GEAP-4032

VIBRATIONAL COMPACTION OF URANIUM DIOXIDE

By
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March 1, 1962

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VIBRATIONAL COMPACTION

of

URANIUM DIOXIDE

by

W. R. DeHollander.

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March 1, 1962

U.S. Atomic Energy Commission
Contract No. AT(04-3)-361

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VIBRATIONAL COMPACTION OF URANIUM DIOXIDE

SUMMARY

1. Rough, angular particles of fused uranium dioxide of mesh size ranges defined by Tyler screen sizes the square root of two apart in diameter, will pack to densities between 58-65 per cent of theoretical in tubes close to one-half inch internal diameter or smaller.
2. Binary mixtures of 2 size ranges are capable of producing much higher densities, with one, an 8/10, -200 mix, yielding 82 per cent. The density achieved is directly related to the separation in size.
3. Making the coarse component of a binary mix pack to higher density is responsible for a significant increase in density. A 3-size range of coarse, together with 5 micron powder, went to 87.8 per cent.
4. Ternary mixtures are required to get greater than 85 per cent on a routine basis. Such mixtures are easily capable of 88 per cent.
5. Quarternary mixtures or higher are probably the only approach to the consistent achievement of greater than 90 per cent.
6. The most important factor is the size difference between particles.
7. Segregation can be controlled and minimized by the use of noise during feeding and slight restraint during sine wave cycling.
8. Plastic deformation is involved in packing UO_2 since mixtures above 85 per cent are removed with difficulty from their containing tubes.
9. Powder stress is variable from lot to lot and constitutes an important variable, since the friability determines the best starting formula for a given final density.

RESULTS AND CONCLUSIONS

Using high density uranium dioxide powder particles such as are obtained from arc-fused powder, consistent densities in the range of 88 ± 1 per cent of theoretical density can be consistently and economically obtained if certain rules of combination of sizes are followed. In general, at least three sizes of particles are required, labeled coarse, medium, and fine, in the weight ratios varying around the values of 60 per cent coarse, 20 per cent medium, and 20 per cent fines. The size ratio is roughly in the order of 1:8:64, but many variations are possible.

Economical and complete utilization of powder appears probable, since there are many formulas by which such densities may be obtained. The appendix contains a listing of several hundred formulas and the densities obtained.

SECTION I

INTRODUCTION

The concept of simply pouring uranium dioxide into a tube and sealing it off for use as a nuclear fuel has a certain intriguing sound to it which has prompted many people to try simple powder compaction as a way of making ceramic fuel. However, without special preparation these tubes will be only about 50-70 per cent of theoretical density (TD), depending on what kind of powder is used. This low density leads to certain penalties in use. First, an enrichment penalty must be paid because higher enrichment is required to get the necessary reactivity. Second, in power reactors, enough heat is generated in the fuel to cause extensive sintering which causes the fuel to lump together in isolated clumps of high density, which affects the reactor performance.

These effects can be mitigated to some extent by initially packing the fuel to higher densities.

It is the object of this document and the work described therein to explore some of the criteria which are necessary to pack uranium dioxide to higher densities in the tubes of final use by the application of sonic vibration. Such fuel can be economically produced and is a satisfactory substitute for the standard pelletized fuel.

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SECTION II

DESCRIPTION OF EQUIPMENT

2.1 Primary Equipment

The equipment used in this investigation consisted of an MB Corporation Model C-10 electrodynamic vibration exciter rated at 1200 force-pounds, driven by an MB Model T351MC power amplifier and control console, complete with oscillator, automatic cycling, and vibration meter. The C-10 exciter can be driven to a 1" peak-to-peak displacement or 70"/second velocity or 68 G's acceleration or 27 amperes in the driver coil. Any one or more of these parameters may be the limiting factor in performance. The electrodynamic system was chosen because precise control of conditions of vibration is possible. The specimen mounting table is cast magnesium and contains a pattern of stainless steel inserts for specimen mounting. There is incorporated within the shaker a velocity coil which permits monitoring the table motion.

The T351 MC power amplifier and control console supplies 12,000 watts plate dissipation from a total of 25,000 watts input. However, power for the field also comes from the console. The console is provided with an automatic cycling oscillator which has a useful range of 5-5000 cps on one position and 5005 to 10,000 cps in the second position. It is provided with circuitry which can maintain constant acceleration or displacement while the frequency is varied. The frequency can be varied by a motor-driven capacitor which rotates

the dial at a given number of degrees per minute. Thus sweep rates are adjustable to require from one minute to 100 minutes to sweep from 10 to 2000 cps. Any desired portion of the frequency band may be selected for sweep. The built-in level control has correction rates of 10, 20, 40, or 80 decibels per second.

In the particular setup as used at APED, the basic equipment has been modified in the following ways:

1. A bank of 5 HP200AB oscillators has been added.
2. These oscillators feed a Bogen model MXM mixer.
3. The output of the mixer or of the cycling oscillator may be selected at will to be fed to the power amplifier.
4. The input signal may be half-wave negative or positive or pure sine wave.
5. The mixer, oscillator and sweep speed, as well as amplitude control, are remotely connected so that an operator at the loading box can adjust the parameters of vibration frequency and amplitude.

The bank of five oscillators provides for selecting any combination of exciting frequencies to be simultaneously fed to the exciter. Thus several rod resonances may be simultaneously excited if this is deemed necessary or desirable. Even the cycling oscillator can be blended with other frequencies at will. A remote vibration meter at the loading station allows close observation of displacement, velocity, or acceleration. Plug-in jacks have been installed in order to be

able to observe the wave form at several positions. A set of three cathode followers will accept the input from three accelerometers for display on a Tektronic dual trace oscilloscope. A Slip-Sync system, model D, manufactured by the Chadwick-Helmuth Company, permits slow motion study, motion pictures, and direct observation to be employed. This latter equipment is useful only with pure sine waves and hence, in the latter stages of the program, has been of little use. Initially, it was quite beneficial in establishing just which modes were being excited.

Photographs of the console, shaker, and accessory equipment illustrate their general characteristics. (See Figures 1 and 2.)

2.2 Accessory Jigs and Fixtures

Before rods can be filled with uranium oxide on the shaker, means must be found for holding the rods on the table, pouring in powder, controlling dusting and contamination, positioning operators and glove boxes at desirable heights. The approaches at APED have been slanted toward versatility and quick change in order to meet the demands of a broad development program. It has been deemed advisable to be able to quickly change from one diameter to another without first machining new jigs, etc. For mounting single rods on the table, a modified Jacobs Flex-a-collet chuck has been most useful and when properly used is quite satisfactory. The hand wheel was removed from a hand wheel type. The collet is tightened by using a drift pin and hammer against the normal hammering tips. This collet will accept diameters from 1/8" to 1-3/8".

FIGURE 1
ELECTRO MAGNETIC VIBRATION EQUIPMENT SHOWING
JIG FOR VIBRATING 24 RODS AT ONE TIME

CUTAWAY OF TYPICAL EXCITER

FIGURE 2

In order to meet the requirements of variable height of specimen, two elevators were purchased from Economy Engineering Company. One is hand operated and is used for positioning the loading box at the desirable height. The second is motor driven and positions the operator at a convenient height at the box. In this way rods from 4" high to 12' high can be loaded.

The rods protrude through the bottom of the box by way of a special pipe nipple assembly locked to the box with O ring seals top and bottom to prevent sifting of UO_2 . The top of the nipple is closed with a specially molded rubber cap. The rubber cap tightly seals the rod from leakage. A specially molded 6" rubber funnel is slipped onto the protruding end of the rod. A tubular Syntron feeder with a right angle bend at the end protrudes into this funnel, loosely, with only slight clearance, to minimize dusting. The Syntron feeders are equipped with hoppers for holding a previously weighed charge of powder. They are operated by a master switch and a Variac which allows variable level operation to ensure complete emptying of the charge. Directly above each tube opening is a pneumatic cylinder which can apply pressure to a rod which presses on the powder during the final stages of compaction. In the event that a charge of powder is too large for filling the tube correctly, a small suction hose and catch bottle allow removal of the powder from the upper part of the funnel so that the system can be opened without spillage.

SECTION III

PACKING OF SINGLE-SIZE FRACTIONS

The first starting point was to determine how rough particles of arc-fused UO_2 of narrow sieve size range packed all by themselves in the tubing of interest. Consistent with the data of McGeary¹, a dependence of the density on the tube diameter was shown, although almost all size fractions packed to densities between 58 and 65 per cent of theoretical. Table I shows one typical set of data.

TABLE I

DENSITIES OF SINGLE-SIZE FRACTIONS IN 7/16" OD,

0.020" WALL, 304 S.S. TUBING

(ID = 0.4375 - 0.040 = 0.3975")

Tyler Size	Average Size of Particles (d)	$\frac{\text{ID}}{\text{(d)}}$	% TD
+6 mesh	~0.200"	~2.0	53.0
6/8	0.112"	~3.5	55.8
8/9	0.079"	~5.0	57.2
9/10			57.5
10/14	~0.055"	7.0	58.0
14/20	~0.040"	10.0	56.7
20/28	~0.028"	~14.0	55.7

Such data as this indicates nicely how certain size particles fit best in a given tube when the size difference is quite small. The data in Table I were taken at low G levels and represent as-packed densities without working. When the 20/28 fraction was worked harder and more attrition had occurred, it was worked up to a density of 62.4 per cent. However, considerable attrition had occurred at this time. Table II lists, for reference purposes, all the data on single-size fractions that have been run at APED. There is a wide spread of tubing size, sample size, and column height represented as well as a material quality variation in the fused materials. It should be evident from these data that high densities will require more than one particle size, as can be deduced from the few wider-band mixes included.

TABLE II
SINGLE SIZE DENSITY EXPERIMENTS

(Not Including Table I)

Exp. No.	Mat'l	Size	Conditions	% TD
1	MgO	+48	Worked Hard	58-1/2
2	lead shot	2 mm	" "	60.7
3	MgO	+48	" "	60.6
4	lead shot	2 mm	" "	57.0
5	MgO	+48	" "	64.6
6	MgO	-325	" "	61.5
7	MgO	+8	" "	60.0
8	U ₂ O ₃	10/14	" "	55.0
9	MgO	65/100	" "	54.0
10	MgO	100/270	" "	53.6
11	MgO	270/325	" "	56.5
12	MgO	-325	" "	53.5
13	MgO	60/65	" "	57.0
14	MgO	60/65	" "	59.0
15	MgO	65/100	" "	59.3
16	MgO	100/270	" "	57.9
17	MgO	270/325	" "	54.8
18	MgO	-325	" "	56.1
19	MgO	60/65	" "	58.5
20	lead shot	2 mm	" "	57.4
21	UO ₂	3/6	" "	63.0
22	UO ₂	6/8	" "	59.5
23	UO ₂	3/6	Worked Extensively	71.0
24	MgO	6/20	" "	60.0
25	UO ₂	3/6	" "	54.2
26	UO ₂	3/6	" "	45.7
27	UO ₂	3/20	" "	75.8
28	UO ₂	65/200	" "	58.8
29	UO ₂	20/35	" "	59.8
30	UO ₂	-200	" "	62.5
31	UO ₂	10/14	" "	61.1
32	UO ₂	-200	" "	64.4
33	UO ₂	8/10	" "	60.5
34	UO ₂	6/8	" "	59.5
35	UO ₂	2.3μ	" "	47.0
36	UO ₂	5μ	" "	65.0
37	UO ₂	10/14	" "	62.9
38	UO ₂	4.2μ	" "	73.0

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SECTION IV

BINARY MIXTURES

Simple binary mixes would seem to offer a possible approach to higher densities; these higher densities have been observed by several investigators. Theoretically the density can be calculated by the formula,

$$d_b = \left[(100 - d_1) \frac{d_2}{100} \right] + d_1$$

where d_b = per cent TD of binary mixture

d_1 = per cent TD of first fraction only

d_2 = per cent TD of second fraction only (if there were no wall effect).

As an example, if 6/8 were to pack to 60 per cent by itself and 35/48 also packed to 60 per cent by itself, then a binary maximum of these two would yield $60 + 0.6 (40) = 84$ per cent. Figure 3 is a graphic representation of various values substituted into the equation and d_b calculated. It would be naive to suspect that the second fraction would pack just as well in the spaces between the first size as it would all by itself in the tube. Hence one should assign an efficiency factor to the packing. Such efficiency factors can be calculated from the graph of 6/8 mesh in binary combinations, Figure 4. As the size separation gets larger, the curve approaches the theoretical limit of possible density where the efficiency factor is unity. These efficiency factors which would be calculated are "lumped" efficiency factors and are simply good "fudge factors" to be used in guesstimating final densities. If, however, attempts are made to

6/8 MESH IN BINARY COMBINATIONS
FIGURE 3

596 - 1

6/8 MESH IN BINARY COMBINATIONS VS. "LUMPED" EFFICIENCY
FIGURE 4

calculate the composition of the binary mix from the formula, then erroneous results are obtained. The correct formula then becomes,

$$d_b = d_1 F_1 + \frac{F_2 d_2}{100} (100 - d_1 F_1) = d_1 F_1 + d_2 F_2 - d_1 d_2 F_1 F_2 / 100$$

where F_1 and F_2 are factors used to describe how much each fraction is packed, based on its performance alone. The interaction portion of the formula above essentially contains most of the problem. In the event that the coarse fraction is loaded first and is held in place so it cannot move, then F_1 can be made unity. McGeary (loc cit) did just this. However, most investigators do not add one fraction into another but load a mixture of the two and calculate the density. In this way, particles of the second phase can get between particles of the first phase and cause a change of spacing. Figures 5, 6, 7, 8, 9, 10, 11, 12, 13, 14, and 15 summarize the data on several binary systems of interest. The efficiency factor on the second phase varies from 40 per cent to 100 per cent. In general, the maximum for any binary system can be quickly found by running experiments from 60 per cent coarse to 75 per cent coarse. The figures quoted easily demonstrate that binary mixtures alone are worthy of attention; the density of 82 per cent has been attained using 8/10 and -200 mesh. Even higher values are possible with fines of -200 mesh.

In the graphs of binary mixtures, the dotted line running from the coarse to the maximum is drawn between the starting density of the coarse only and the point of the calculated binary maximum. The real form of this line should be a portion of an hyperbola given by

$$d_b = \frac{d_c}{x_c}$$

6/8, 10/14 BINARY
FIGURE 5

6/8, 8/10 BINARY
FIGURE 6

6/8, 14/20 BINARY
FIGURE 7

FIGURE 11

FIGURE 12

FIGURE 13

6/8, 8/10, 10/14 AND JET FINES BINARY
FIGURE 14

8/10, -200 BINARY
FIGURE 15

where d_b = density of binary mixture

d_c = density of coarse fraction only

x_c = fraction of coarse particles

For practical purposes, the straight line drawn is good enough to see how well a system is performing. The equation used here is based on the assumption that the volume occupied by the combination is identical to the volume occupied by the coarse alone, with the second fraction merely filling the voids between the larger particles. The equation holds for the region between the pure coarse fraction alone and the saturated binary maximum, when all the holes are just filled to the maximum possible.

On the other side of the diagram or starting from the fine fraction only, it can be assumed that each coarse particle added to the fines, "dissolves" in the fines and gives a volume increase equal to the volume of the particle alone. On this basis then the density would be

$$d = \frac{\text{mass}}{\text{volume}}$$

in which $\text{mass} = m_f + m_c$

where m_f is the mass or weight of fines

m_c is the mass or weight of coarse.

Let x refer to the fraction of each size present,

$$x_c + x_f = 1$$

Let us also assume a normalized particle density of 1 such that

$$\text{Vol}_c = \frac{\text{mass}_c}{d} = x_c$$

that is, the particles are wholly dense. Then,

$$d_b = \frac{x_f + x_c}{x_c + \frac{x_f}{d_f}} = \frac{d_f}{x_f + x_c d_f} = \frac{d}{x_f + d_f - x_f d_f} \quad \text{or times 100 for per cent of theoretical}$$

The graph of this equation is also part of an hyperbola but the curvature is so slight as to be approximated by the dotted straight line.

Simultaneous solution of these two expressions for the binary density should yield the theoretical composition of the binary maximum as

$$x_F = \frac{d_F (1 - d_c)}{d_c + d_F - d_c d_F}$$

In the case of 60 per cent for d_F and d_c , this yields $x_F = 0.287$ and d_c (max) as 84.2 per cent.

The equations developed above must only be expected to hold when the size difference is quite great and when only the first part of the curve is considered. It is surprising how soon the curve deviates on the fine side of the diagram. In general, the coarse side of the field is more closely adhered to; this is the basic wisdom behind the approach taken by McGeary.

As was seen in the discussion on the packing of single mesh sizes, the coarse fraction should be so chosen as to fit the geometry to the best possible density and to use a fine fraction which also packs well by itself. The size separation between a 6 to 8 mesh fraction and a -200 mesh fraction is quite large, large enough to make for efficient fitting of fines between the coarse. This is also true of a 10 to 14 mesh fraction and -200. Hence if the 10/14 mesh fraction packs one per cent higher in density than a 6/8 mesh fraction, one could expect to see the benefit in a higher final density. Corroborating evidence will be presented later.

It is evident from the form of the equations that a one per cent benefit will not be obtained from a one per cent increase in either d_c or d_F . For example, use of d_F as 60 per cent and d_c as 60 per cent yields x_F as

0.287 and d_b (max) as 84.2 per cent. Using d_F as 60 per cent and d_c as 61 per cent yields x_F as 0.277 and d_b (max) as 84.4 per cent. Thus only a 0.2 per cent increase was seen for a change of 1 per cent in the density of the coarse fraction. Figure 3 shows a mesh size separation of one size fraction is good for at least 1 per cent improvement in density.

The binary maximum approach is probably the best basic means of achieving high densities, especially when used in a cascade manner. One set of results, presented under the discussion of ternary and higher systems, underscores the basic wisdom of the binary approach.

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SECTION V

TERNARY SYSTEMS

The usual maximum achieved in a pure binary system has been observed to be of the order of 82 per cent of theoretical. However, a density of 87.8 per cent was obtained with a binary mixture (Figure 14). That system was composed of a coarse fraction which, in turn, was a maximum among three adjacent mesh size ranges. It therefore constituted a quaternary rather than a binary. However, it was composed of a coarse and a fine fraction, with no intermediates.

In order to achieve higher densities it seems necessary to add still a third component which will be called the middle fraction. Systems of three particle sizes can still be plotted on graph paper if triangular coordinates are used. Thus the study becomes quite analogous to phase diagram studies of the physical chemist. By plotting the experimental data in this manner, a mental picture of the interactions can be obtained.

Various investigators^{1,2,3} have observed that a maximum can occur in a 3-phase system at only one region, situated in the vicinity of 65 per cent coarse, 15 per cent middles, and 20 per cent fines. This is the same conclusion which is drawn by theoretical considerations of fitting particles within the voids between larger particles. The analyses given by Westman and Hugill² and by McGeary¹ illustrate the limiting case of infinite separation. In most cases the practical range of sizes is from about a 6/8 mesh range down to about -325. This barely allows a diameter

ratio of 100:10:1 which is not quite infinite but reasonably good. Combustion Engineering people, Bruce Murtha, et al.,⁴ feel they will approach >90 per cent routinely by simple three-phase mixes. In reality, in their method of compaction, they may start with three particle sizes but quickly create a multi-particle system.

In this investigation, simple three-phase systems have not yielded densities in excess of 88 per cent.

Again, the use of the analytical expressions given by Westman and Hugill are quite helpful when no interaction is allowed between the various sizes of particles. The assumption that the volume is equal to the volume of only the coarse particles implies that the coarse component is in contact and therefore that the next size is fitting between the holes. The more practical system involves letting the coarse particles separate a little if need be, to accommodate the next size which may be slightly too large to fit the voids. This is a far more complicated system to study, and is probably best studied just by experiments. To this end the system of three particles consisting of 10/14, 65/100, 200/270 was studied entirely in the field. If the 10/14 is assigned an average size of 0.0555 inches, the 65/100, 0.070 inches, and the 200/270 as 0.0025 inches, the ratio of 1:2.8:22.2 is a long way from infinite separation. Such a system cannot be expected to yield very high densities, but can shed some light on the interactions which can occur. Figure 16 is a triangular plot of the experimental data. The general agreement with the treatment of Westman and Hugill is very good. The agreement along the coarse-fine boundary is best, the coarse-medium next best, and the medium-fine the

THE UO_2 PARTICLE SYSTEM

FIGURE 16

poorest, as would be predicted for the diameter ratios involved. From this diagram it seems evident that little hope can be held for attaining high densities outside of the region predicted by particle packing theory.

The best method of determining what the optimum composition should be for any three specific powder sizes in any specific geometry should be as follows: First determine the maximum of the coarse-medium binary. Second, draw a line from this binary maximum composition on an equilateral triangle diagram to the fine corner. Third, determine the maximum of compositions along the line. With good luck, it should take about 8 to 12 experiments to decide on the optimum for that powder and that geometry. This point will shift with changes in powder character and geometry. Table III illustrates the sensitivity of density to composition. The composition would surely be different for a different powder and for other geometries.

TABLE III
SELECTED PARTICLE COMPOSITIONS

Powder Size	% of Mix	% TD	Powder Size	% of Mix	% TD
8/10	63)	88.2	8/10	60)	85.1
	)			)	
48/65	24)		48/65	24)	
	)		)		
5 micron	13)		5 micron	16)	
8/10	65)	86.3	S.S. 304, 0.400 in. ID tubing.		
48/65	25)				
5 micron	10)				

Table IV shows that shifting the middle fraction one size had no effect on the density, whereas shifting the coarse fraction down two sizes increased the density. These results point to the importance of precision fitting within a specific geometry.

TABLE IV
SELECTED PARTICLE DENSITIES IN 304 S.S. TUBING,
0.400" DIAMETER

Powder Size	% of Mix	% TD	Powder Size	% of Mix	% TD
6/8	60)	86.8	10/14	60)	87.5
48/65	20)		48/65	20)	
5 micron	20)		5 micron	20)	
6/8	60)	86.8			
35/48	20)				
5 micron	20)				

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SECTION VI

ARRANGEMENT OF POWDER SIZES

It is apropos at this time to discuss the possible arrangement of powder sizes. The model which consists of particles of the coarse fraction touching each other, hexagonally closest packed on each layer, with cubic packing in a vertical direction as mentioned by McGeary and by Westman and Hugill, has already been discussed.

A new model is now proposed which will be called the emulsion model. In this model, maximum density is attained when each coarse particle is surrounded (and thus lubricated) by a layer of middles and/or fines. The maximum density is attained at this composition because all powders are added simultaneously and this model leads to the least functional resistance. This model, therefore, calls for less coarse than the theoretical model calls for. There is evidence to indicate that perhaps both models can and do obtain, and that roughly similar densities are observed. Combining both models would lead to a double-peaked phase diagram.

For hexagonal closest packing in any layer, the optimum size of particle would have a statistical diameter of $D/3$ where D is the ID of the tube. For a tube 0.400 in. ID, this would be 0.133 in. This diameter corresponds to about a 6 mesh size. If the particle were surrounded by a layer of 48/65 at an average diameter of 0.010 in., then the basic coarse particle would only be 0.113 in. However, neither of these models fit the data of Tables III and IV. Instead, 8/10 with 48/65 fit the best.

8/10 averages only 0.079 in. which is about 1/5 of the diameter. When the shape of the particles is taken into account, and also the fact that the particles are not single sized but range from 1 to 1.4 in size, it can perhaps be seen that expecting the D/3 model to fit exactly would be quite optimistic. However, by the time the model approaches D/5 there is enough redundancy of fit to expect a reasonably good peak to occur. If perfect spheres of a known diameter were to be employed, the D/3 model would perhaps be the best one.

After a great number of experiments on many kinds of powders, it seems reasonable to conclude that densities in excess of 85 per cent of theoretical are routinely achievable. Because of the great number of possible formulas for achieving this goal, very excellent powder utilization can be expected, provided that at least 60 per cent of the starting powder is in the +20 mesh size range. Powders can be comminuted to achieve the necessary medium and fine sizes but there is no method, short of fusing, which can build up small particles into large particles.

Rods with starting densities of 85 per cent can be cold swaged to densities of the order of 91-92 per cent with one nominal reduction not exceeding 40 per cent. Some internal clad indentation occurs with the larger particles but can be tolerated occasionally, especially in heavy-walled tubing.

There is nothing which precludes the possibility of achieving greater than 90 per cent TD by vibratory compaction alone with simple ternaries, especially if slightly broader bands are employed so as to obtain a little more redundancy of fit. The formulas so obtained, if any, would be unique to a given powder and geometry as well as to technique of fill and vibration.

For general purposes, the size ratios may approach 1:10:50 and still achieve greater than 85 per cent. Spreading out the size ratios is beneficial; the one mix in Table III which went to 88.5 per cent was in the ratio 1:48:394, which is perhaps excessive.

Wherever the ratio of any two sizes goes below about 1:7, particular attention must be paid to the blending beforehand to ensure adequate distribution since the particles cannot migrate through the holes. However, if the feed is slow enough, the effects of vibration are to open up the bed and allow migration and mass transfer.

This problem will be treated in more detail in the section on segregation, but it must be remembered that coarse fractions move up and small fractions move down. One should attempt to utilize this information by counter-current-flow techniques, making sure that the coarse fraction leads into the tube and the fine fraction enters last. One can ordinarily activate about 2 in. of powder height in a small-diameter tube. Hence, each 2 in. equivalent ought to contain all the ingredients needed for the correct density.

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SECTION VII

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QUATERNARY AND HIGHER SYSTEMS

From an analysis of many ternary systems it soon became apparent that densities in excess of about 87 per cent of theoretical would be obtained either by very severe working of ternary mixes or by using more than three particle sizes to begin with. Only limited work has been done at this time on the higher systems but that which has been done is encouraging. All mixes which achieved more than 88 per cent have been more than 3 sizes. One multi-component mixture has been brought to 92.8 per cent. The approach to the quaternary system has been by the cascade binary route in some instances, and in others by a strictly empirical approach. This study has not been completed at this time and it would be difficult to make a definitive statement about achieving greater than 90 per cent routinely. Several false starts have been made and the best or optimum approach is still open. One of the first approaches was to try a cascade binary using immediate-nextdoor neighbors. Since most binary maxima occur in the region of 70 per cent coarse and 30 per cent smaller, a matrix of 35/48 at 30 per cent was used in the system 6/8, 8/10, 10/14. Figures 17, 18, 19 summarize the data taken here.

Of particular interest is the undulating nature of the density-composition plots. These data are highly reproducible and the variations are real. Each point is good to at least ± 0.1 per cent at the level indicated, i.e. 74 ± 0.1 per cent. Notice that the curves with 35/48 added

FIGURES 17 (TOP), 18 (MIDDLE), AND 19 (BOTTOM)
BINARY DIAGRAMS OF TERNARY SYSTEM
6/8 - 8/10 - 10/14

are more grossly periodic than the simple binaries themselves. This is interpreted as resulting from the adding and subtracting action of the small 35/48 onto the larger 6/8, 8/10, or 10/14. The high redundancy of fit which is possible when more than one size is used is again illustrated.

All of the systems exhibit maxima and minima, but none of the minima go below the density of the lowest member. It is to be expected that the minimum, in some systems, could go below the density of the lowest member. The data are even more interesting when replotted on triangular paper. Figures 20, 21, 22 illustrate these data. It can be seen that in all cases the maximum in the ternary system lay on the line joining the coarse-coarse binary maximum to the 35/48 corner. In one case, namely 6/8-10/14, 35/48 the most maximum point lay off the line. There is reason to believe from later work, as will be shown, that there is a high probability that a maximum would be found at the point where the line from 35/48 through the 77 per cent value intersected the 6/8-10/14 edge.

Some systems show a sudden rise and fall at very critical fit positions where the particles either just fit or are badly out of fit. It is possible that the true maximum was missed in that one instance.

From the work on the system 6/8, 8/10, 10/14, a composition which yielded 66 per cent TD when vibrated was chosen for use as the coarse phase in the following:

50%	6/8)		)	
15%	8/10)	60%	)	
35%	10/14)		)	
			)	
65/100		20%	)	
			)	
Jet fines (0.0002")		20%	)	

which in turn yielded 89% of TD.

6/8, 8/10, 35/48 TERNARY DIAGRAM
FIGURE 20

596 - 7

6/8, 10/14, 35/48 TERNARY DIAGRAM
FIGURE 21

596 - 8

8/10, 10/14, 35/48 TERNARY DIAGRAM
FIGURE 22

A simple binary mixture of this same coarse and jet fines in the proportion 65 per cent coarse and 35 per cent fines yielded 87.8 per cent TD.

It would seem that the surface has hardly been scratched at this time, and surely continued exploration will open still further pathways.

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SECTION VIII.

SEGREGATION

It is a well known fact that under vibration a mixture of particles will separate, with the heavier and/or larger particles rising above the lighter and/or smaller particles. This relative movement is related to Newton's laws of motion, and to the laws of the conservation of momentum. If particles are accelerated in a given direction by the shaker table and then the accelerating force is removed by the reversal of the table, then for a given final velocity of the shaker table and tube containing the particles a larger mass possesses greater momentum and hence against the retarding force of gravity will move a greater distance before the kinetic energy is dissipated by being converted into potential energy. Even if the larger particles are of lower density (and thus possibly lighter than the smaller particles), the smaller particles will work into the interstices between the larger particles; segregation is achieved in the same manner as is seen when rocks rise to the surface of the ground. As might be suspected, certain frequencies, related to the size and mass of the particles, are more efficient at performing this segregation than others. The greater the linear displacement of the table and the greater the force, the more rapidly the segregation occurs.

In particle packing in tubes, the lower frequencies are most effective, with frequencies of the order of 250 cps being quite effective for most systems. To prevent segregation, the experimenter has at least two

possible routes to follow. The first and most obvious is to put a sufficient restraining force on the top of the column to prevent individual particles from leaving the upper surface and moving in free air, but still of small enough magnitude that some degree of freedom of rotation and small translation is permitted to aid in migrating particles to the position of lower energy. This is very important when working with single frequencies, at high G levels and large displacements. When the displacement is held to a few thousandths of an inch, the problem is of much less significance.

The other, not-so-obvious solution has been used with success - the use of a combination of frequencies approaching a noise spectrum. Thus, high G levels can be obtained with small displacements and enough randomness of motion to forestall any aggressive segregation. However, even with the noise spectrum, segregation can and will occur if vibration is continued at length. The use of noise, or mixed frequencies, has been especially helpful in the practical solution of the loading problem.

During the initial filling of the tube it is desirable to achieve high densities by aggressive vibration before a long column of powder increases the frictional forces and delays the attainment of high density. If pure sine waves are used, then very low G forces must be employed. By using noise, high G levels can be used with consequent excellent packing.

After the tube is loaded, a restraining force can be applied and high G level pure sine waves of varying frequency can be employed to effect a considerable improvement in density.

When systems were studied in glass and plastic tubes, segregation could be easily followed. If pure sine waves were employed with no restraint

and at high G forces, ternary blends could be cleanly separated in three distinct bands: coarse at the top, middles in the middle, and fines at the bottom. Quaternary mixes were not studied.

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SECTION IX

POWDER UTILIZATION

It has been shown that if the fines one is using will pack to densities of the order of 60-plus per cent, this same density can be achieved by packing in the voids between the larger particles, provided that the difference in size is of the order of 20. Thus, if densities of 87-90 per cent are desired, the cut-off density for mixtures containing particles 20 times larger than the fines must be around 73-75 per cent. For example, suppose some fines capable of packing to 60 per cent alone are available and their average size is 0.0002 in. diameter. Then the average size of the next higher particles should be not less than 0.004 in., or about 100/150 on the Tyler scale. Table V demonstrates what might be achieved if various coarse-medium densities are achieved.

TABLE V

FINAL DENSITIES PREDICTED FOR VARIOUS COARSE DENSITIES

(Density of Fines at 60 Per cent)

(1)	(2)	(3)	(4)
Density Attained by Sizes Above 100/150	Volume Remaining To Be Filled	Contribution of Fines = 60% of (2)	Final Density Sum of (1) and (3)
90	10	6	96
85	15	9	94
80	20	12	92
75	25	15	90
70	30	18	88
65	35	21	86
60	40	24	84
55	45	27	82
50	50	30	80

In actual practice it is observed that the coarse-medium densities lie in the region of 60 to 75 per cent, thus guaranteeing achievement of at least 84 per cent to 90 per cent TD. It appears possible to achieve 72 per cent with many combinations of sizes larger than 150 mesh. This happens in binary, ternary, and higher systems. A system of linear programming will be required for utilization of powder in an efficient manner. Following is an outline of a suggested procedure. The material is assumed to have been ordered as a 6/20 mesh arc-fused powder.

1. The powder is started through the sieving Sweco or equivalent system.
2. After one or two batches have been sieved, and a sieved powder inventory is on hand, trial runs can be started.
3. Material in the -20 range is ground to move powder into the 30/60 range.
4. -60 mesh material is sent to the jet mill for creation of jet fines.
5. Each of the upper size ranges are tried for binary maxima with middles, say 30/60.
6. Those which can make 73 per cent are used with fines.
7. The remainder must be combined to reach the goal.

A representative system is as follows (6/20 mesh arc-fused MgO was ordered):

6/8	0
8/12	~19%
12/16	32%

16/20 25%

-20 24%

The first formula will be 40 per cent 8/12, 30 per cent 16/20, 30 per cent 30/60, plus fines to make target goal. Portions of 12/16 will be ground to 30/60 range and to jet fines. Middles and fines are required to the extent of about 40 per cent. Thus at least 16 per cent must be obtained from higher fractions. The first formula will consume all of the 8/12, 14 per cent of the 16/20 leaving 11 per cent 16/20 on hand. The 11 per cent 16/20 will be added to the minus 20 mesh to make 35 per cent -20. Now trial runs will be made on 12/16 with 30/60. The target of 73 per cent is reached at 70 per cent 12/16, 30 per cent 30/60. Fortunately, the yield of ground powder in the desired range is a little over 50 per cent. Thus it is possible to grind and not accumulate too many fines.

Toward the end of the run, it may be that a third formula must be sought which will achieve the same target density. In all cases, care must be taken that powder is not moved down to the fine sizes so rapidly that material which can only be used as jet fines does not accumulate much above 15 per cent of the total, until it is certain that more will be required. Ordinarily, this is no real problem, but sizes to be ground must be selected with care. It is better to keep other middle fractions on hand so that other ternary mixes can be used to achieve the desired goal.

In the case of some rods made for a VBWR assembly, a simple serial-degradation of sizes was used, with a very limited amount of powder, to achieve greater than 85 per cent in all rods. The mix started out as

6/8, 35/48, and fines in 60,20,20 proportions. When the 35/48 was consumed, the formula was switched to 48/65. After the 6/8 was all gone, it switched to 8/10, and finally to a mixture of 8/10 and 10/14 and 65/100. In all instances, target densities in the 87 per cent range were obtained. Better results might have been achieved if the mixes had been optimized for each size on hand. However, for this particular application it was not necessary.

It remains to be demonstrated on a large run of several hundred or thousand segments as to the exact nature of the linear programming difficulties to be encountered. It should be evident that a successful powder line will incorporate methods of grinding to the -20 +150 range and also a way of comminuting powders to the 1-10 micron range.

SECTION X

LOADING AND FILLING TECHNIQUE

Many different loading and filling techniques have been employed but the presently-preferred method is the one described below. For the development phase of the work, all tubing used was calibrated for volume by filling the tube with water or alcohol from a buret and calculating the volume-per-inch from the length measurement. After a tube had been filled with a weighed quantity of powder, a flat-footed probe was pressed on the upper surface of the powder and the position of the top edge of the tube to a reference mark was measured with a ruler. For convenience purposes a table was prepared for a 500-gram sample of powder in a particular tube, giving the density directly from the measured distance.

For other weights or other tubes, the formula used was as follows:

$$\text{Per cent of TD} = \frac{(\text{weight of powder}) (100)}{(\text{tube length-depth to interface}) (10.97) (\text{factor})}$$

where the factor is the cubic centimeters per linear inch. All lengths are in inches and weights are in grams. Thus, only an over-all or effective density was calculated in every instance. It is obvious that regions of inhomogeneity could exist, but by successive sampling techniques it was soon learned that high density and homogeneity go hand-in-hand. Reference to a coarse-fine binary is probably the best way of demonstrating the pitfalls involved.

Assume a matrix of coarse particles within a tube at a fixed height. This height is held by a restraining member throughout the experiment. Let the mass of the coarse be m_c and the volume of tubing defined by the height be V . Then the starting density is $\frac{m_c}{V}$. If fine powder is now fed in, it will migrate to the bottom of the matrix and pack in the holes there to some maximum local density. The over-all density will now be $\frac{m_c + m_F}{V}$, but obviously only the lower portion is really of greater density. Not until the binary maximum is reached where the fine powder just equals the height of coarse matrix will the density be correctly calculated. Thus, it is almost imperative that only mixes in the region of maximum be used when uniform density is desired. To some extent the same reasoning will hold for multiparticle mixes, but the region of homogeneity is quite a bit broader in the practical application where the whole mix is fed into a tube at one time. If the mix were fed in successively, then the same reasoning could be expected to hold.

10.1 Preliminary Blending

This brings up the question of blending prior to a run. If the mix has been made up in proportions exceeding 1:7:49, then blending is not nearly as necessary as in other mixes, but it is imperative that measures be taken to insure that the first particles entering the tube are the coarse particles. When the size ratios are as given or even more, the middles can migrate through the coarse, and the fines can migrate through the coarse and through the middles with the aid of vibration at least for short distances. It again will be stressed that coarse particles must be the first to enter since there is no way, short of turning the tube over, of causing the coarse particles to migrate through middles or

finer to achieve uniformity in the bottom portion. As the proportions go down from the 1:7:49 values, it becomes much more important to blend thoroughly before filling, and it becomes even more essential to insure a uniform feed to the tube.

It is actually surprising to see how uniformly the tube can be packed despite all the theoretical reasoning which would tend to convince one that segregation would be a problem. It should be remembered that vibration causes the lattice to loosen up and hence permit some migration of particles from one point to another. Again, it is desirable that the largest particles enter the tubing first. When a Syntron feeder is used, this tends to happen automatically, because the large particles tend to lead down the tray.

In some instances, mixes have been made up by weighing first the fines, then the middles, and then the coarse into a jar. The jar was inverted into the cup of the Syntron feeder and fed to the tube without blending. When the proportions of size were close to 1:7:49 or greater, the same density was achieved as in well-blended samples. Maximum density took somewhat longer to attain, by 2 to 3 minutes. Even mixes in lower proportions have been successfully loaded by this technique.

Occasionally a certain mix which has uniformly been yielding a certain density time after time with maybe ± 0.1 or ± 0.2 per cent variation, will all of a sudden be 5 per cent low or so. These are called "statistical goofs", and are usually caused by fine powder leading into the tube, and other times by bridging of some very irregular particles. In essentially all instances, the powder can be unloaded from the tube,

the tube refilled with the same powder, and immediately attain the right density. Thus a certain amount of art is involved in loading tubes to uniform density.

However, in order to achieve a certain density the primary factor is choice of mix and the secondary factor is art or technique. It would be interesting to set up an experiment where the coarse was fed from one feeder, the medium from another, and the fines from another with the speeds so adjusted that coarse led in first, middle second and fines last, with the order remaining throughout the feed period.

10.2 Filling Procedure

After the method of feeding has been mastered, the actual filling will start. The five oscillators have been set to a set of frequencies which initially were selected on the basis of system resonances. However, later work showed that this was not a necessary criterion and that a well-blended noise was all that was needed. The wave shape can be seen by observing the output on the oscilloscope and can be felt by lightly fingering the tubes. A good setting will have a slightly undulating pattern on the oscilloscope; the pieces of tubing will feel very much alive. More than anything else this feeling of "aliveness" is a good indication, and an operator soon learns that the tubing is activated over its entire length and not just at certain spots. The oscillator settings are not critical but the following is a good guide.

The first oscillator is set on some resonance in the vicinity of 1000 cps, being careful not to choose a table or case resonance which may be present there. Number two is set between 500-600 cps (where powder

is activated), but avoiding a sub-harmonic of number one oscillator. Number three is set on about 250 cps. Number four should be set at about 90-100 cps, and number five is used to "fill in" the scope picture to smooth the pattern out and avoid beat phenomena. One favorite setting is as follows:

1 = 960 cps

2 = 600 cps

3 = 500 cps

4 = 250 cps

5 = 92 cps

This setting has been used for much of the work. It is blended with different amplitudes to produce the effect desired.

After the oscillator settings have been made and the particular tubes are very much alive and the subjective feeling of good settings has been made, actual loading will start. Despite the fact that the noise will minimize segregation, the first portion, about three to six inches, is always loaded with G forces around 5-7 G's. As the loading progresses the amplitude control is gradually advanced so that the maximum driver-coil current is being used by the time the column is around two feet high. Vibration is stopped immediately upon completion of feeding. The restraining foot is lowered into place and a slight pressure (~1-2 psi) is applied. The vibration is started again and brought up to maximum G level. The vibration is stopped about every minute to see if further gains are being made. When maximum density has been achieved, the noise is switched off and a pure sine wave is applied, starting with 1000 cps and sweeping down to 200 cps at the rate of 31°/minute on the MB oscillator.

The sweep goes back to 1000, down to 200, back to 1000, and is shut off. Ordinarily this is the end of the run, but occasionally some further, very slight, gain can be had by switching back to the noise again, and then back to a sweep.

During the first sweep there will be certain frequency regions where the marker foot will show a sudden drop indicating a densification has occurred. It does no good to stop at this point and continue further vibration at this frequency. The effect is seen only while the frequency is changing and is most pronounced at the speed of sweep mentioned. Apparently the system must move into and out of resonance in order for this to occur.

The most difficult kind of rod to make is the kind that calls for powder to within a quarter of an inch or so from the top edge of the tube. In order to fill these, the rubber funnels were designed with a straight length of about two inches before flaring out to match the feeder. Excess powder over that which goes in during the fill cycle remains in this region. When the foot is placed on the powder there is no clearance around the foot, and as the sweep proceeds the powder will work down into the tubing.

Whether the tube requires a certain interface depth or a certain density makes little difference. In general, a fixed weight of powder is put into a tube rather than a certain density. Since commercial tubing ordinarily varies a little in diameter, either the interface or the density must vary for a fixed weight of powder. Since the reactor designer is most concerned with the core load, the weight is held constant.

After filling, a temporary plug or cork is inserted into the end to minimize contamination spread when the tube is removed. The end which was in the box is wiped clean and the rod sent to a welding station. It has been found very beneficial to have all vibration controls and air pressure controls remotely located from the console, such that the operator has complete control of the situation at all times.

After many runs it was noticed that there was a tendency for a little powder to remain in the Syntron at the end of a moderate feed. To overcome this, a Variac has been inserted in series in the line. It is set low for the feed and then at the end, the operator increases the line voltage to all feeders simultaneously. This vigorously vibrates all Syntrons and insures a complete delivery of even the finest powder. These latter techniques are of most use in production, since a highly flexible arrangement is desired. Each Syntron can be individually set by its own control to account for differences in behavior. Also, all can be raised or lowered in amplitude simultaneously to adjust the gross feed rate.

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SECTION XI

POWDER WORKABILITY OR FRIABILITY

It has been frequently observed that substantial changes in powder size composition occur during vibrational compaction. This ability of the powder to break down, round off corners, and grind into the available hole may be directly related to the ability to go to high densities. It probably accounts for many of the discrepancies observed around the country where the use of identical starting formulas do not lead to the same final density. All of the data have been reported in the form of starting formulas and very little in the form of final composition. This is somewhat due to the fact that post-vibrational sieve analyses are laborious, tedious, and time-consuming.

An attempt was made here to evaluate in a semi-empirical way the differences in powder character, in such a manner as to pinpoint the degree of breaking-up which had occurred. It was felt that arc-fused powder, having cooled in some extremely steep thermal gradients, would be highly stressed. The relief of stress during vibration would account for a large measure of the attrition. Annealing the powder in hydrogen at temperatures well into the plastic range of UO_2 should aid in relieving the stress and make for a much tougher ceramic.

11.1 Experimental Procedure and Results

The procedure chosen was as follows:

1. A 7/16 in. OD, 0.020 in. wall stainless steel tube, 46 in. long, with a stud-type end plug was used.
2. The oscillators were set as follows:
 - a. at 30 cps to 10 G level
 - b. add 95 cps to 20 G level
 - c. add 250 cps to 30 G level
 - d. add 1000 cps to 40 G level
3. A total of ~200 grams of trial powder was used in the following proportions:

6/8	160 grams	80%
8/35	0	0
35/42	40 grams	20%
-42	0	0
4. The powder was poured all-at-once into the tube without vibration.
5. The depth to the interface was measured.
6. Power to 40 G, vibrated exactly 30 seconds.
7. Measured depth.
8. Repeated for total of 2 minutes.
9. Measured interface depth each time.
10. Performed a sieve analysis as

+8
8/35
35/42
-42

TABLE VI

ATTRITION OF POWDERS DURING VIBRATION

	Run 1* (Arc-fused UO_2)	Run 2** (Previously-worked UO_2)	Run 3** (Annealed arc-fused UO_2)
Vibration Time (total)	Interface Measurement		
As loaded	15-12/16"	15-2/16"	14-7/16"
30 seconds	12-8/16"	12-6/16"	12-2/16"
60 seconds	11-11/16"	12-2/16"	11-15/16"
90 seconds	11-10/16"	11-15/16"	11-14/16"
120 seconds	11-7/16"	11-15/16"	11-14/16"
≈ % TD	77.0	74.5	75.0
Sieve Analysis (after)	Weight %	Weight %	Weight %
Mesh size			
+8	89 grams 43.2	111 grams 55.0	149 grams 71.0
8/35	62 30.0	47 23.2	16 7.6
35/42	5 2.4	11 5.4	9 4.3
-42	50 24.4	33 16.4	36 17.1
Total	206 100.0	202 100.0	210 100.0

Notes:

*Notice the very great loss of the 35/42 fraction because it was crushed between particles of the 6/8 mesh. The 6/8 mesh also lost almost half, and notice that it moved down to -42 mesh, not just to the next bracket.

**The powder used had already been used in several experimental runs; that is, it had already been worked to some extent. The 6/8 mesh fraction moved slightly into the 8/35 range, and the 35/42 to the -42 range. The lesser work also resulted in a decrease of about 2.5 per cent final density. Whether these results are reproducible is not known at this time.

***24 pounds of arc-fused material was annealed in the regular sintering furnace for about 12 hours @ 1650 C. The aggregates were broken up and the work run made. Again, notice that annealed powder did not change as much as green powder did. Also, notice the difference of about 2 per cent final density for supposedly similar mixes.

11.2 Evaluation of Experiment

Not much further work was done on this particular idea, but the work which was done did serve to illustrate the possibility of some differences between powders, which might explain some of the observed data. Rather than trying to characterize all powders, it was felt that a more profitable approach would be to find the optimum density for each new batch of powder in the system of interest.

At this time it might be hypothesized that a powder's breaking up and relieving the stresses, at the same time causing (or enabling) the particles to fit into the holes available for them, is a necessary procedure for achieving maximum density with angular, odd-shaped particles. This may not be true with spherical particles which have been chosen in the right size relationships.

The shift in density noted for the 80-20 per cent binary under test may mean that a shift to another composition would yield the same final density. At this time it would be hypothesized that more fines and less coarse would achieve the same results with highly-worked or stress-relieved powder, as with green powder.

During these "work" runs and also during the ordinary runs, significant hot regions can be felt on the tube walls as the vibration proceeds. These hot spots are undoubtedly caused by the mechanical heating caused by stress relief during vibration. The lack of this tube heating has been intuitively associated with low density runs, although no definitive experiments have been run which would demonstrate such a correlation. In some instances the tube wall gets so hot that

it is impossible to hold the hand on the tube more than a second or two. There is some concern that with fine powders such heating could lead to oxidation of the uranium dioxide, but such oxidation has not been observed as yet. It is estimated that temperatures around 60-65 C have been occasionally produced, but they are the exception. Temperatures around 30-40 C are more common.

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SECTION XII

RECOMMENDATIONS FOR FURTHER WORK

Additional work on the cascade binary system would undoubtedly be valuable, from the standpoint of yielding controlled, higher densities.

Another area of profitable work would be in the selection of 100 per cent-dense larger particles and medium particles in order to assess the value of high particle density.

The study of the fines, as mentioned above, will proceed at a slow rate under other funds and will undoubtedly yield valuable information.

Finally, a rigorous investigation of the effect of powder friability upon final density would be in order. This one area probably contains the key to the variable results of the many investigators.

APPENDIX

FORMULAS FOR DENSITIES ABOVE 75% TD

(A figure in parentheses indicates a broad fraction with limits indicated by positions of the brackets.)

	6/8	8/10	10/14	14/20	20/28	28/35	35/48	48/65	65/100	100/150	150/200	200/270	270/325	-325 or Jet Fines	% TD
+6															
50					20.0										85.3
	(55.0		(12-1/2	)			(12-1/2	)				(30.0		)	85.1
	18.6	19.4	16.9	5.1		5.0	5.0	5.0				(20.0		)	85.4
	60.0											(25.0		)	85.3
	60.0											(20.0		)	86.2
	45.0	(15.0					(25.0	)				(20.0		)	86.5
			60.0					20.0						15.0	87.5
			71.7											20.0	87.5
														28.3	85.1
		62.0						24.0						14.0	86.5
		30.0	30.0					24.0						16.0	86.7
		63.0						23.0						14.0	87.0
		60.0						15.0						25.0	86.4
	4.8	55.2						23.0						17.0	85.8
	60.0							23.0						17.0	86.0
	60.0							18.0						20.0	86.0
	60.0							20.0						20.0	86.0
	59.0						18.0	3.0						20.0	86.8
	62.0						20.0							18.0	86.8
	62.0						18.0							20.0	85.5
	62.0						21.0							17.0	86.8
	60.0						24.0							15.0	87.0
	65.0						20.0							15.0	86.8
	60.0						20.0							20.0	87.7
				60.0							20.0			20.0	85.0
		65.0						25.0						10.0	86.4
		63.0						24.0						13.0	88.2
	27.0	9.0	24.0						20.0					20.0	88.5
	30.0	9.0	21.0						20.0					20.0	89.0
	30.0	9.0	21.0						25.0					15.0	88.5
	30.0	9.0	21.0											40.0	87.6
	32-1/2	9-3/4	22-3/4											35.0	87.8
	35.0	10-1/2	24-1/2											30.0	86.8
	37-1/2	11-1/4	26-1/4											25.0	85.7
	32.5	9-3/4	22-3/4						15.0					20.0	88.3
	32.5	9-3/4	22-3/4						20.0					15.0	87.6
	31-1/4	9-3/8	21-3/4						5.0					32-1/2	88.3
	31.0	9.3	21.7						12.0					26.0	88.5
	30.0	9.0	21.0						10.0					30.0	87.8
	6.0	14.7	17.3	18.2	1.9	0.8	7.7	6.6	00.7	00.3	00.3	4.1	3.2	18.3	90.0+
	48.4						26.6				25.0				80.3
				20.0	40.0				20.0					20.0	83.2
	63.0									25.0				10.0	82.4
	70.0									25.0				5.0	81.2
	65.0									17.0				18.0	80.6
	70.0									15.0				13.0	80.0
	60.0									30.0				10.0	80.4
	60.0						40.0								82.3
	66-2/3							33-1/3							82.4
	66-2/3														81.4
	48.4			25.0			26.6								82.0
	48.4				25.0		26.6								81.0
	60.0						20.0								82.4
			22.0	47.0										20.0	82.4
			71.4											31.0	84.5
	45.0	5.0	5.0	5.0			(25.0	)						28.6	83.3
	45.0	(15.0		)			(15.0	)						15.0	84.8
50														25.0	82.0
			20.0										30.0		83.3
	60.0						30.0						10.0		82.8
	60.0						22.0						18.0		83.5
	60.0						15.0						25.0		80.5
	48.4						26.6						25.0		81.8
	60.0						25.0						15.0		81.0
	55.0						25.0						20.0		83.2
	50.0						35.0						15.0		81.9
	55.0						30.0						15.0		83.2
	58.0						26.0						16.0		82.8
		54.4						24.4				21.2			82.5
	30.0						40.0					(30.0		)	80.8
	30.0						40.0					(30.0		)	80.8
		65.0										(35.0		)	81.5
		55.2						22.8				(22.0		)	84.4
		56.8						20.0				(23.2		)	84.6
		40.0						40.0				(20.0		)	81.0
	60.0											(40.0		)	80.8
		57.0						16.0				(27.0		)	84.4
		32.0	33.0									(35.0		)	82.0
	43.0						37.0					(20.0		)	83.5

														-325 or Jet Fines		TD
+6	6/8	8/10	10/14	14/20	20/28	28/35	35/48	48/65	65/100	100/150	150/200	200/270	270/325			
60					20.0							(20.0		)		84.4
55					20.0							(25.0		)		81.4
		21.5	41.5				(15.0					(37.0		)		82.2
	10.0	(50.0		)								(25.0		)		82.8
	25.2	(36.5		)	6.0	(87.0			(7.3			(16.2		)		83.2
	18.6	19.4	16.8	05.1		8.3	8.3	8.3				(15.0		)		83.5
			60.0									(40.0		)		80.3
			70.0									(30.0		)		81.7
		70.0										(30.0		)		80.1
		60.0										(40.0		)		80.7
	18.6	19.4	16.8	5.1		5.0	5.0	5.0				(25.0		)		84.4
	18.6	19.4	16.8	5.1		6.7	6.7	6.7				(20.0		)		81.2
	16.7	17.5	15.2	4.6		7.3	7.3	7.3				(24.0		)		80.4
	20.1	21.0	18.3	5.5		3.3	3.3	3.3				(25.0		)		80.6
	17.1	17.8	15.5	4.7		6.7	6.7	6.7				(25.0		)		80.6
		(60.0		)		5.0	5.0	5.0				(25.0		)		82.8
		(60.0		)			(20.0					(20.0		)		83.7
		(60.0		)			(25.0					(15.0		)		80.7
		(65.0		)			(25.0					(10.0		)		83.4
		(67.0		)			(13.0					(20.0		)		81.5
		(60.0		)			(15.0					(25.0		)		82.9
	10.0	(57-1/2		)			(12-1/2					(20.0		)		84.1
	15.0	(50.0		)			(14.0					21.0		)		81.5
	45.0	(15.0		)			(20.0					20.0		)		83.4
	45.0	(15.0		)			(20.0					(20.0		)		82.3
	50.0	(10.0		5.0	(15.0							(20.0		)		84.3
	45.0	(10.0		5.0			(20.0					(20.0		)		84.0
	45.0	(10.0		5.0			(20.0					(20.0		)		84.5
	60.0							20.0				20.0		)		83.4
	15.0	20-1/2	29.3				4.0	8.0				23.0		)		80.3
	45.0	(15.0		)					(20.0			(20.0		)		81.7
	60.0										20.0			)		80.2
		60.0							(30.0					)	20.0	82.7
		60.0							(30.0					)	10.0	82.7
	50.0	(10.0		)		(20.0						(20.0		)		83.0
	45.0	(15.0		)		(20.0						(20.0		)		82.6
		(60.0		)		(22.0						(18.0		)		82.0
		60.0						20.0					(20.0	)		81.5
		60.0						10.0							30.0	80.7
		60.0						20.0							20.0	82.1
		60.0						30.0							10.0	82.2
		60.0						20.0				(20.0		)		81.8
		60.0						30.0				(10.0		)		80.7
		60.0						30.0					(10.0	)		81.1
		70.0						10.0				(20.0		)		80.7
		70.0						30.0								80.3
		63.0						15.0				(22.0		)		82.8
		63.0						15.0							22.0	82.9
		61.0						18.5				(20.5		)		83.3
	2.0	16.0	32.0	16.0	1.5		3.0	6.5	3.0			3.0	12.0	5.0		83.7
	67.0								33.0							82.0
	67.0									33.0						80.0
		30.0							20.0			(50.0		)		77.1
		30.0							50.0			(20.0		)		76.3
		30.0							30.0			(40.0		)		77.4
		20.0							30.0			(50.0		)		76.0
		30.0							40.0			(30.0		)		77.8
				(65.0		)			(25.0			(10.0		)		75.5
				(60.0		)			(25.0			(15.0		)		76.6
				(60.0		)			25.0			(15.0		)		75.5
				(60.0		)				(25.0		(15.0		)		76.0
				(65.0		)			(25.0			(10.0		)		76.6
				(65.0		)			(20.0			(15.0		)		76.8
				(75.0		)			(15.0			(10.0		)		75.4
		70.0							20.0			(10.0		)		78.7
		60.0							40.0							78.5
		50.0							50.0							78.2
		40.0							60.0							73.6
	70.0						30.0									75.9
	60.0			25.0			15.0									75.3
	35.0		35.0				30.0									75.0
	35.0		35.0				30.0									75.3
	63.0		7.0				30.0									76.8
	60.0			20.0			20.0									75.9
		100		)												75.8
		66-2/3							26.6					33-1/3	77-1/2	
	48.4								22.7					25.0		75.3
	62.3												15.0			79.7
		50.0							40.0			(10.0		)		79.0
		50.0							30.0			(20.0		)		79.8
		50.0							10.0			(70.0		)		78.7
		50.0										(50.0		)		78.2
		40.0							50.0			(10.0		)		76.6
		40.0							40.0			(20.0		)		78.2
		40.0							30.0			(30.0		)		78.3
		40.0							20.0			(40.0		)		78.0
		40.0							10.0			(50.0		)		76.6
		40.0										(60.0		)		76.0
		50.0							20.0			(30.0		)		79.8

#6	6/8	8/10	10/14	14/20	20/28	28/35	35/48	48/65	65/100	100/150	150/200	200/270	270/325	-325 or Jet Fine	% TD
			30.0						50.0			(20.0	)		76.3
			30.0						30.0			(40.0	)		77.4
		50.0										(50.0	)		77.8
			20.0						40.0			(40.0	)		76.2
			20.0						50.0			(30.0	)		76.5
				(60.0	)				(20.0			(20.0	)		75.9
20.0	21.0	18.3	5.5			5.0	5.0	5.0				(20.0	)		78.2
15.5	16.2	14.1	4.25			3.3	8.3	8.3				(25.0	)		78.2
17.0	17.8	15.5	4.7			8.3	8.3	8.3				(20.0	)		79.7
17.0	17.8	15.5	4.7			10.0	10.0	10.0				(15.0	)		79.4
18.6	19.4	16.9	5.1			3.3	3.3	3.3				(30.0	)		76.9
10.6	10.8	9.4	2.8			11.0	11.0	11.0				(33-1/3	)		77.8
45.0	(15.0	)				(20.0	)					(20.0	)		78.7
10.0	(60.0	)				(10.0	)					(20.0	)		77.6
50.0	7.0	11.0	14.0	3.0								(15.0	)		76.6
50.0	10.0		10.0	5.0								(30.0	)		75.8
50.0	5.0		10.0	5.0								(30.0	)		78.7
50.0	12.0		20.0	4.0								(14.0	)		76.3
50.0	10.0		15.0	5.0								(20.0	)		78.2
50.0	10.0		10.0	5.0								(25.0	)		79.5
18.6	19.7	16.9	5.1									(40.0	)		76.8
			45.0	10.0		(25.0	)					(20.0	)		77.0
60.0			10.0			(20.0	)					(10.0	)		77.7
44.0	16.0					(12.0	)					(28.0	)		77.8
	50.0		5.0	10.0		(20.0	)					(15.0	)		79.1
	45.0			15.0		(20.0	)					(20.0	)		79.5
20.0	40.0			5.0	10.0				5.0	10.0					78.5
				(60.0	)				(25.0	)		(15.0	)		77.4
				(65.0	)				(25.0	)		(10.0	)		79.6
				(70.0	)				(20.0	)		(10.0	)		74.4
				(70.0	)				(15.0	)		(15.0	)		75.9
				(60.0	)				(15.0	)		(25.0	)		75.9
				(65.0	)				(10.0	)		(25.0	)		76.3
				(67.5	)				(20.0	)		(12.5	)		76.6
				(65.0	)				(20.0	)		(15.0	)		76.8
				(75.0	)							(25.0	)		75.5
	30.0	30.0						15.0				25.0			78.5
48.4							26.6					25.0			76.4
				(60.0	)				(30.0	)		(10.0	)		76.4
				(75.0	)							(25.0	)		76.2
50.0												(50.0	)		78.2
	40.0	40.0										(20.0	)		75.3
	30.0							40.0				(30.0	)		79.0
			60.0									(40.0	)		77.7
			50.0									(50.0	)		78.6
			70.0									(30.0	)		79.0
60.0						30.0						(10.0	)		79.6
80.0												(20.0	)		77.9
45.0										35.0				20.0	77.1
		34.6	70.0					52.6	30.0			(12.8	)		76.6
		9.1													75.1
60.9						30.0									77.0
90.0	10.0					30.0									75.1
56.0	14.0					30.0									77.9
49.0	21.0					30.0									75.7
42.0	28.0					30.0									76.4
28.0	42.0					30.0									75.5

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