

Fundamentals of Granulation

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The batch ammoniation of superphosphate, as was commonly practiced in the 1930's and 1940's, sometimes resulted in partial granulation of the reaction mass. Investigators then determined the physical and chemical parameters for granulation so that processing methods could be developed to provide consistent granulation of fertilizers. Introduction of the rotary drum continuous ammoniator in the 1950's was a result. The mechanism of the agglomeration and the sources of liquid phase for granulation are described. The effect of temperature upon the quantity of liquid phase and the thermal chemistry of the major chemical reactions of ammoniation and neutralization is reviewed. The role of the formulator is to establish ideal conditions for agglomeration in addition to providing the guaranteed plant food ingredients for any given fertilizer product. Finally, the effect of ammoniator drum dimensions on optimizing the product output for any given formulation is investigated.

Mixed fertilizers is a term used to describe fertilizers containing two or more major nutrients which are produced by combining, both physically and chemically, several raw materials which are nutrient carriers. In the past, these products were made in batch mixers in non-granular form. They were sometimes termed "pulverized". Superphosphates were the preferred sources of phosphate, and nitrogen solutions containing free ammonia were used to "ammoniate" the normal superphosphate or triple superphosphate to make various ammonium calcium phosphate compounds. The solutions containing free ammonia were used because they were the least expensive sources of nitrogen and because the resulting compounds were fairly stable.

Chemical reactions did occur, however, in the storage piles, and the piles became very severely caked after a short period of time. This was called pile set. The continuation of the chemical reactions was termed "curing". Curing was often accelerated by moving the piles several times during the storage period. To do this, it was necessary to blast the caked piles with explosives and to process the lumped material through heavy duty crushers.

Granulation occurred more or less accidentally when superphosphate was ammoniated in rotary batch mixers. The liquid phase supplied with the ammoniating solution wetted the dry materials. The wet particles rolled together forming small agglomerates. The amount of liquid phase also increased as various salts became dissolved in the water. The chemical reactions caused the temperature to increase and this further promoted additional liquid phase.

It was eventually discovered that the amount of granulation could be controlled by formulating the materials, both liquid and solid, to yield a maximum number of agglomerates of the desired size. Fertilizer in this form still contained small particles which were generally left in the product as the granules were somewhat wet and soft and screening was almost impossible. These products were termed "semi-granular". They usually handled better than "pulverized" fertilizers and were better accepted by farmers.

However, the semi-granular products still tended to cake in bulk piles and in bags and segregation of nutrients was a common problem attributable to the nonuniform sizing. Effort was then directed toward controlling the process to maximize granule formation. Equipment was designed to produce smoother, more spherical granules, to dry and cool the granules, and to separate and recycle the off-size portion of the process stream. This is how the modern granulation unit came to be developed.

In most plants today, agglomeration takes place in a rotary drum ammoniator. Dry materials passing through the drum form a rolling bed and the liquids are added through drilled pipes placed under the surface of this bed. These pipes are called spargers.

Along with the simple mixing of liquids and solids that takes place in the drum, two chemical reactions—ammoniation and neutralization—also occur. Ammoniation involves reacting ammonia with monocalcium phosphate, the basic constituent of normal superphosphate. This process produces an ammonium-calcium-phosphate compound. Neutralization occurs when the ammonia is reacted with either sulfuric or phosphoric acid to produce ammonium sulfate or ammonium phosphate.

The key to successful agglomeration is a proper liquid-to-solid relationship, both as to the proportions of these materials in the drum and as to how well the solids are wetted by the liquids. The main reason some formulations granulate better than others is that the liquids-to-solids ratio is nearly ideal.

The liquid portion or phase of the mixture comes from several sources. There is water in the nitrogen and acid solutions, in the materials themselves, and extra water can be added. This is usually done through the nitrogen solution sparger. Steam supplies both heat and water. All of these sources of water plus the dissolved salts make up the liquid phase.

Researchers identified the reasons why the liquid and solid materials in the drum tended to agglomerate or granulate. Two phenomena can be credited. One is the natural surface tension of the liquid that draws wetted solid particles into contact with each other and holds them together. The second is the mechanical forced contact of wetted particles as the drum rotates. These two forces work together and must occur at the same time.

To explain the first phenomenon, the surface of water and many other liquids tends to form what can be described as an elastic film of molecules that hold tightly together. For example, water from an eye dropper forms drops rather than a steady stream and water placed on a nonporous surface tends to bead up.

In the ammoniating drum, this surface tension causes wetted particles to cling to one another, giving the resulting agglomerates a degree of plasticity—in other words, they can be deformed or moved by mechanical action without breaking up. As the small wetted particles roll around in the drum, they come in contact with each other. Surface tension from the liquid phase draws them even closer together. The continued rolling action causes them to grow

Table I. Solubilities of Fertilizer Material (g/100 g of Water)^a

temp, °C	(NH ₄) ₂ SO ₄	NaNO ₃	urea	NH ₄ NO ₃	KCl	KNO ₃	NH ₄ Cl
0	70.6	73.0	66.7	118.3	27.6	13.3	29.4
10	73.0	80.0	85.2		31.0	20.9	33.3
20	75.4	88.0	108.3	192.0	34.0	31.6	37.2
30	78.0	96.0	135.3	241.8	37.0	45.8	41.4
40	81.0	104.0	166.7	297.0	40.0	63.9	45.8
50		114.0	203.0	344.0	42.6	85.5	50.4
60	88.0	124.0	250.9	421.0	45.5	110.0	55.2
70			309.8	499.0	48.3	138.0	60.2
80	95.3	148.0	400.0	580.0	51.1	169.0	65.6
90			525.0	740.0	54.0	202.0	71.3
100	103.3	180.0	733.3	871.0	56.7	246.0	77.3
increase: 0-100 °C	32.7	107.0	666.6	752.7	29.1	232.7	47.9

^a Source: "Handbook of Chemistry and Physics", 34th ed.; CR Publishing Co.: Cleveland.

larger. This is called coalescence.

If the mechanical contact continues in the proper liquid/solid environment, the granules will continue to form and grow until no small particles remain that have the proper surface area to mass relationship.

At this point, our mixture of liquids and solids has been transformed into a group of aggregates or granules. Ideally, they are all about 1-4 mm in diameter. This does not always happen.

The wet bond strength of the agglomerates must then be translated into a dry bond strength in the final granules. This is accomplished by maximizing the amount of dissolved fertilizer salts in the water. The space in the agglomerates taken by the water becomes filled with precipitated salts after the water is evaporated. These salts bridge the voids between the particles, making for a strong, dense granule.

If the factors so far discussed were the only ones involved in the granulation process, perhaps its control would not be particularly difficult. In reality, however, the temperature of the materials in the drum has a very important bearing on the delicate liquid-solid relationship, and controlling temperature is both difficult and vital.

Heat increases the solubility of the fertilizer salts in water. The hotter the water, the more salt it can dissolve. Complicating this effect is the fact that the various salts behave differently as far as solubility is concerned at various temperatures.

Table I shows the solubility of a number of the more commonly used fertilizer materials. The solubility data are given as weight equivalents of the salt which will dissolve in 100 weight equivalents of water. You will note that the solubility of all of the salts listed increases as the temperature increases, but that some salts dissolve more easily than others—both at low temperatures and at high temperatures.

The heat generated by chemical reactions varies, depending on which materials are reacting, and it also depends upon the extent that the reactions go to completion. When ammonia is reacted with normal superphosphate, approximately 1480 Btu are released for every pound of ammonia reacted. This is equivalent to 373 killogram-calories kg-cal/lb or 823 kg-cal/kg of ammonia.

Other approximate heat output values, based on 1 kg of ammonia reacted are: triple superphosphate releases 873 kg-cal/kg; phosphoric acid, 1170 to 1220 kg-cal/kg; and sulfuric acid from 1330 to 1550 kg-cal/kg depending on the concentration of the acid.

When heat must be added to raise temperatures, an ideal external source is steam. Steam is particularly effective because it permits the operator to vary the heat content of the ammoniator bed mass without a change in the basic formula. This enables the operator to adjust for

fluctuations in recycle or other changing conditions and yet maintain a consistent output of properly agglomerated fertilizer ingredients.

The raw material and recycle that enter the drum have the capability to absorb or release heat. Each fertilizer material has a heat value referred to as its "specific heat". The average of most fertilizer materials is about 0.25-0.33 kg-cal/kg °C.

There are other heat losses which must be calculated. They fall into two general classes—latent heat losses and sensible heat losses.

Latent heats include the heat required to change a salt from the solid to the liquid phase. They also release heat when they crystallize. This is a form of latent heat called heat of fusion. Another form of latent heat is heat of vaporization, the heat required when water in the ammoniator is converted to steam.

The heat required to bring the raw materials up to granulation temperature and the heat lost from the ammoniator shell to the surrounding air are examples of sensible heat losses. These losses explain why it is more difficult to get good granulation in cold weather.

We summarize as follows: (a) Granulation is achieved through proper proportioning and controlled mixing of liquid phase with dry material. (b) Capillary action and surface tension hold the particles together in agglomerates when mechanical tumbling in the rotating cylinder bring them into contact. (c) Continued mechanical contact strengthens the bond and forms the agglomerate into a more spherical configuration. (d) Liquid phase, which is significantly affected by temperature, must be controlled by the operator to attain optimum granulation. (e) The formulator chooses his raw materials very carefully to provide the best combination of soluble salts to achieve strongly bonded granules.

Ammoniators

Background. The rotary drum ammoniator was developed in the early 1950's by F. T. Nielsson and several co-workers at TVA. The patent application was filed in November 1953 and U.S. patent no. 2 741 545 was issued on Apr 10, 1956.

This device has since become the standard method, used world-wide, for achieving ammoniation of normal and triple superphosphate. It is also extremely effective as a means of accomplishing granulation by both agglomeration and layering mechanisms. The drum ammoniator has also proved to be an effective way to react ammonia with acids to make ammonium sulfate and various ammonium phosphates.

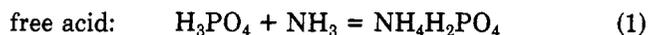
Nielsson's original objective was to develop a means of adding ammonia to superphosphate on a continuous basis. It was found that when this was done under controlled

conditions, agglomeration would occur. The next step was to add extra ammonia and capture it with acids which produced even better granulation conditions. They soon learned that potash salts, fillers, and other materials could be introduced, along with the superphosphate, and the entire mixture would granulate into fairly homogeneous particles, each containing nitrogen, phosphate and potash in the desired ratio.

Spargers

One of the most important design considerations involves the piping through which ammonia-containing liquids and acids are introduced to the dry raw materials. The liquids are customarily added under the rolling bed of dry materials through drilled pipes called spargers. Length, positioning, and drilling pattern for the various spargers have been developed, based mainly on the chemical reactions and the sequence in which they should occur to yield the best granulation with the least amount of loss. Two basic concepts must be kept in mind: (1) ammonia must be distributed to contact the absorbing medium at the proper rate; (2) the less hardware under the bed, the better the operation.

The drilling of the individual sparger pipes is dependent on the sequence of chemical reactions. These reactions, listed in sequence, are

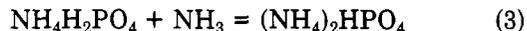


water-soluble P_2O_5 :

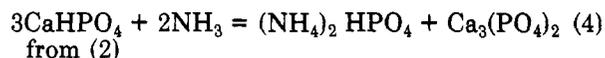


The above reactions occur rapidly up to 2 lb of NH_3 per unit of P_2O_5 .

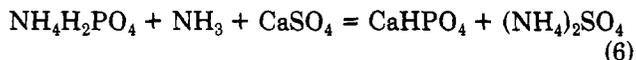
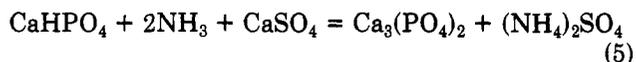
Next, a series of secondary reactions take place. These occur more slowly, and at the 2 to 4 lb ammoniation level



where the reactants are taken from reactions 1 and 2 and



If gypsum is present, these reactions occur at the 4 to 6 lb ammoniation level



If the formula contains triple phosphate made from wet process acid, only a small amount of gypsum is present, and reaction 5 will occur to only a small extent. The resultant product will have about 50% water-soluble P_2O_5 because of the MAP and DAP made by reactions 1, 2, 3, and 4.

When the formula contains normal superphosphate, the water solubility of the phosphates in the product is reduced to as low as 25% by reactions 5 and 6. Reactions 5 and 6 produce ammonium sulfate, but at a slow rate. If the formula requires sulfuric acid, and the acid is added too soon, the ammonia will combine with that acid and reactions 5 and 6 will be further retarded.

Logically, ammonia should be added at a uniform rate, and sulfuric acid should be added stepwise, in increasingly larger amounts as the bed moves toward the discharge end of the drum. This permits the ammoniation of superphosphate to the greatest extent before reacting ammonia with acid.

If a plant uses relatively small amounts of phosphoric acid in its formulas, the phosphoric acid can be mixed with the sulfuric acid in a tee and the combined acids sparged

Table II. Effects of Speed and Drum Diameter

diameter		% of critical speed, rpm				
ft	cm	25%	30%	35%	40%	45%
6	183	7.8	9.4	10.9	12.5	-
7	213	7.2	8.7	10.1	11.6	13.0
8	244	6.8	8.1	9.5	10.8	12.2
9	274	6.4	7.7	8.9	10.2	11.5
10	305	6.1	7.3	8.5	9.7	10.9
12	366	-	6.6	7.7	8.8	9.9

under the bed. This will require a larger diameter pipe and more holes, or larger holes, than would be needed for sulfuric acid alone. If large amounts of phosphoric acid are needed, spraying it on the surface of the bed is an alternative.

It is known that a pipe will discharge equally through all orifices drilled along its axis if the sum of the areas of the holes does not exceed one-half the internal cross-sectional area of the pipe. There is some flexibility to this, a sparger should be drilled for the "average" operating formula. If formula requirements differ greatly, separate spargers will be needed for each formula.

To avoid frequent sparger changes, when both acids are used in one formula, an option is to split the phosphoric flow, putting part on the surface of the bed. Phosphoric acid does not produce fumes by reacting with chlorides, as does sulfuric acid. This makes surface spraying acceptable. Sulfuric acid, on the other hand, must be introduced under the bed or fuming will be excessive.

Spargers should be installed with about 3 or 4 in. clearance from the shell in 6-, 7-, or 8-ft drums. Clearances up to about 6 or 8 in. in 10- or 12-ft drums are satisfactory. A clearance too close to the shell inhibits rolling action, and too near the bed surface causes ammonia losses.

The distance between the ammonia sparger and the acid sparger depends upon the heat effect desired. Some plants place these pipes only 6 in. apart. This produces a more concentrated heat which may help granulation, but it also results in more fuming. Generally, plants making low nitrogen grades place the spargers close together, and those making high nitrogen grades move them further apart.

Rotational Speed

The rotational speed of the ammoniator drum has an important effect upon the efficiency of granulation. If it is too slow, the bed rolls lazily and the materials do not move past the spargers fast enough to take up the liquids and undergo the desired chemical and physical changes. If the drum turns too fast, the bed of wetted materials will carry too far up the ascending side of the shell, roll back down the top of the bed, and over-agglomeration will result.

The critical speed has been defined as the speed of rotation at which the bed ceases to roll or tumble, but is instead held in place by centrifugal force. The formula for critical speed is

$$\text{critical speed} = 76.5 \div D^{1/2}$$

Most authorities agree that best granulation is achieved when the rotational speed of the drum is between 25% and 45% of the critical speed. The desired speed is dependent on the diameter of the drum. Table II contains a few examples.

The Rainbow Division of International Minerals and Chemicals Corp. operates six 8-ft diameter drums. At the present time, two of these are rotating at 7 rpm (26% of critical) and four are being operated at 9 rpm (33% of critical). There is very little noticeable difference in granulation efficiency, except that one plant which recently

Table III. Ammoniator Comparisons

A. Six New Southern Plants			
drum size 8 ft diameter × 12 ft long, 10 ft ammoniation section with 16 in. dam, plus 4 in. extra ring to make 20 in. bed depth			
B. Chicago Heights and Texarkana			
drum size 7 ft diameter × 14 ft long, 10 ft ammoniation section; bed depth is 14 in.			
C. Lockland			
drum size 6 ft diameter × 10 ft long, with 14 in. bed depth			
	unit		
	A	B	C
ammoniation section dimensions (ft, ft, in)	8 × 10 × 20	7 × 10 × 14	6 × 10 × 14
volume bed, ft ³	76.0	42.2	38.7
bed surface, ft ²	65.0	52.2	47.5
heat loss area (shell + 2 ends, filled part of drum) ft ²	91.1	72.2	62.6

changed from 7 rpm to 9 rpm reports a slightly improved granulation rate on some of the more difficult to granulate grades. These are grades containing low levels of soluble salts and which depend heavily upon steam for heat and liquid phase.

Ammoniator Dimensions

In 1964, our division decided to build six NPK granulation plants in the Southern states. Previously we operated several smaller NPK granulation plants in the North. These were nominal 10 to 15 ton-per-hour plants. The new plants were designed to produce at 30 tons/h. The ammoniators were 8 ft in diameter and 12 ft in length, with a retaining dam 2 ft from the discharge end.

A very popular grade at the time was 10-10-10, and all of the new plants were assigned to make substantial tonages of this grade. Previously, the several older plants had been producing 10-10-10 with a least-cost formula which derived all ten units of nitrogen from 448 solution. In the U.S., this is a name for a solution marketed commercially which contains 44.8% N, consisting of 25% free ammonia, 69% ammonium nitrate and 6% water. The free ammonia reacts with phosphates and acids in the formula to produce heat, and the ammonium nitrate provides a soluble salt binder to make strongly structured granules.

When the new plants attempted to make 10-10-10 using the 10 units from 448 formula, they found that they had to cut the production rate to between 16 and 20 tons/h to avoid overgranulation, fuming, and flash fires in the ammoniator. This was not an acceptable production rate for a new plant rated at 30 tons/h.

A compromise formula was then developed. The cost of ingredients was somewhat higher, but it enabled the new plants to make 10-10-10 at 25 tons/h. This formula de-

rived eight units of N from 448 solution, and the remaining two units from N came from crystalline ammonium sulfate.

The above related experience led us to investigate the relationship between ammoniator dimensions, formula heat, and production rate. We began by comparing the ammoniator sizes of the six new Southern plants with those at three 1954-56 era locations: Chicago Heights, Texarkana, and Lockland. The comparisons are given in Table III.

Table IV gives two typical formulas, one used by the new southern plants, with eight units of N from 448 solution and one used by the older plants with all ten units of N from 448 solution. The heat generated and the water content of each formula are given. Evaporation to 1% moisture is assumed. Costs given are typical of 1965/66 when this study was made.

It is known that the ability to control the liquid phase in the bed (to prevent overgranulation, nitrogen losses, heavy noxious fuming, and flash fires) is a function of heat generated by the reactants and water content. It was also learned, during many years of experience at Lockland using the 6 ft × 10 ft × 14 in. ammoniator, that 10 tons/h was about the practical limit in production rate that the operator could control when using ten units of 448 (25-69-0) solution in making 10-10-10.

For establishing a starting point in the study, 10 tons/h, using a 240 050 Btu/ton formula, in the old Lockland ammoniator was selected as a control limit. In other words, the capacity of the Lockland ammoniator was 2 400 500 Btu/h.

If reaction volume governs bed behavior, this limit is 2 400 500 Btu/h through a 38.7 ft³ bed, or 62 028 Btu/(ft³ h). If heat loss surface area governs bed behavior, this limit is 2 400 500 Btu/h with a 62.6 ft² area or 38 347 Btu/(ft² h).

It is not known which of the above is the true limiting factor; in fact, it is probably a combination of both of them plus a third factor based upon evaporation of water through the top surface area of the bed. This is important because the escape of water into the vapor phase will improve bed condition by reducing heat content as well as liquid content of the bed. Because we do not dry all the way to 1% moisture in the ammoniator using either formula, we can say that water release into vapor is strictly proportional to bed surface area, irrespective of water contained in the formula. If bed surface area governs bed behavior, this limit would be 2 400 500 Btu/h with a 47.5 ft² area, or 50 537 Btu/(ft² h).

Table V applies the above-developed heat factors for the Lockland ammoniator to other ammoniators. The two 10-10-10 formulas given in Table IV are used.

Because the limiting factor is probably a combination of all three of those discussed above and developed in Table V, a generalization can be made that the new Southern plants would be limited to production rates of about 16 tons/h when using a formula for 10-10-10 which derives all N from solution 448 (25-69-0). These same

Table IV. Formulas for 10-10-10 Fertilizer

raw material	new Southern plant formula				older Northern plant formula			
	lb	Btu	H ₂ O	R/M cost, \$	lb	Btu	H ₂ O	R/M cost, \$
66° sulfuric acid	91	79 750	6	0.87	172	151 250	12	1.65
448 solution	356		21	9.70	458		27	12.48
sulfate of ammonia	214		0	3.73	--		--	--
R/P super	1025	88 800	62	9.72	1025	88 800	62	9.72
60% muriate of potash	334		0	6.39	334		0	6.39
dry filler	49		0	0.07	92		0	0.13
evaporation	-69		-69		-81		-81	
total	2000	168 550	20	30.48	2000	240 050	20	30.37

Table V. Application of Heat-Dimension Parameters at Lockland to Other Ammoniators

A. Bed Volume Is Limiting Factor	
1. Chicago Heights, Texarkana	
62 028 Btu/(ft ³ h) × 42.2 ft ³ = 2 617 582 Btu/h	
A. using Northern plant formula	
$\frac{2\ 617\ 582\ \text{Btu/h}}{240\ 050\ \text{Btu/ton}} = 10.9\ \text{tons/h}$	
B. using Southern plant formula	
$\frac{2\ 617\ 582\ \text{Btu/h}}{168\ 550\ \text{Btu/ton}} = 15.5\ \text{tons/h}$	
2. new Southern plants	
62 028 Btu/(ft ³ h) × 76 ft ³ = 4 714 128 Btu/h	
A. using Northern plant formula	
$\frac{4\ 714\ 128\ \text{Btu/h}}{240\ 050\ \text{Btu/ton}} = 19.6\ \text{tons/h}$	
B. using Southern plant formula	
$\frac{4\ 714\ 128\ \text{Btu/h}}{168\ 550\ \text{Btu/ton}} = 28.0\ \text{tons/h}$	
B. Heat Loss Area Is Limiting Factor	
1. Chicago Heights, Texarkana	
38 347 Btu/(ft ² h) × 72.2 ft ² = 2 768 653 Btu/h	
A. using Northern plant formula	
$\frac{2\ 768\ 653\ \text{Btu/h}}{240\ 050\ \text{Btu/ton}} = 11.5\ \text{tons/h}$	
B. using Southern plant formula	
$\frac{2\ 768\ 653\ \text{Btu/h}}{168\ 550\ \text{Btu/ton}} = 16.4\ \text{tons/h}$	
2. new Southern plants	
38 347 Btu/(ft ² h) × 91.1 ft ² = 3 493 412 Btu/h	
A. using Northern plant formula	
$\frac{3\ 493\ 412\ \text{Btu/h}}{240\ 050\ \text{Btu/ton}} = 14.6\ \text{tons/h}$	
B. using Southern plant formula	
$\frac{3\ 493\ 412\ \text{Btu/h}}{168\ 550\ \text{Btu/ton}} = 20.7\ \text{tons/h}$	
C. Bed Surface Area Is Limiting Factor	
1. Chicago Heights, Texarkana	
50 537 Btu/(ft ² h) × 52.2 ft ² = 2 638 031 Btu/h	
A. using Northern plant formula	
$\frac{2\ 638\ 031\ \text{Btu/h}}{240\ 050\ \text{Btu/ton}} = 11.0\ \text{tons/h}$	
B. using Southern plant formula	
$\frac{2\ 638\ 031\ \text{Btu/h}}{168\ 550\ \text{Btu/ton}} = 15.7\ \text{tons/h}$	
2. new Southern plants	
50 537 Btu/(ft ² h) × 65 ft ² = 3 284 905 Btu/h	
A. using Northern plant formula	
$\frac{3\ 284\ 905\ \text{Btu/h}}{240\ 050\ \text{Btu/ton}} = 13.7\ \text{tons/h}$	
B. using Southern plant formula	
$\frac{3\ 284\ 905\ \text{Btu/h}}{168\ 550\ \text{Btu/ton}} = 19.5\ \text{tons/h}$	

plants could make 10-10-10 at about 23 tons/h when using a formula deriving eight units of N from solution and two units from sulfate of ammonia. The above statements were borne out by actual experience in the plants.

Also, the older plants could probably improve their production rates by using less solution in the formula. Whether this is practical or not depends upon capacity of other equipment. Many of the older plants were limited in cooler and screening capacity.

Drying, cooling, screening, and so forth, were not limiting factors in the new Southern units; therefore, it was decided

Table VI. Development of a Combination Heat Dimension Parameter

1. Basic Premise	
If ammoniator bed volume governs granulation efficiency, heat content should be 62 000 Btu/(ft ³ h).	
If surface area of the ammoniator bed governs granulation efficiency, heat content should be 50 500 Btu/(ft ² h).	
If shell area of the filled part of the ammoniator drum governs granulation efficiency, heat content should be 38 300 Btu/(ft ² h).	
2. Ammoniator Dimensions	
size	8 ft diameter × 10 ft long ammoniating section with 20 in. high retaining dam
volume of bed	76.0 ft ³
surface of bed	65.0 ft ²
heat loss area (shell + 2 ends, filled part of drum)	91.1 ft ²
3. Multiply the Values Given in 1. by the Dimensions Given in 2.	
bed volume:	62 000 Btu/(ft ³ h) × 76.0 ft ³ = 4 712 000 Btu/h
bed surface:	50 500 Btu/(ft ² h) × 65.0 ft ² = 3 283 000 Btu/h
shell area:	38 300 Btu/(ft ² h) × 91.1 ft ² = 3 489 000 Btu/h
4. Proportion the Values Given in 3. According to Our Estimate of Their Relative Importance	
$4\ 712\ 000 \times 0.60 + 3\ 283\ 000 \times 0.30 + 3\ 489\ 000 \times 0.10 = 4\ 160\ 863\ \text{Btu/h}$	

Because approximations were used throughout this study, round this to 4 160 000 Btu/h ammoniator heat parameter for the 8 ft × 10 ft × 20 in. ammoniators

to maximize production rates irrespective of small increases in formula costs.

It was next decided to apply the concept of heat-dimensional parameters, as discussed in the foregoing, to formulas containing low reaction heats, but first, a combination parameter had to be developed, one that combined the effects of bed volume, bed surface and shell surface.

There was no way to measure the radiant heat loss from the ammoniator shell and to measure each of the various forms of heat release from the bed surface. Accordingly, it was necessary to estimate the relative importance of each factor and proportion these into a combination heat-dimension parameter.

By slightly rounding the values given in Table V, a set of values is developed which are proportioned 60% to bed volume, 30% to bed surface, and 10% to shell area. The ultimate approximate heat parameter for the 8 ft × 10 ft × 20 in. ammoniator drum is determined to be 4 160 000 Btu/h. The development of this value is given in Table VI.

It was found that the ammoniator heat parameter could be applied to low heat formulas as well as high heat formulas. A few examples follow.

1. 5-10-15 with heat generation of 127 140 Btu/ton; $4\ 160\ 000\ \text{Btu/h} \div 127\ 140\ \text{Btu/ton} = 32.7\ \text{tons/h}$ optimum production rate. *Experience:* plant ran very successfully at a production rate of 33 tons/h.

2. 5-10-15 with heat generation of 104 940 Btu/ton; $4\ 160\ 000\ \text{Btu/h} \div 104\ 940\ \text{Btu/ton} = 39.6\ \text{tons/h}$ optimum production rate. *Experience:* ammoniator granulation very good at 40 tons/h; however, total system load was excessive for efficient screening. Reduced rate to 30 tons/h and used steam for granulation control.

3. 4-12-12 with heat generation of 105 300 Btu/ton; 4 160 000 Btu/h ÷ 105 300 Btu/ton = 39.5 tons/h optimum production rate. *Experience*: granulation good at 40 tons/h. Too much load on screens for efficient removal of fines. *Judgement*: this formula would be satisfactory at 40 tons/h if more screening surface were provided. Several plants made this grade at 30-33 tons/h, using steam as a granulation control.

In the development of the ammoniator heat parameter, the authors have disregarded effects on granulation attributable to formula water, added water, temperature or particle size of the dry materials, soluble salts contained in the formulas, etc. These items all have a significant influence on bed conditions and must be considered in all actual situations. It is felt, however, that the heat parameter concept can be employed very usefully in selecting ammoniator dimensions, as in the design of a new plant, when the operating formulas are known, and any limiting effects of other equipment can be eliminated in the engineering stage.

This concludes the discussion on the fundamentals of granulation and also the rotary drum ammoniator, which

is the most universally used device for achieving granulation. It was not the intention of this paper to go into elaborate detail on all aspects of granulation. The paper was intended to be introductory to the category entitled "Granulation" and for the other papers which will follow.

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Corrosion of Aluminum-Matrix Composites. Status Report

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Light-weight aluminum-matrix composites, some of which may find applications in military or other vehicles, have not been examined extensively with regard to corrosion behavior. This paper collects the corrosion data that are available to summarize the observations made, identify questions that need attention, and assess the potential corrosion characteristics of these materials. The problems that may be encountered include selective attack at fiber-matrix or other interfaces (B/Al, G/Al), galvanic coupling with a continuous cathodic fiber (G/Al), and segregated matrix microstructures resulting from solidification processing (Al_2O_3/Al , SiC/Al). Additional testing is required. Attractive candidates for further development efforts would be those composites for which the corrosion problems turn out to be relatively minor ones and which also have favorable estimated production costs.

Aluminum-matrix composites have high potential for providing high-strength and -stiffness light-weight materials. Research and development over some years was initially stimulated by the needs of the aerospace industry, but more recently there has been awareness that economical light-weight composites with less than the highest strength performance would have a large field of application in transportation and military vehicles. The mechanical properties of the product are sensitive to fabrication technique and have been used to monitor and guide process development. Some information is available on composite microstructure and its relation to processing and to mechanical properties, especially for the older composites. Several general reviews of composites are available (Lynch and Kershaw, 1972; Wright and Levitt, 1974; Kendall, 1974; Kreider and Prew, 1974; Christian and

Adsit, 1977; Miller and Robertson, 1977). Although considerable progress and understanding have been achieved in the processing area, substantial problems remain. Because of the preoccupation with other problems, corrosion has received relatively little attention despite its importance for the viability of the product. In this report, observations on the corrosion behavior of aluminum-matrix composites have been collected from various sources for insight into what problems have been identified, what questions need attention, and what degree of corrosion resistance might be expected eventually for a given composite system.

Composite Fabrication

Composite fabrication techniques vary from conventional powder metallurgy to specially adapted CVD coating