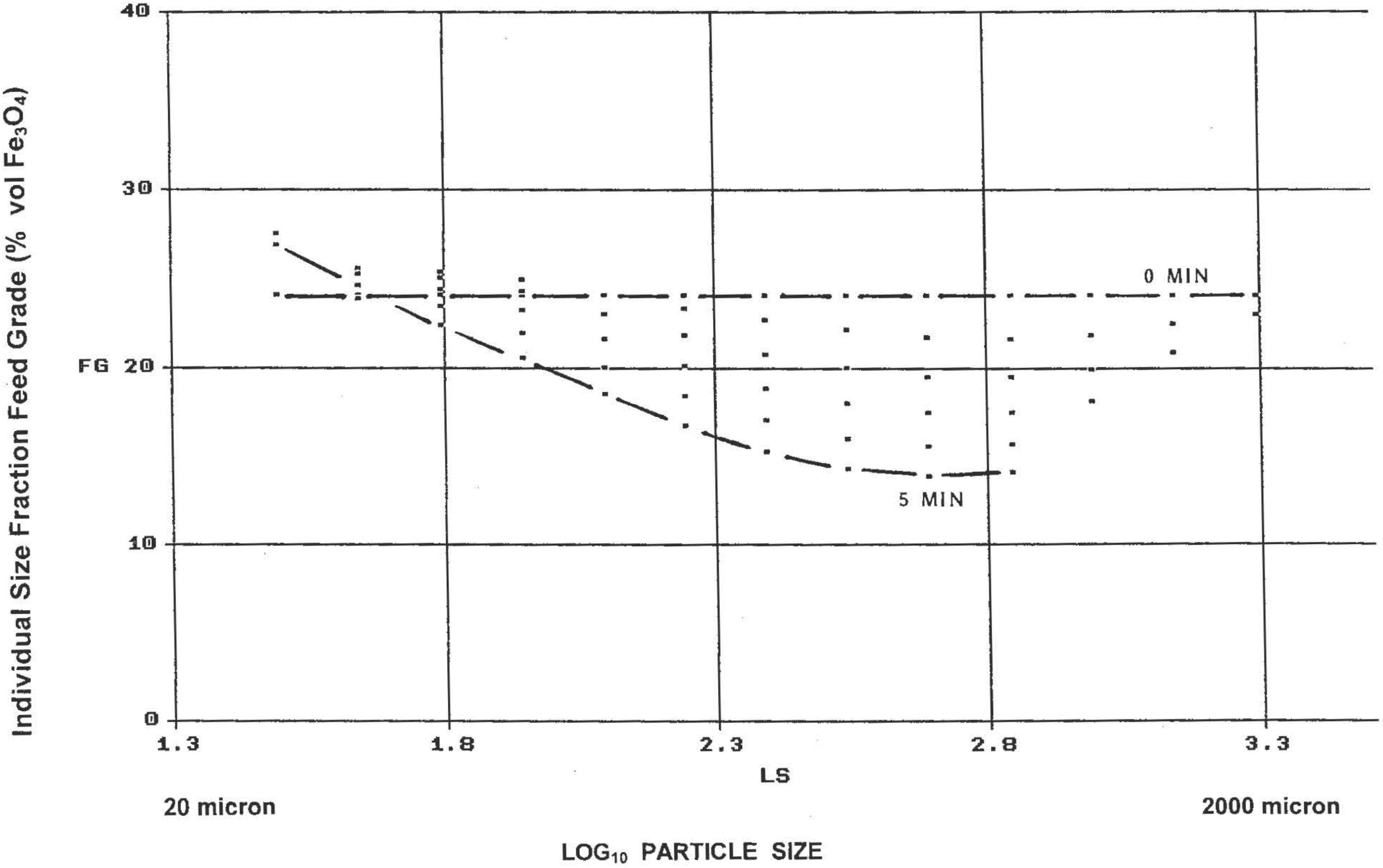


FIGURE 14 – SIMULATION RESULTS – CONCENTRATE QUANTITY VERSUS PARTICLE SIZE
FOR GRIND RATIO OF 0.67

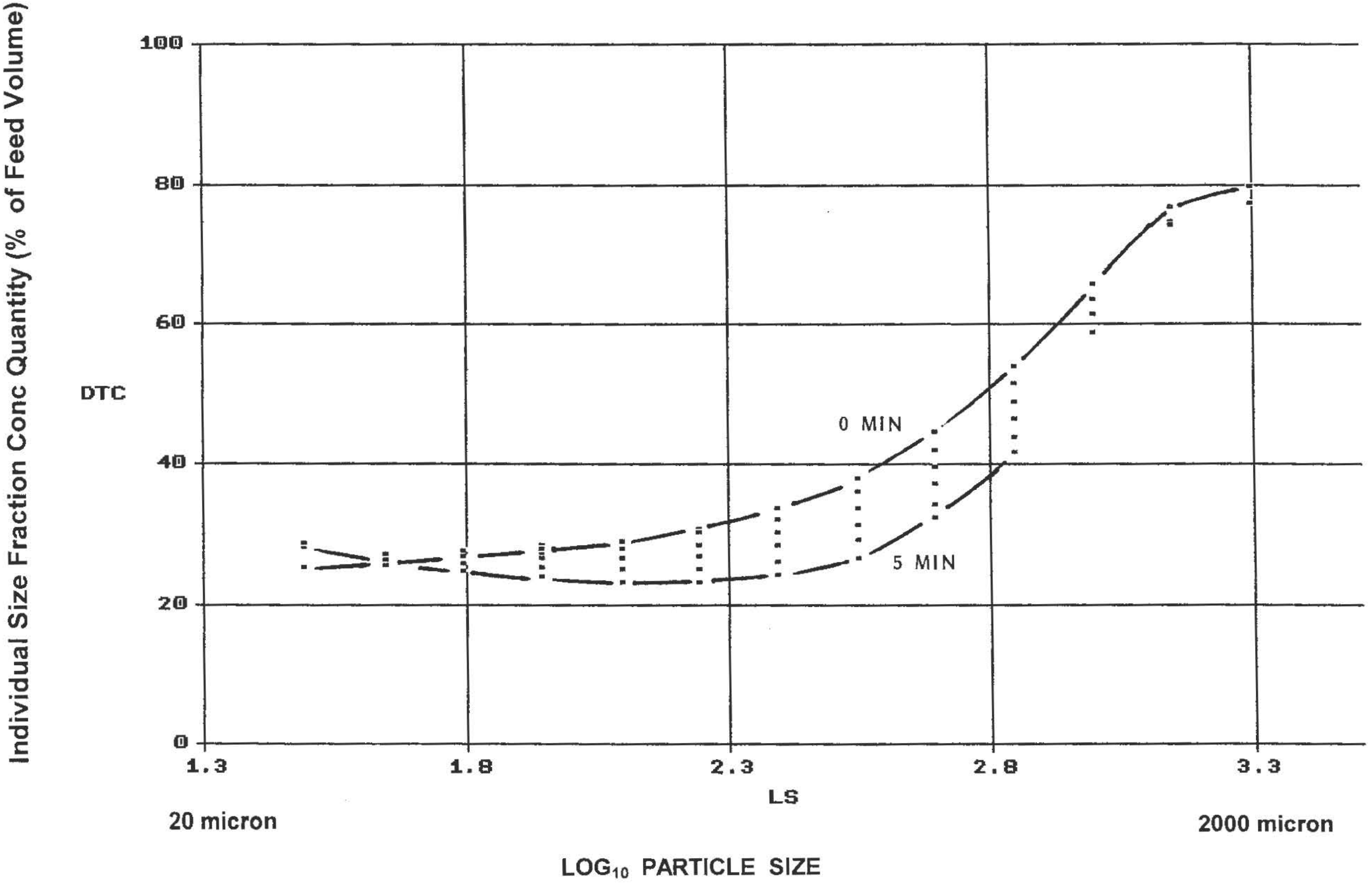


FIGURE 15 – SIMULATION RESULTS – CONCENTRATE GRADE VERSUS PARTICLE SIZE FOR GRIND RATIO OF 1.5

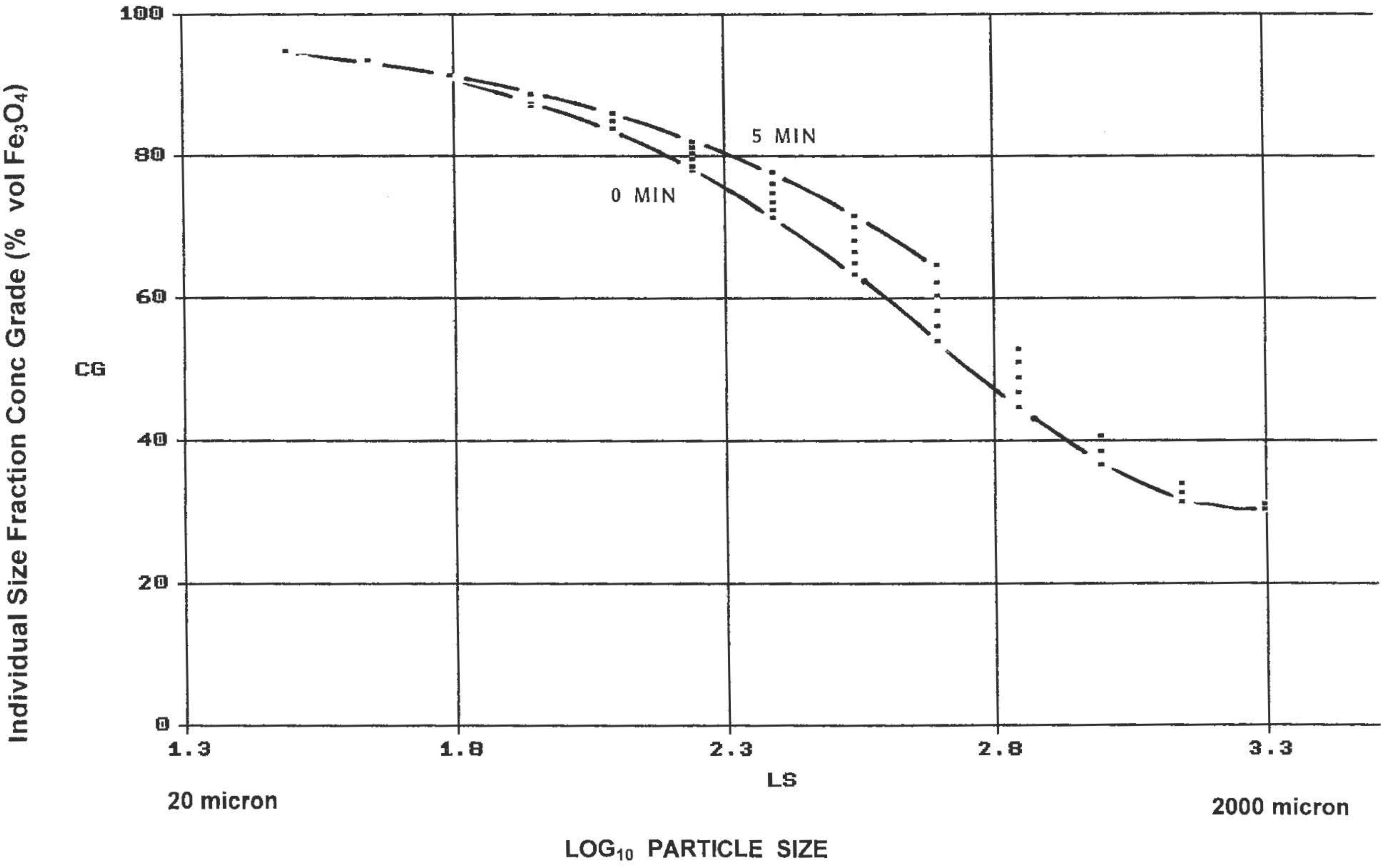


FIGURE 16 – SIMULATION RESULTS – FEED GRADE VERSUS PARTICLE SIZE FOR GRIND RATIO OF 1.5

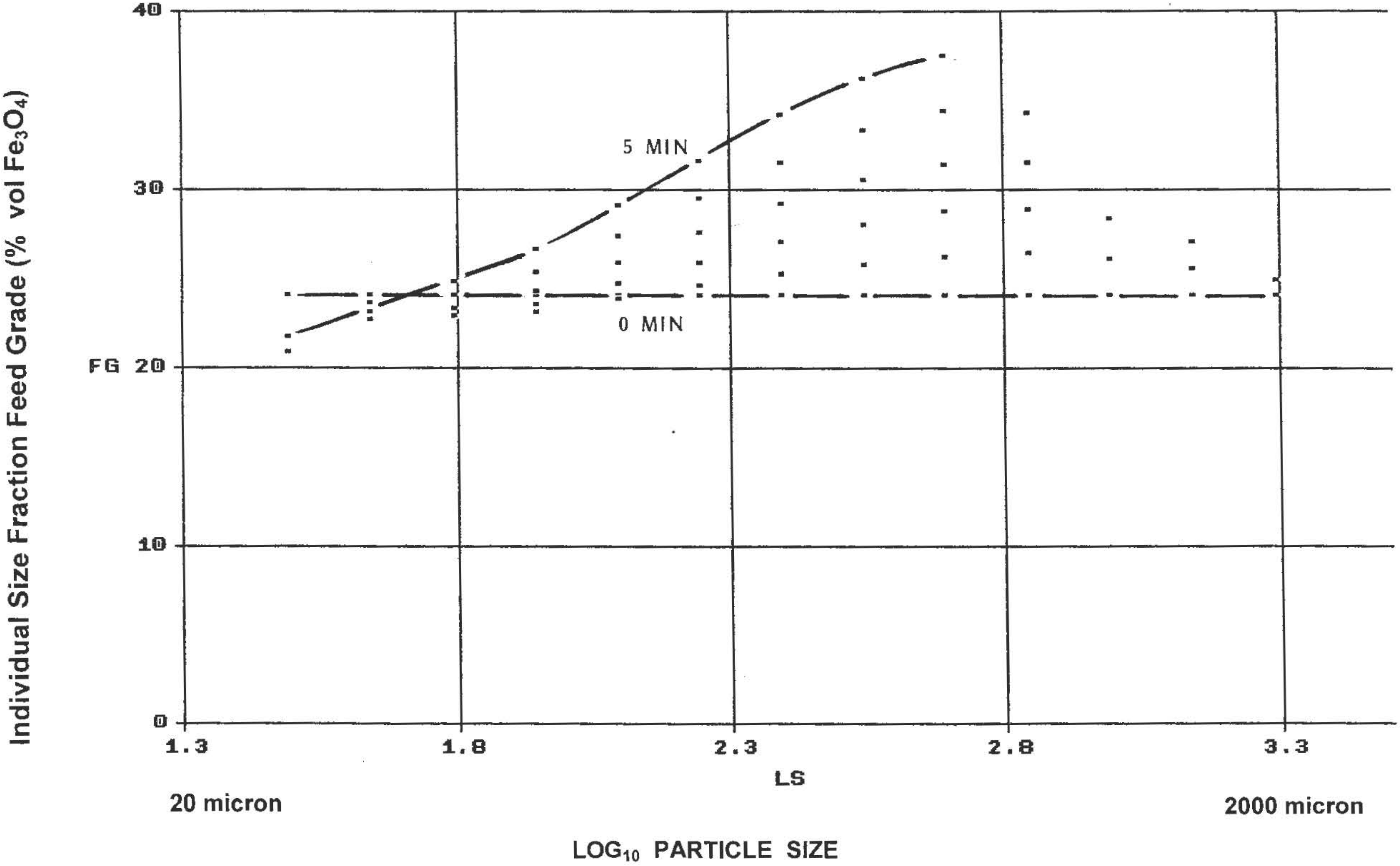


FIGURE 17 – SIMULATION RESULTS – CONCENTRATE QUANTITY VERSUS PARTICLE SIZE
FOR GRIND RATIO OF 1.5

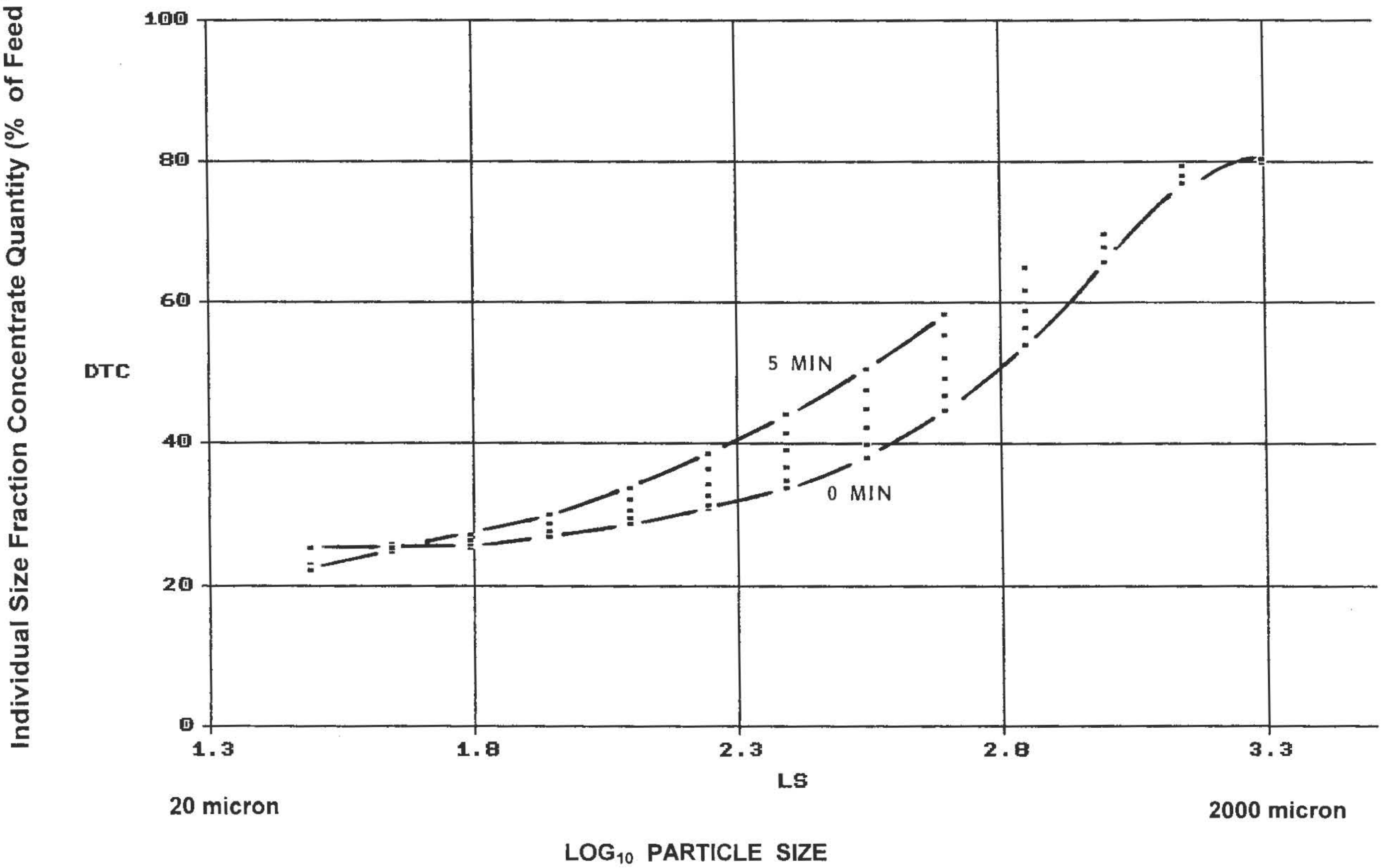


FIGURE 18 – SIMULATION RESULTS – EFFECT OF BATCH GRINDING TIME ON PARTICLE SIZE OF PRODUCT

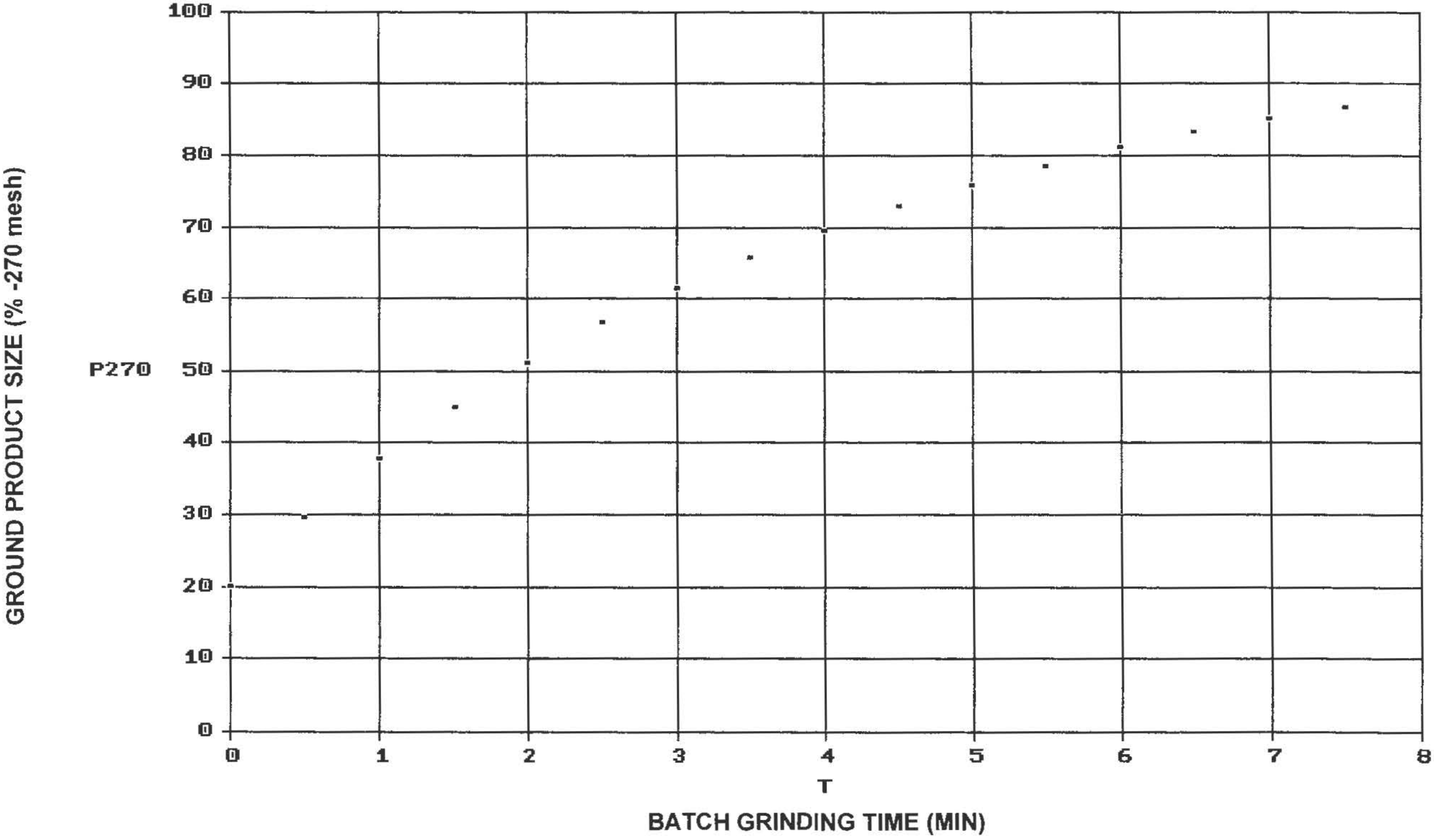


FIGURE 19 – SIMULATION RESULTS – EFFECT OF PRODUCT SIZE ON CONCENTRATE GRADE

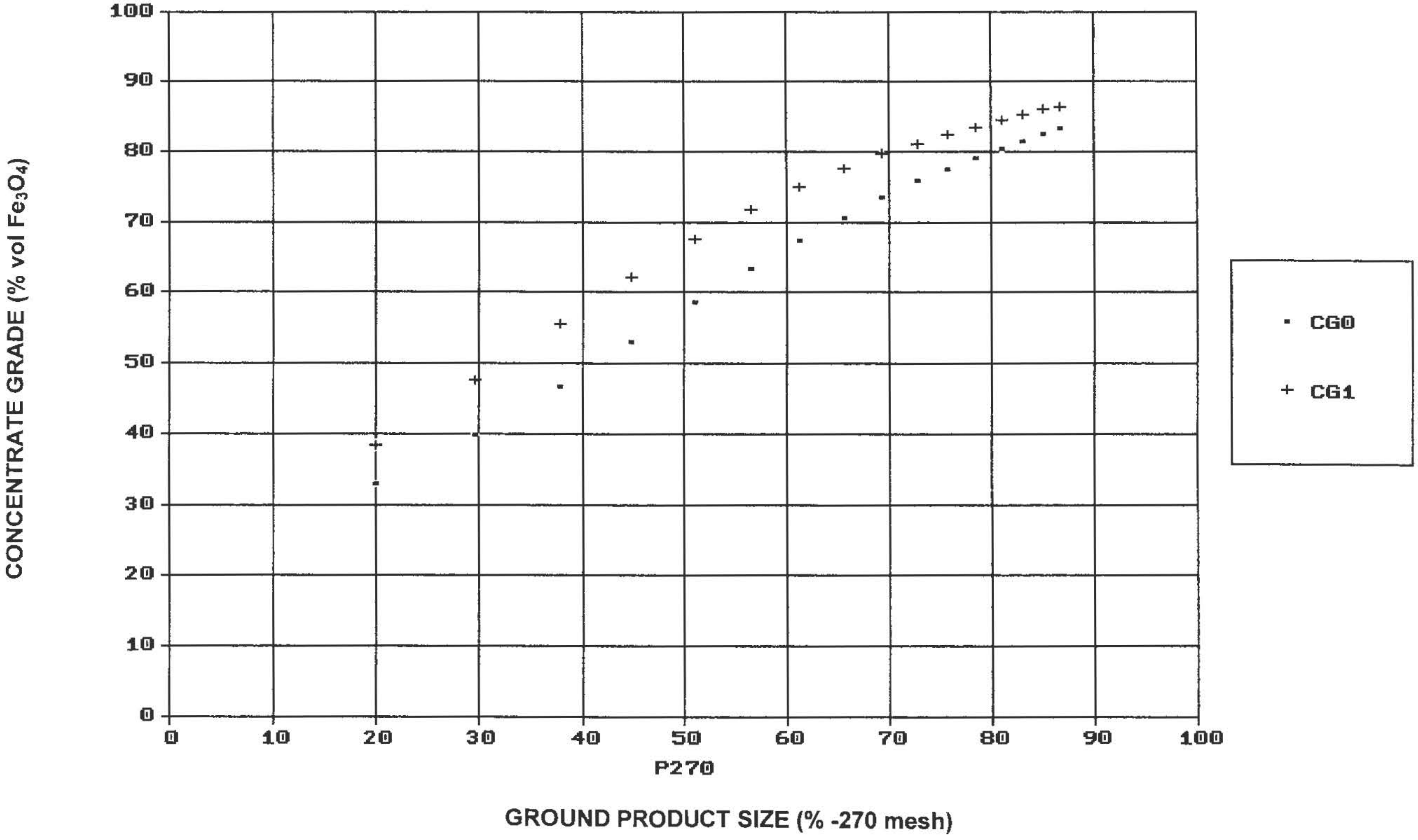


FIGURE 20 – SIMULATION RESULTS – EFFECT OF PRODUCT SIZE
ON CONCENTRATE QUANTITY

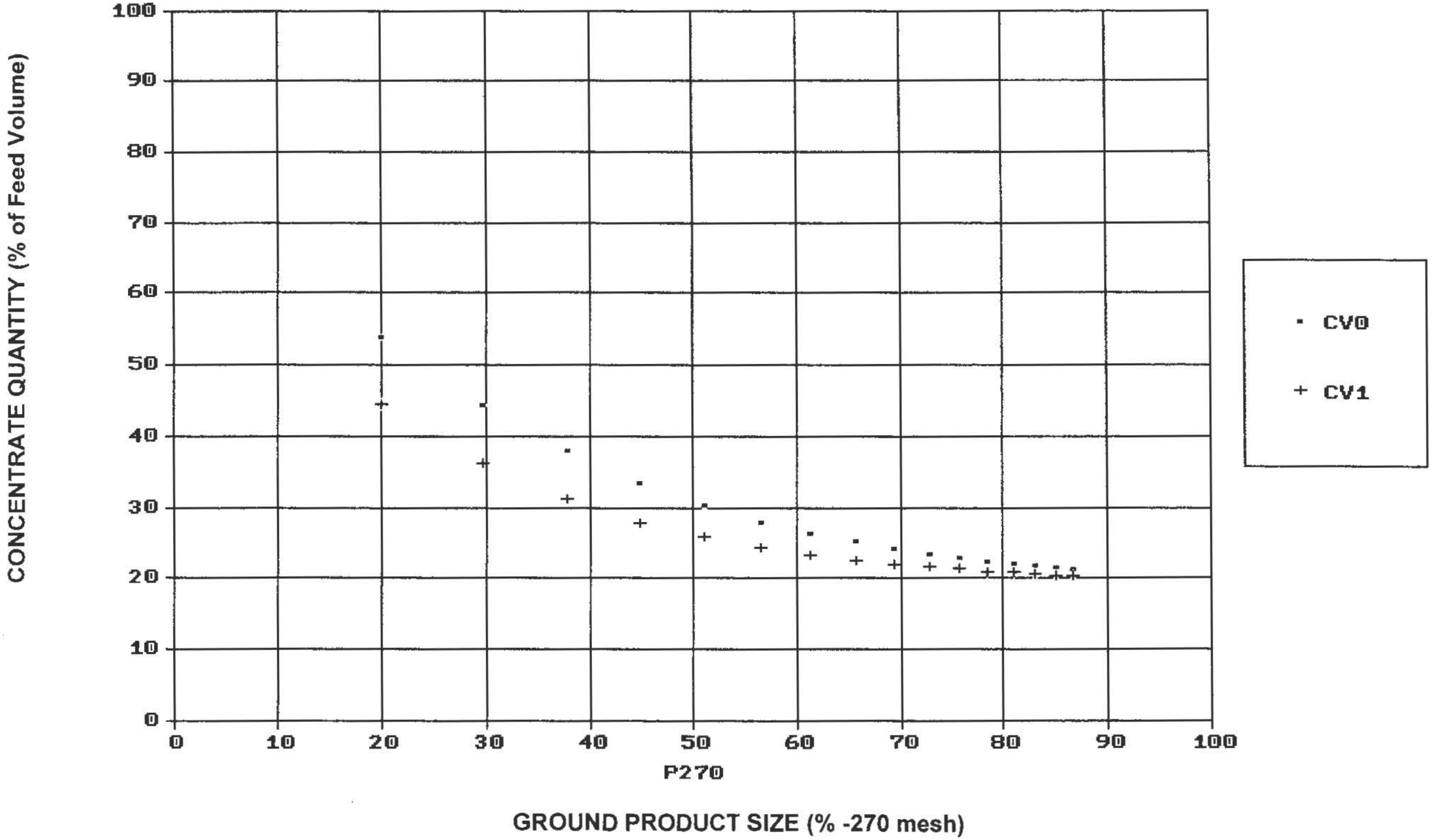


FIGURE 21 – SIMULATION RESULTS – EFFECT OF PRODUCT SIZE ON MAGNETIC SEPARATION TAILING GRADE WHEN REJECTING PARTICLES CONTAINING LESS THAN 10% MAGNETITE

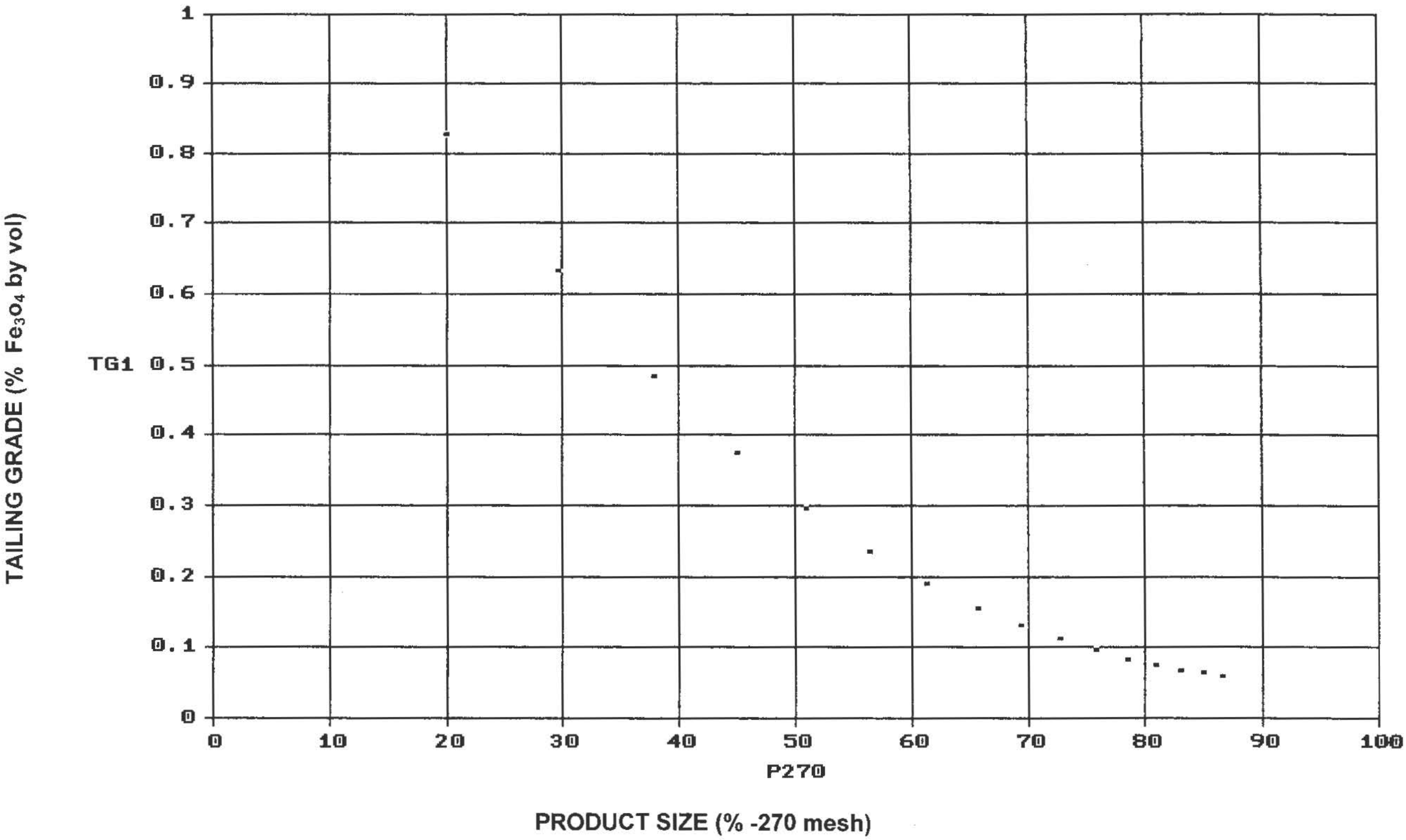


FIGURE 22 – SIMULATION RESULTS – EFFECT OF PRODUCT SIZE ON MAGNETIC SEPARATION RECOVERY LOSS WHEN REJECTING PARTICLES CONTAINING LESS THAN 10% MAGNETITE

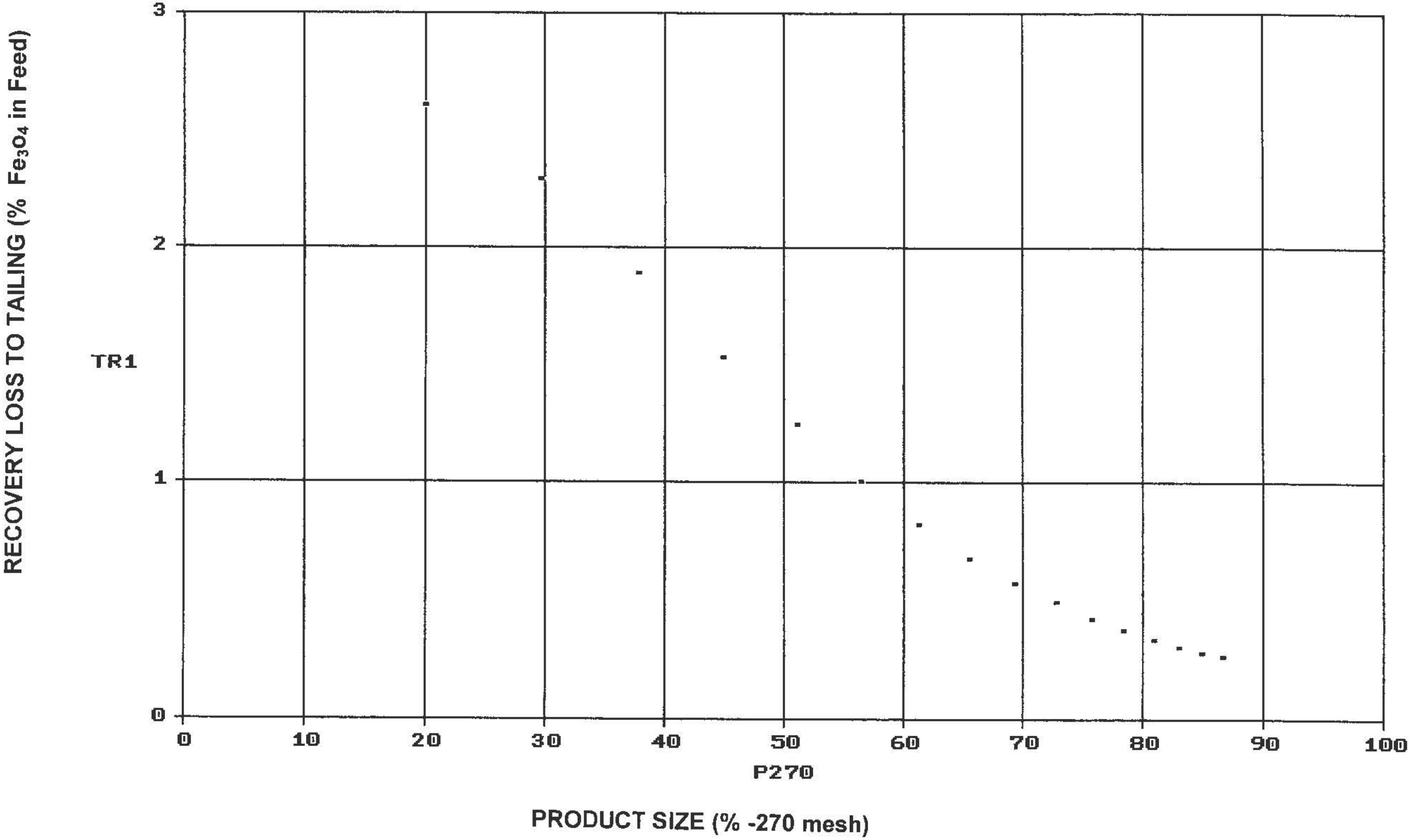


FIGURE 23 – SIMULATION RESULTS – CONCENTRATE SiO_2 VERSUS CONCENTRATE GRADE

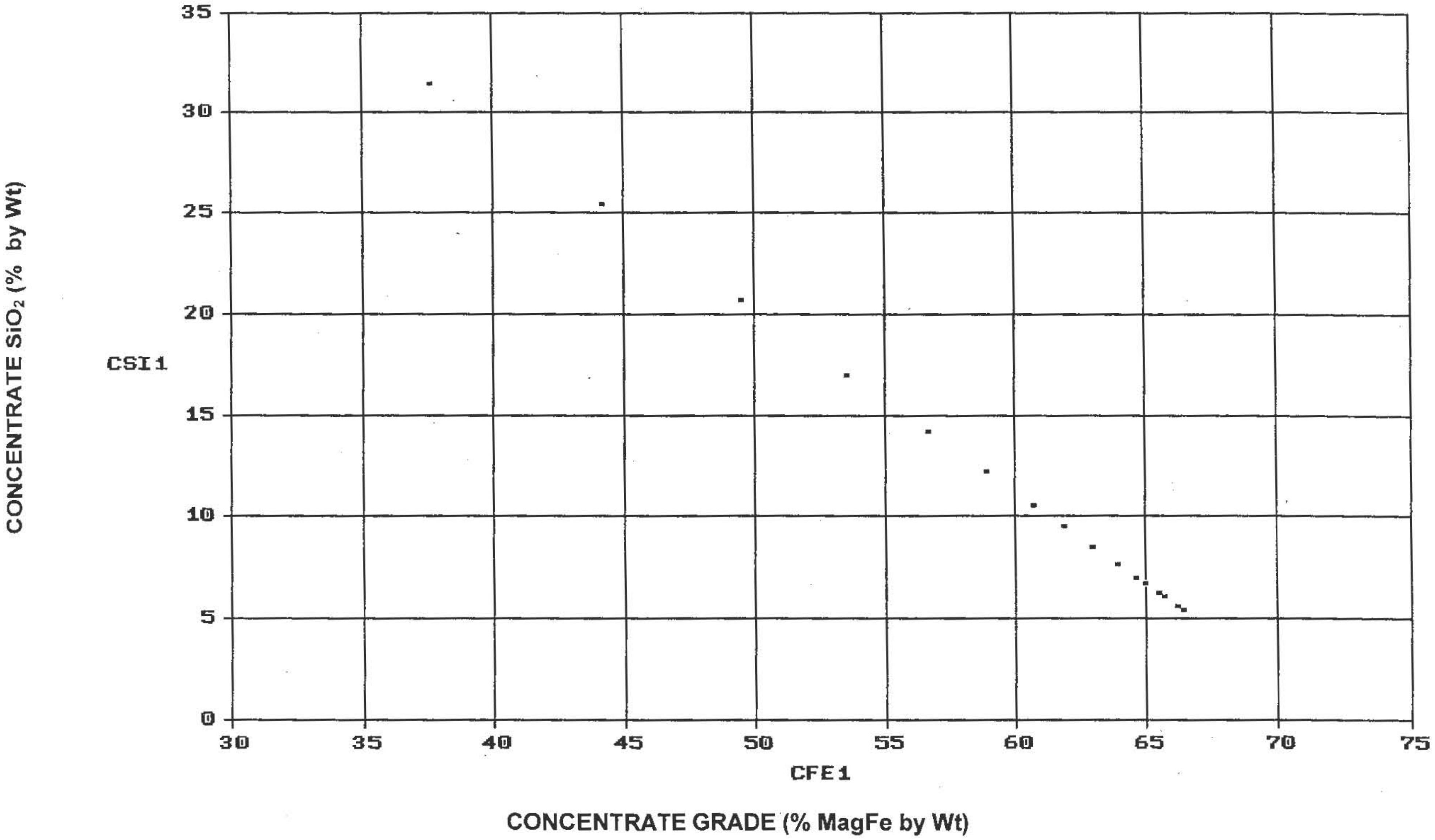


FIGURE 24 – SIMULATION RESULTS – EFFECT OF PRODUCT SIZE ON CONCENTRATE GRADE

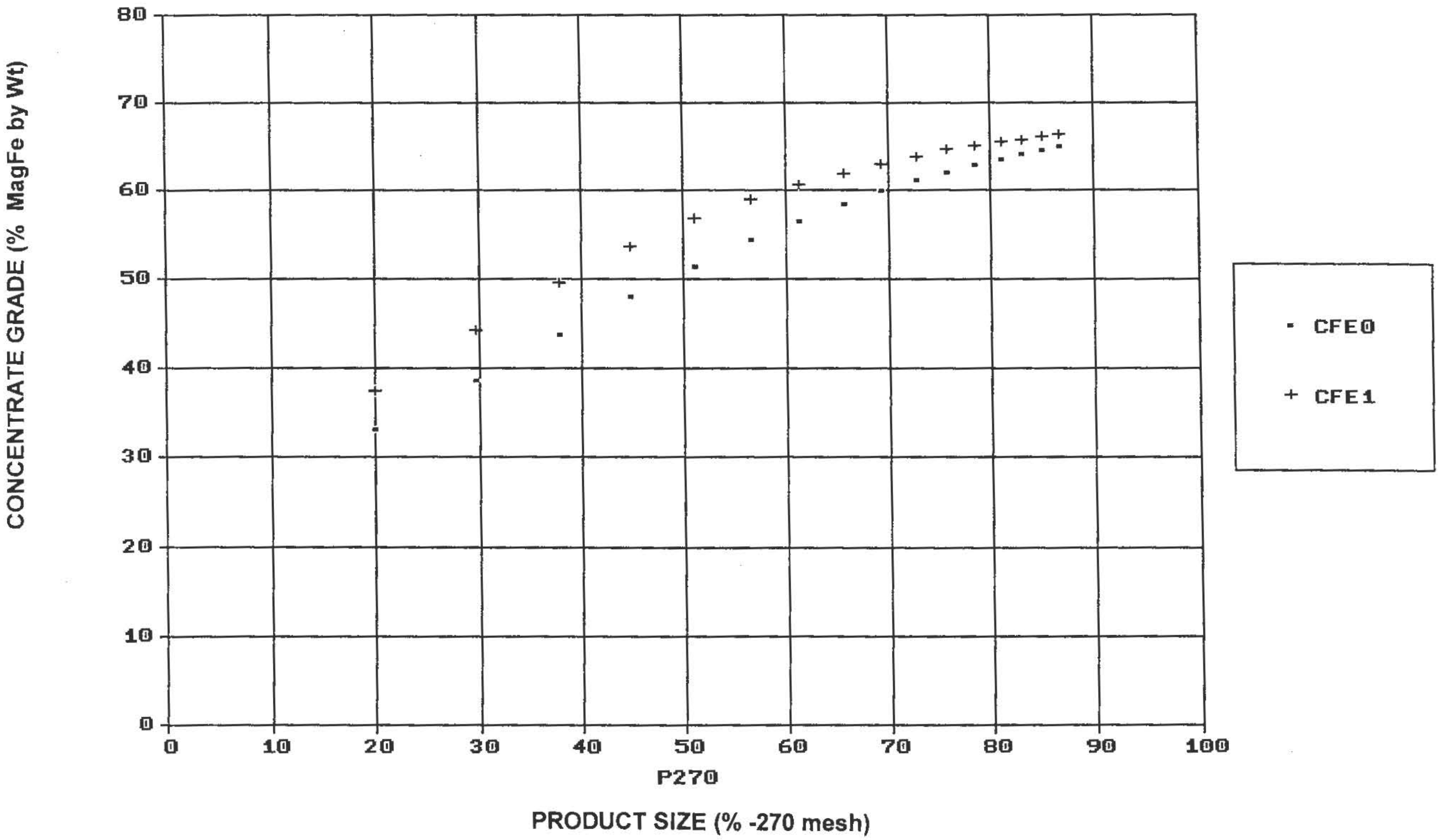


FIGURE 25 – SIMULATION RESULTS – EFFECT OF PARTICLE SIZE ON CONCENTRATE SiO_2

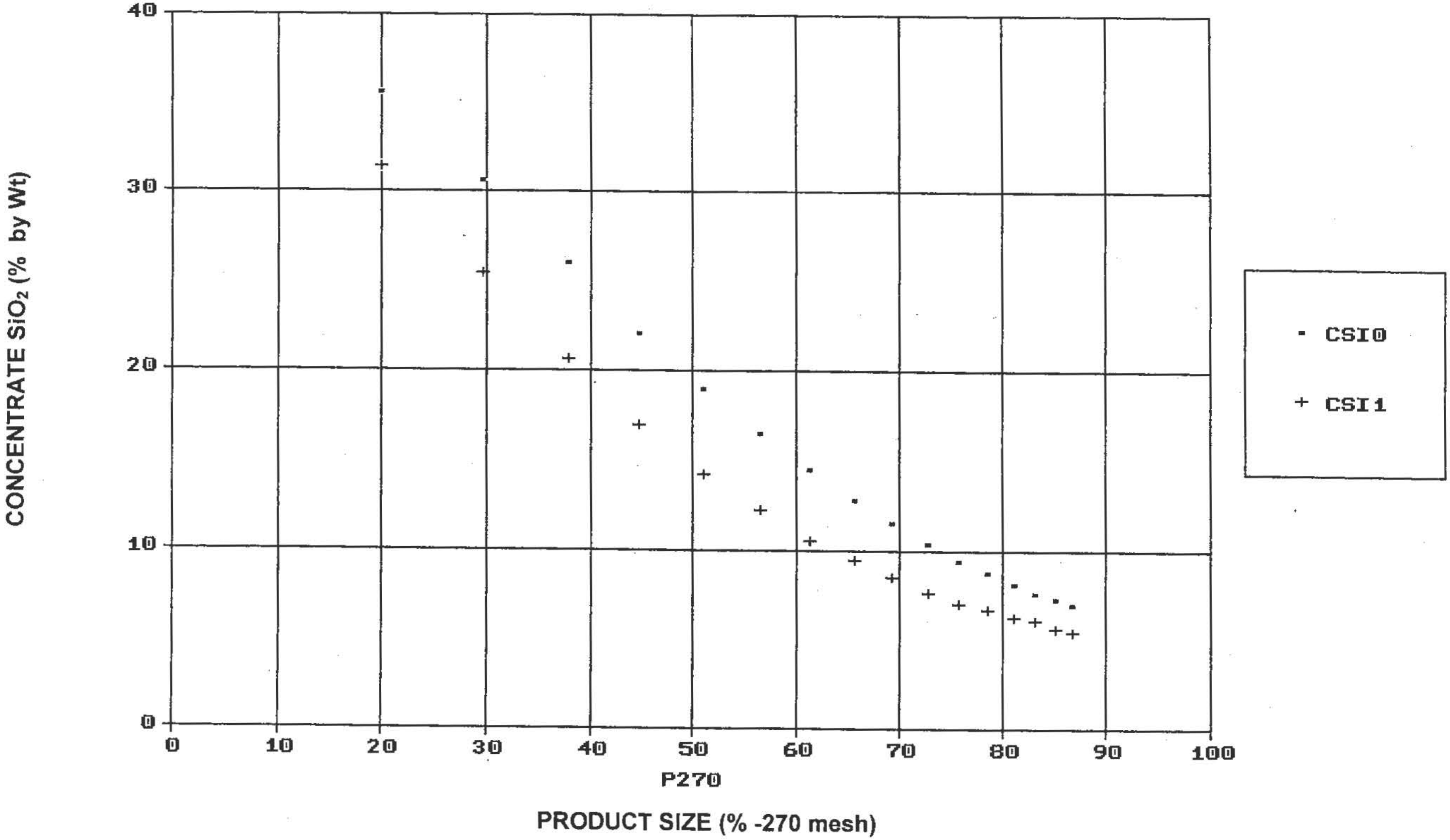


FIGURE 26 – SIMULATION RESULTS – EFFECT OF PARTICLE SIZE ON CONCENTRATE WEIGHT

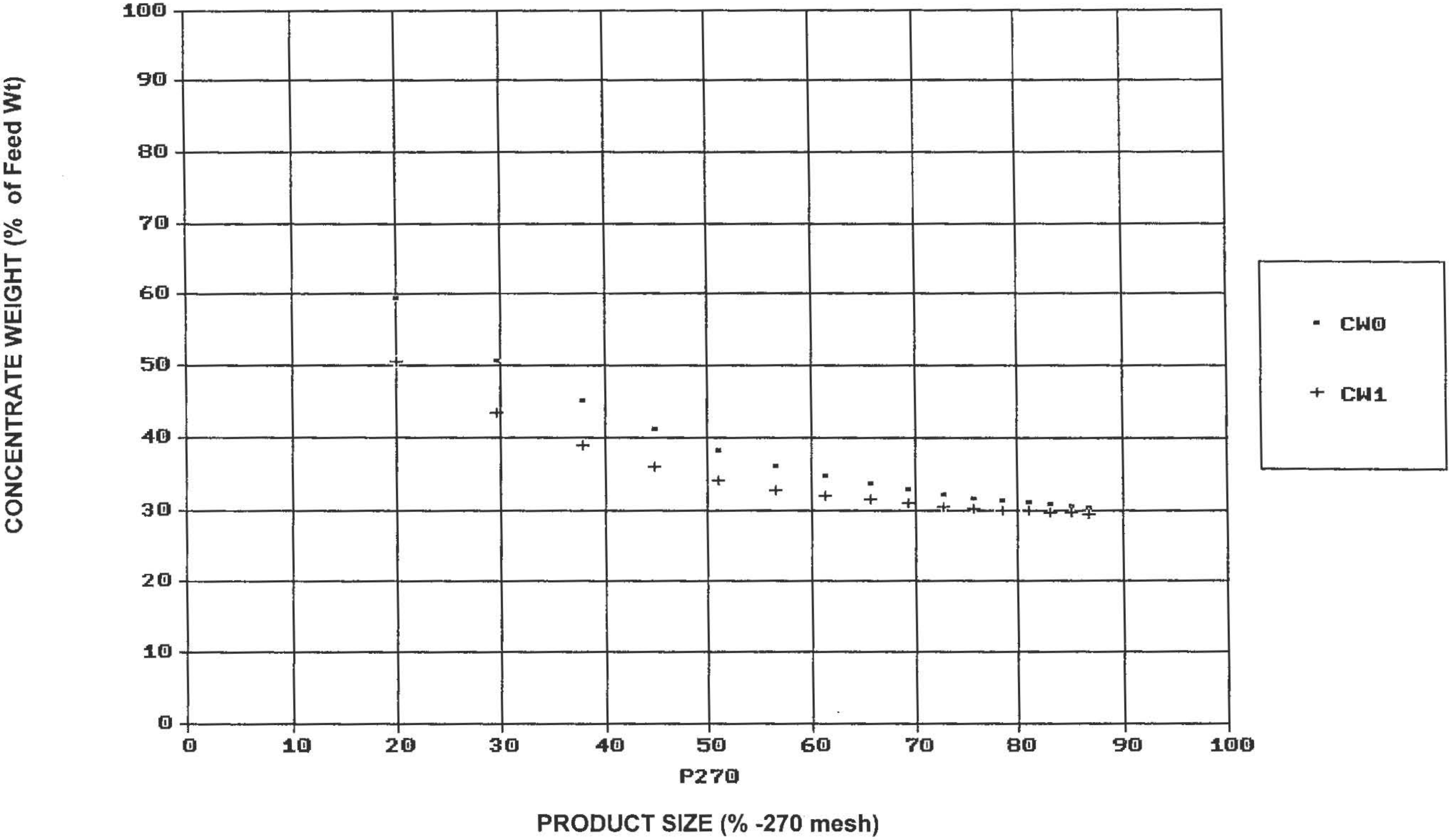


FIGURE 27 – SIMULATION RESULTS – EFFECT OF PRODUCT SIZE ON TAILING GRADE WHEN REJECTING PARTICLES CONTAINING LESS THAN 10% Fe_3O_4 BY VOLUME