

FRACTIONATION REQUIREMENTS FOR PRODUCING ANHYDROUS AMMONIA
FROM AMMONIA-WATER VAPOR SYSTEMS

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In several proposed processes^{1, 2, 3}* for recovering ammonia from coke-oven gas, the ammonia is absorbed in an aqueous solution that is subsequently stripped of its absorbed ammonia. If the stripping operation is performed at the normal boiling point of the solution and if the absorbent used is nonvolatile, the vapors leaving the stripper will consist of ammonia and water at a pressure of 1 atmosphere. These vapors can then be fractionated to produce anhydrous ammonia. If the fractionation is performed at the original pressure of the vapor feed, the anhydrous ammonia leaving the top of the column would have to be condensed in a refrigerated condenser. The cost of refrigeration will in general make this process economically unattractive. Consequently, the anhydrous ammonia must be produced in a column operating at a pressure high enough to permit ordinary cooling water to be used to condense the ammonia. At 200 pounds per square inch gauge (psig), ammonia condenses at approximately 100 F. With 80 F cooling water, the ammonia leaving the top of a fractionator operating at 200 psig can be condensed in a condenser with a 10 F approach and a 10 F cooling-water rise. Since the bottoms of the fractionator will be essentially pure water, open steam would be used and, consequently, steam at approximately 200 psig could be used. (Steam at this pressure is available at many plants.) The fractionation of the vapor feeds, initially at a pressure of 1 atmosphere, in a column operating at 200 psig is complicated by the desire to utilize as much as possible of the latent heat already contained by the vapor but at the same time to avoid high vapor-compression costs. Several alternative methods of accomplishing the fractionation are possible. These are shown in Figures 1 through 4.

Method I

As shown in Figure 1 the vapor, originally saturated at 14.7 psia, is compressed directly into a fractionator operating at 200 psig to produce an anhydrous-ammonia overhead. The vapor leaving the compressor at 200 psig is assumed to be essentially saturated at that pressure.

Method II

As shown in Figure 2 the vapor, originally at 14.7 psia, is first compressed only to a pressure where it can be readily condensed, and the condensate is then pumped into a fractionator operating at 200 psig to produce an anhydrous-ammonia overhead. The condensate, pumped to 200 psig, is heated to its saturation temperature with the fractionator bottoms prior to entering the fractionator. It was chosen to compress the vapor to a pressure where the bubble point of its condensate is 100 F so that the vapor could be condensed with cooling water available at 80 F in a condenser with a 10 F approach and a 10 F cooling-water rise. As a limiting case of this method, the vapor can be totally condensed without any compression if it is lean enough. At a pressure of 1 atmosphere, a vapor containing 25 per cent ammonia can be totally condensed at about 100 F. Consequently, vapors containing 25 per cent ammonia or less would be totally condensed without any compression.

* See references.

Method III

As shown in Figure 3 the vapor is first partially condensed at atmospheric pressure, and the liquid and vapor portions are then pumped and compressed, respectively, into a fractionator operating at 200 psig to produce an anhydrous-ammonia overhead. The liquid portion, pumped to 200 psig, is heated to its saturation temperature with the fractionator bottoms prior to entering the fractionator. The vapor portion leaving the compressor at 200 psig is assumed to be essentially saturated at that pressure. It was chosen to partially condense the vapor to a point where the dew point of the vapor and the bubble point of the resulting condensate are 100 F so that the vapor could be partially condensed with cooling water available at 80 F in a condenser with a 10 F approach and a 10 F cooling-water rise. At a pressure of 1 atmosphere, a condensate containing 25 per cent ammonia has a bubble point of 100F. The vapor leaving the partial condenser will be in equilibrium with this condensate and will therefore contain 95.4 per cent ammonia. As one limiting case of this method, if the vapor contains 25 per cent ammonia or less, the partial condenser becomes a total condenser and no subsequent compression is required. Consequently, for feeds containing less than 25 per cent ammonia, this method degenerates to the same limiting case as did Method II. As the other limiting case of this method, if the vapor contains 95.4 per cent ammonia or more, no partial condensation will occur, and this method will become identical with Method I.

Method IV

Instead of totally condensing feeds containing less than 25 per cent ammonia, as would be done in Methods II and III, or simply compressing them into the fractionator, as would be done in Method I, these lean feeds can first be fed to a pre-fractionator operating at atmospheric pressure and enriched to a composition that can still be totally condensed with ordinary cooling water as shown in Figure 4. The condensed overhead leaving this first unit would then be pumped to 200 psig and heated to its saturation temperature with the water waste from the high-pressure fractionator. It would then enter the high-pressure fractionator to produce an anhydrous-ammonia overhead.

In all four methods, the vapor feeds at 1 atmosphere were assumed to be at their saturation temperature. Actually, the ammonia-water vapors arising from the stripping of an ammonia-absorbing solution will often be somewhat superheated with respect to their own dew point. However, the small amount of additional sensible heat will have very little effect upon the condenser and fractionator calculations. The results of calculations, which are to follow, were all based upon producing 1 ton per hour of anhydrous ammonia.

In analyzing the four fractionation methods described to ascertain in what range of feed composition each is most economical, only utility costs were considered and capital costs were ignored. This could be done for two reasons. First, the capital costs were relatively small compared with the utility costs. For example, the cost of the fractionating tower in terms of its depreciation and maintenance per year, did not amount to more than 5 per cent of the utility costs per year. Also, the capital costs involved in all of the different methods, especially in the ranges of feed compositions where the methods were competitive with each other, were roughly equal, and thus were not a significant factor in evaluating the different methods.

The power requirements for compressing the vapor feed, originally at 0 psig, into a fractionator at 200 psig producing one ton per hour of anhydrous ammonia are shown in Figure 5. Since the ammonia content of the feed is essentially 1 ton per hour at all feed compositions, the feed rate will increase and the power requirements will correspondingly rise as the feed becomes increasingly lean in ammonia.

Shown in Figure 6 are the power requirements for compressing the vapor feed, initially at 1 atmosphere, to a pressure where the bubble point of its condensate is 100 F, and the cooling-water duty for subsequently condensing the partially compressed vapor. As seen, the pressure to which the vapor must be compressed becomes greater as the ammonia content of the feed increases above 25 per cent ammonia. This factor causes the power requirement to increase as the feed becomes increasingly rich in ammonia. However, at the same time the feed rate decreases and this factor causes the power requirement to decrease. Consequently, the curve showing the horsepower requirements will go through a maximum as seen in the slide. Vapor feeds containing 25 per cent ammonia or less can be totally condensed at a pressure of 1 atmosphere and, hence, the horsepower requirements reduce to the negligibly small amounts needed to pump the condensate into the tower. The cooling-water duty for condensing the vapor decreases as the feed becomes increasingly rich in ammonia, owing to the decreasing feed rate. The cooling-water duty curve changes from a concave to a convex shape at a composition of approximately 85 per cent ammonia because of the very rapidly decreasing heat of condensation of ammonia-water vapors richer than 85 per cent ammonia.

Shown in Figure 7 is the cooling-water duty required to partially condense the vapor feed at atmospheric pressure to a temperature of 100 F (that is, to a condensate containing 25 per cent ammonia) and the power requirement for compressing the vapor portion leaving the partial condenser to a pressure of 200 psig. Consistent with what has been said earlier, the fraction of the feed leaving the partial condenser in the vapor state varies between 0 at a feed composition of 25 per cent ammonia and 1.0 at a feed composition of 95.4 per cent ammonia. Hence, as the feed composition increases beyond 25 per cent ammonia, an increasingly large fraction of the feed must be compressed, but at the same time the total feed rate is decreasing. Hence, the horsepower curve is convex and goes through a maximum as seen. The cooling-water duty decreases as the feed becomes increasingly rich in ammonia, both because the feed rate decreases and because for feeds richer than 25 per cent ammonia the fraction of the feed that is condensed also decreases with increasing ammonia concentration. The cooling-water duty is zero for a feed composition of 95.4 per cent ammonia, since at this composition none of the feed is condensed.

Shown in Figure 8 is a comparison of the utility requirements for sending the feed, which is initially a vapor at atmospheric pressure, to a fractionator operating at 200 psig by means of Methods I, II, and III. Method IV will be considered separately later. Method I, in which all the vapor is compressed from 0 to 200 psig, entails the greatest consumption of power, as would be expected. However, since in Method I the feed is sent to the fractionator in the vapor state, it will entail the lowest steam consumption in the fractionator. As explained earlier, Methods II and III have identical requirements for feeds containing less than 25 per cent ammonia. For feeds richer than 25 per cent ammonia, Figure 8 shows that Method III entails a smaller condenser duty than does Method II because in Method III only part, rather than all, of the feed is condensed. It is also clear from Figure 8 that Method III entails a smaller power consumption than does Method II. Method III entails the compression of a relatively small amount of vapor through a relatively large pressure ratio, and Method II entails the compression of a relatively large amount of vapor through a relatively small pressure ratio. That Method III should require a smaller power consumption than Method II is not evident from any prior considerations but is a consequence of the particular properties of the ammonia-water system.

With the feeds now at 200 psig and at different thermal states depending on the method used to elevate their pressure, it remains to calculate the utility requirements for fractionating them. All fractionation requirements were based on producing 1 ton per hour of anhydrous ammonia and a water waste containing not more than 0.5 per cent ammonia. The steam and condenser-duty requirements were calculated by the Ponchon-Savarit Method since the widely different molar latent heats of ammonia and water render the McCabe-Thiele Method inapplicable to this system.

Fractionation requirements are usually calculated by first selecting an optimum reflux ratio. Although this can always be done by a balance of capital and operating costs, a rule of thumb that is often used is that the optimum reflux ratio will be about 1.5 times the minimum reflux ratio. This rule was found to be a poor guide for the ammonia-water system. A better guide was to first select an optimum number of theoretical plates.

Because of the very favorable vapor-liquid equilibrium of the ammonia-water system, it is extremely easy to fractionate ammonia from ammonia-water feeds, and it was found that a tower containing about 10 theoretical plates would require but slightly more steam and condenser water than would an infinitely high tower. Therefore, by providing the tower with more than 10 theoretical plates very little could be saved on steam and cooling water. However, if the number of theoretical plates were reduced substantially below 10, the steam and cooling-water rates would begin to increase more quickly. For the purposes of this paper it is assumed that a tower containing 10 theoretical plates represents an optimum installation. Consequently, the steam and cooling-water requirements were obtained by the Ponchon-Savarit Method to correspond to a fractionator containing 10 theoretical plates. For any given application it is necessary to more accurately establish the optimum tower size.

Shown in Figure 9 are the steam and condenser-duty requirements for a 10-theoretical-plate fractionator, operating at 200 psig and producing 1 ton per hour of anhydrous ammonia and a water waste containing not more than 0.5 per cent ammonia. Anhydrous ammonia contains no more than 0.3 per cent water. For both all-liquid and all-vapor feeds, the steam rate and condenser duty decrease as the feed becomes richer in ammonia primarily because of the decreased amounts of feeds that need be handled. For an all-vapor feed, the condenser duty required is higher and the steam rate is lower than for a liquid feed, as would be expected. For a liquid feed, the steam rate and condenser duty do not approach zero as the feed composition approaches 100 per cent ammonia. This is because as long as any fractionation at all is accomplished the feed must be vaporized and recondensed. Of course, when the feed composition reaches 99.7 per cent ammonia, no fractionation would be needed and all requirements would drop discontinuously to zero. For a vapor feed, the steam rate approaches zero as the feed composition approaches 100 per cent ammonia, since the feed already enters the column in a vaporized state. However, the condenser duty for a vapor feed does not approach zero as the feed composition approaches 100 per cent ammonia since the vapor feed must always be condensed to produce liquid anhydrous ammonia. The mixed vapor-liquid feed line shown indicates the steam rate and condenser duty required to fractionate feeds containing the proportions of liquid and vapor leaving the partial condenser in Method III. For each over-all feed composition, the fraction of the feed that will leave the partial condenser in the vapor state has been shown in Figure 7. As explained earlier, and as shown, the mixed vapor-liquid feed will become an all-liquid feed at a feed composition of 25 per cent ammonia, and will become an all-vapor feed at a feed composition of 95.4 per cent ammonia.

From the utility requirements shown on the previous two slides, Figures 8 and 9, the utility costs can be computed, the following assumed utility rates being used:

Power at 1 cent per kilowatt-hour
Steam at 70 cents per thousand pounds
Cooling water at 2 cents per thousand gallons

These are average utility rates applicable to many plants.

The cooling-water rate is computed from the condenser duty on the basis of a cooling-water rise that will yield a 10 F approach in the condenser. Consequently, the allowable cooling-water rise in the column condenser will be 10 F. For feeds containing more than 25 per cent ammonia, the allowable cooling-water rise in the feed condenser will also be 10 F because of the manner in which these feeds are handled.

Feeds leaner than 25 per cent ammonia have a bubble point higher than 100 F and, therefore, can be condensed with 80 F cooling water in a condenser with a 10 F approach and a cooling-water rise greater than 10 F. For these lean feeds, the allowable cooling-water rise was based upon a 10 F approach in the condenser, provided that the outlet cooling-water temperature did not exceed 125 F.

Shown in Figure 10 are the utility costs for producing 1 ton per hour of anhydrous ammonia from a vapor feed, initially at atmospheric pressure, by means of Method I. The steam cost for the column and the cooling-water cost for the column condenser (curves 2 and 3) were computed from the vapor-feed curves shown on the previous figure. The power cost for the compressor (curve 1) was computed from the power requirements shown earlier, Figure 5, for compressing the vapor from 0 to 200 psig. All of the utility costs increase and hence the total utility cost increases as the feed becomes increasingly lean in ammonia, primarily because of the increasingly larger amount of feed that must be handled.

Shown in Figure 11 are the utility costs for producing 1 ton per hour of anhydrous ammonia from a vapor feed, initially at atmospheric pressure, by means of Method II. Feeds containing less than 25 per cent ammonia will have a bubble point higher than 100 F at atmospheric pressure and therefore can be totally condensed without compression. The cooling-water cost for the feed condenser (shown by curve 1) is lower for a feed containing 20 per cent ammonia than it is for a feed containing 25 per cent ammonia, because of the greater cooling-water temperature rise that is allowable for the leaner feed. As the feed composition becomes leaner than 20 per cent ammonia, the cooling-water cost for the feed condenser increases, because of the overpowering effect of the increasing feed rate. For feeds containing more than 25 per cent ammonia, the allowable cooling-water temperature rise in the feed condenser will remain constant, since the vapor is always compressed to a pressure where the bubble point of its condensate is 100 F. Hence, the cooling-water cost for the feed condenser gradually decreases as the ammonia content of the feed increases above 25 per cent ammonia. The steam cost for the column and the cooling-water cost for the column condenser (curves 4 and 3) were computed from the liquid feed lines on the slide showing the fractionation requirements, Figure 9. The power cost for the compressor (curve 2) was computed from the power requirements, shown earlier, Figure 6, for compressing the vapor from atmospheric pressure to a pressure where the bubble point of its condensate is 100 F. It is seen that for lean feeds the total utility cost increases primarily as a result of the increasing steam cost for the column rather than as a result of increasing power costs as in Method I. As the feed composition increases beyond 25 per cent ammonia, the power cost for compressing the vapor increases more quickly than the steam and cooling-water costs decrease, and therefore the total utility cost begins to increase. As the power cost begins to level out, the decreasing steam and cooling-water costs then cause the total utility cost to decrease. Hence, the total utility cost goes through a maximum at a feed composition of 45 per cent ammonia. Therefore, if the fractionation were performed as prescribed in Method II, it would cost more to fractionate a vapor feed containing 45 per cent ammonia than a vapor feed containing 20 per cent ammonia, both initially at atmospheric pressure. This leads to the surprising conclusion that it would be advantageous to dilute the feed containing 45 per cent ammonia to a feed containing 20 per cent ammonia in a direct condenser, totally condense it, and pump the condensate into the high-pressure fractionator. It is clear from Figure 11 that this means of operation will be more economical than Method II for feed compositions covering the extent of the dotted line shown, namely from about 20 to 75 per cent ammonia. If the fractionation of these feeds is accomplished by this dilution method, the total utility cost involved will remain approximately constant at about \$4 per ton of ammonia produced.

Shown in Figure 12 are utility costs for producing 1 ton per hour of anhydrous ammonia from a vapor feed, initially at atmospheric pressure, by means of Method III. Feeds containing less than 25 per cent ammonia can be totally condensed at atmospheric pressure and hence no subsequent compression is required. The cooling-water cost for the feed condenser given by curve 1 decreases, then increases, and finally decreases

again for generally the same reasons as given for Method II. The steam cost for the column and the cooling-water cost for the column condenser (curves 4 and 3) were computed from the mixed vapor-liquid feed curves shown in Figure 9. As the feed composition increases above 25 per cent ammonia, the feed rate decreases and the fraction of the feed that enters the fractionator as a vapor increases. Consequently, as the feed becomes increasingly rich in ammonia, the steam cost for the fractionator decreases more quickly than in Methods I and II and the cooling-water cost for the fractionator condenser decreases more slowly than in Methods I or II. In Methods I and II, the thermal state of the feed entering the fractionator did not vary with the feed composition as it does in Method III. The power cost for the compressor (curve 2) was computed from the power requirements, shown earlier, Figure 7, for compressing the vapor fraction leaving the partial condenser from 0 to 200 psig. As the feed composition increases above 25 per cent ammonia, the power cost for compressing the vapor increases. However, the power cost increases slowly enough so that the decreasing steam and cooling-water costs are not offset, and hence, the total utility cost does not exhibit a maximum in this range, but decreases slowly with increasing ammonia content in the feed.

It was seen from the previous figures that it is relatively expensive to fractionate a lean vapor, either because of the compression cost if the vapor is compressed into the fractionator, Figure 5, or because of the steam cost in the fractionator if the vapor is condensed and then pumped into the fractionator, Figure 9. In Method IV, the lean vapor is first sent to a prefractionator where it is enriched to a composition that can still be readily condensed with available cooling water. The overhead from this first column is then pumped into the high-pressure fractionator to produce the anhydrous ammonia. If the lean vapor feed is handled in this manner, some of the latent heat already contained by the vapor can be utilized in its enrichment without incurring any compression costs. Hence, it may be anticipated that for lean vapor feeds Method IV will prove to be most economical.

Shown in Table I are the utility requirements and costs for producing 1 ton per hour of anhydrous ammonia by means of Method IV, from a saturated vapor feed at atmospheric pressure containing 5 per cent ammonia.

Table I

Requirements for Producing Anhydrous Ammonia by Means of Method IV
From a Vapor Feed Containing 5% Ammonia

Basis: 1 ton per hour of anhydrous ammonia produced

Prefractionator:

Pressure: 0 psig
 Feed: Saturated vapor at 0 psig containing 5% ammonia
 Distillate: Ammonia-water solution containing 15% ammonia
 Waste: Water containing 0.2% ammonia

Main Fractionator:

Pressure: 200 psig
 Feed: Saturated ammonia-water solution containing 15% ammonia
 Distillate: Anhydrous ammonia
 Waste: Water containing 0.5% ammonia

Utility Requirements and Costs Per Ton of Anhydrous Ammonia Produced

	Condenser Duty, Millions of BTU	Cooling Water Cost, \$	Steam Rate, Thousands of lbs	Steam Cost, \$
Prefractionator	43.6	2.33	1.4	0.98
Main Fractionator	2.8	0.67	4.4	3.08

Total Utility Cost = \$7.06

The distillate composition of 15 per cent ammonia, chosen for the prefractionator, results in the best balance of utility costs between the prefractionator and the main fractionator. If the distillate composition were made richer than 15 per cent ammonia, the cooling-water cost for the prefractionator condenser would increase because of the smaller allowable cooling-water temperature rise that would result. If it were made leaner than 15 per cent ammonia, the steam cost for the main fractionator would increase sharply. As seen in the next figure, the total utility cost of \$7.06 per ton of ammonia, which results from handling the vapor feed containing 5 per cent ammonia by means of Method IV, is considerably less than would result from handling the same feed by any other method.

Shown in Figure 13 is a comparison of the total utility costs involved in producing 1 ton of anhydrous ammonia by each of the different methods considered. It is evident that for lean feeds a large economic incentive exists for prefractionating the feed as described in Method IV. The total utility cost that results from handling a feed containing 5 per cent ammonia by this method is \$7.06. If this feed were totally condensed and the condensate subsequently pumped into the high-pressure fractionator, as in Methods II and III, a total utility cost of \$10.80 would result. Compressing the feed directly into the high-pressure fractionator, as in Method I, would result in a much higher cost than is involved in either of the two previously mentioned methods. In Method IV the lean feed is enriched to 15 per cent ammonia. Consequently, when the feed composition reaches 15 per cent ammonia, Method IV reduces to simply condensing the feed and pumping the condensate into the high-pressure fractionator. As explained earlier, for feeds containing less than 25 per cent ammonia, Methods II and III reduce to totally condensing the feed and pumping the condensate into the high-pressure fractionator. Hence, at a feed composition of 15 per cent ammonia, Method IV will become identical with Methods II and III.

Figure 13 shows that for feeds containing more than 25 per cent ammonia, Method III is more economical than Method II. For feeds ranging in composition from about 25 to 75 per cent ammonia, it is more economical to first dilute the feed to about 20 per cent ammonia, totally condense it, and pump the condensate into the high-pressure fractionator than it is to handle the feed by means of Method II. However, as can be seen, this method of diluting a rich feed to a composition that can be totally condensed at atmospheric pressure is never more economical than partially condensing the feed and then compressing the vapor leaving the partial condenser as is done in Method III. As explained earlier, for feed compositions richer than 94.4 per cent ammonia, Method III is identical with Method I and the vapor is simply compressed into the high-pressure fractionator.

If utility rates, cooling-water temperature, and steam pressure are significantly different from those assumed in this paper, not only will the utility costs change but the preferred method for handling a feed of a given composition will also change. For example, if the fractionation is performed in a location where power costs are unusually high, the costs of Methods II and III will increase since both involve compressing the vapor. However, the cost of diluting the rich vapor to a composition that can be totally condensed at atmospheric pressure and pumping the condensate into the high-pressure fractionator will remain approximately constant at the value indicated by the horizontal line, Figure 13. Consequently, where power costs are high, it would be more economical, at least over some range of feed compositions, to dilute a rich feed to a composition at which it could be totally condensed rather than handling it by means of Method III. The same procedure would also be used if the available cooling-water temperature is unusually high, for it would become necessary to operate the fractionator at a pressure significantly higher than 200 psig to condense the anhydrous ammonia. Consequently, the compression costs involved in Methods II and III will increase, and it might be most economical to dilute a rich feed to a composition that could be totally condensed at atmospheric pressure.

Summary

For the cooling-water temperature, steam pressure, and utility rates chosen in this paper, the preferred methods of producing anhydrous ammonia from ammonia-water vapors initially at atmospheric pressure are as follows:

1. Feeds containing less than 15 per cent ammonia are first sent to a prefractionator operating at atmospheric pressure in which they are enriched to a 15 per cent ammonia overhead. The distillate from the prefractionator is then pumped into the main fractionator operating at 200 psig to produce anhydrous ammonia.

2. Feeds containing from 15 per cent ammonia to 25 per cent ammonia are totally condensed at atmospheric pressure, and the condensate is pumped into a fractionator operating at 200 psig to produce anhydrous ammonia.

3. Feeds containing from 25 per cent ammonia to 95 per cent ammonia are first partially condensed at atmospheric pressure to a temperature of 100 F. The condensate and vapor leaving the partial condenser are then pumped and compressed, respectively, into a fractionator operating at 200 psig to produce anhydrous ammonia.

4. Feeds richer than 95 per cent ammonia are compressed into a fractionator operating at 200 psig to produce anhydrous ammonia.

Literature Cited

1. Bahr, H., German Patent No. 741,222 (1943).
2. Bergfeld, L., German Patent No. 270,204 (1911).
3. Societe Industrielle et Financiere de Lens, French Patent No. 857,242 (1940).

METHOD II - COMPRESSION FOLLOWED BY CONDENSATION

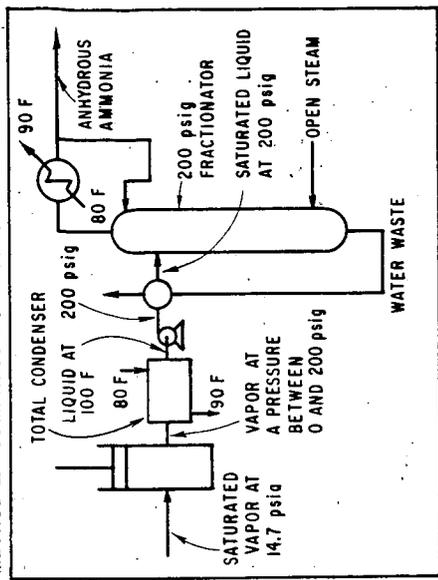


FIGURE 2

METHOD I - DIRECT COMPRESSION TO 200 psig

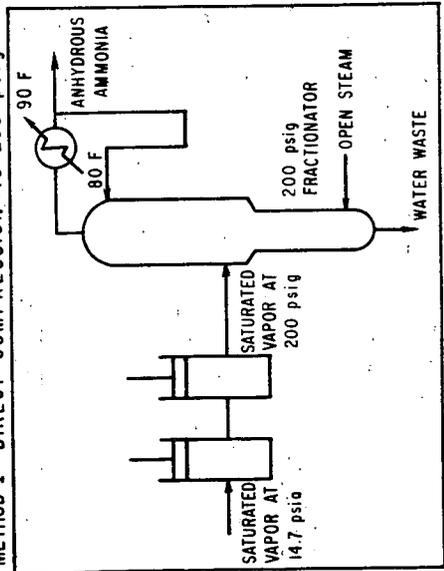


FIGURE 1

METHOD IV - PREFRACTIONATION

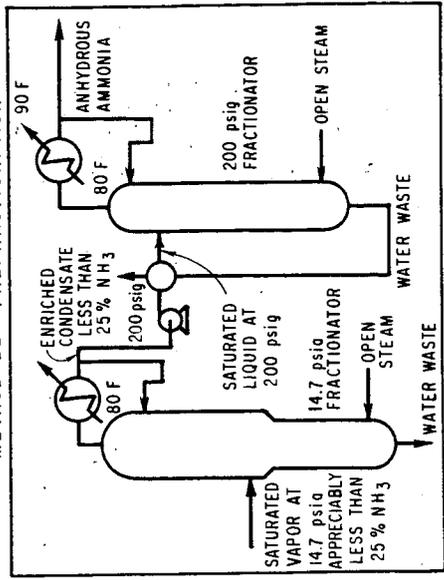


FIGURE 4

METHOD III - PARTIAL CONDENSATION FOLLOWED BY COMPRESSION

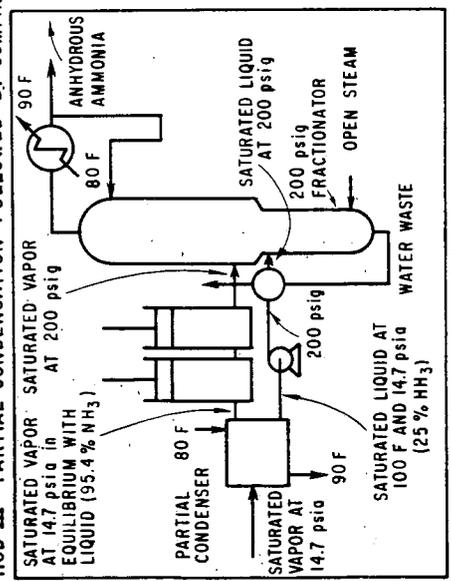


FIGURE 3

REQUIREMENTS FOR COMPRESSING ALL OF THE VAPOR INTO A 200 psig TOWER PRODUCING 1 TON/HR ANHYDROUS AMMONIA AS IS DONE IN METHOD I

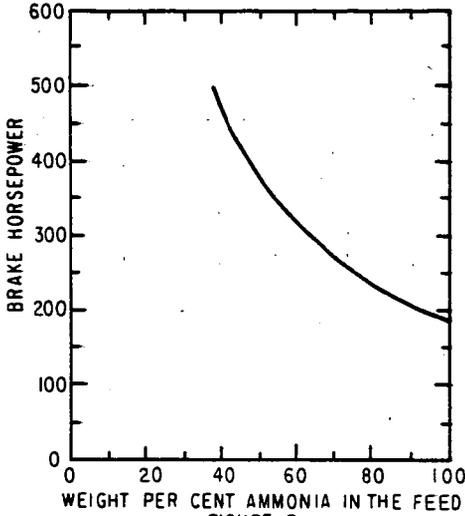


FIGURE 5

REQUIREMENTS FOR COMPRESSING THE VAPOR TO A PRESSURE WHERE ITS BUBBLE POINT IS 100 F AND THEN TOTALLY CONDENSING IT AS IS DONE IN METHOD II (BASIS: 1 TON/HR OF NH₃)

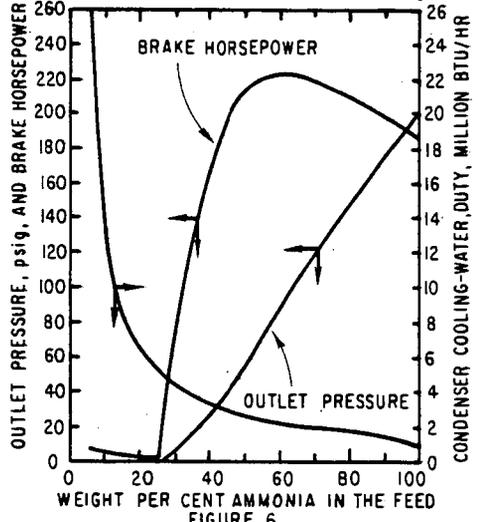


FIGURE 6

REQUIREMENTS FOR PARTIALLY CONDENSING THE VAPOR AT 1 ATM AND THEN COMPRESSING THE VAPOR PORTION INTO A 200 psig TOWER PRODUCING 1 TON/HR AMMONIA AS IS DONE IN METHOD III

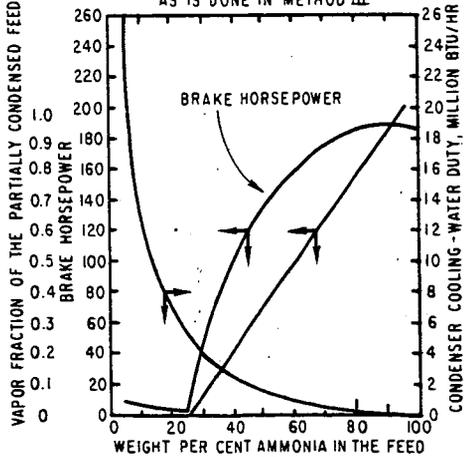


FIGURE 7

UTILITY REQUIREMENTS FOR SENDING THE FEED TO A FRACTIONATOR OPERATING AT 200 psig BY MEANS OF METHODS I, II, AND III

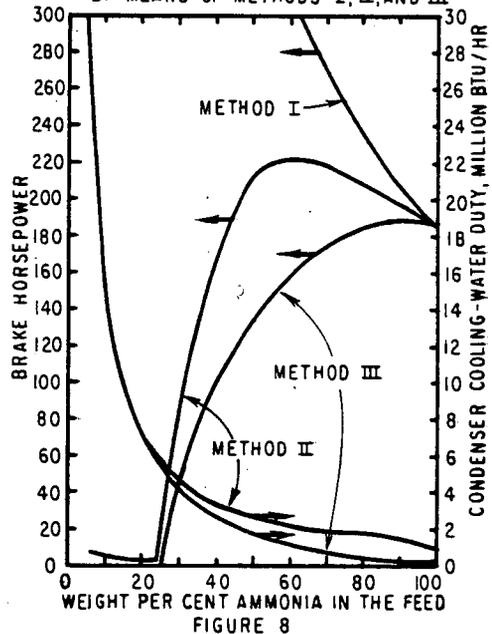


FIGURE 8

STEAM AND CONDENSER-DUTY REQUIREMENTS FOR A FRACTIONATOR AT 200 psig PRODUCING 1 TON PER HOUR ANHYDROUS AMMONIA AND A WATER WASTE CONTAINING NOT MORE THAN 0.5 PER CENT AMMONIA

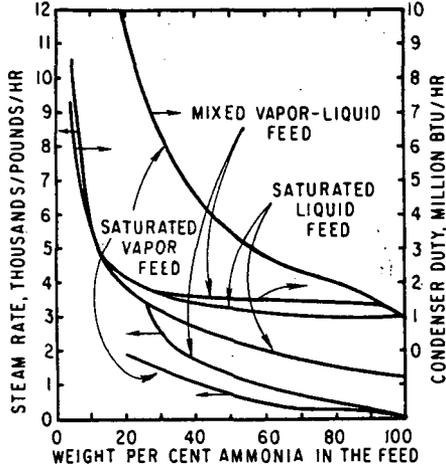


FIGURE 9

UTILITY COSTS FOR PRODUCING 1 TON/HR OF ANHYDROUS AMMONIA BY MEANS OF METHOD I
 ① POWER FOR COMPRESSOR
 ② STEAM FOR COLUMN
 ③ COOLING WATER FOR COLUMN CONDENSER

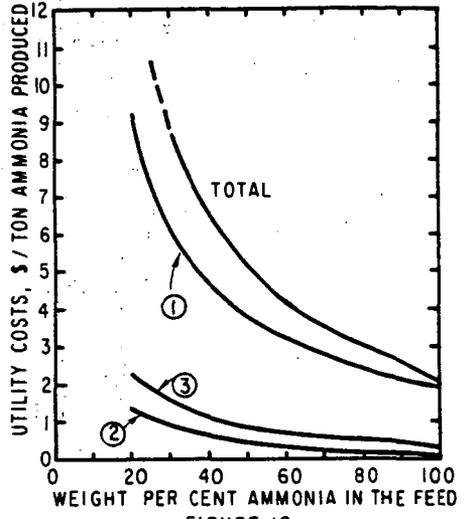


FIGURE 10

UTILITY COSTS FOR PRODUCING 1 TON/HR OF ANHYDROUS AMMONIA BY MEANS OF METHOD II

- ① COOLING WATER FOR FEED CONDENSER
- ② POWER FOR COMPRESSOR
- ③ COOLING WATER FOR COLUMN CONDENSER
- ④ STEAM FOR COLUMN

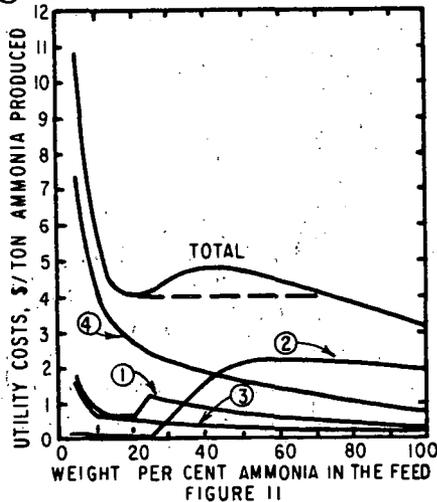


FIGURE 11

UTILITY COSTS FOR PRODUCING 1 TON/HR
ANHYDROUS AMMONIA BY MEANS OF METHOD III

- ① COOLING WATER FOR FEED PARTIAL CONDENSER
- ② POWER FOR COMPRESSOR
- ③ COOLING WATER FOR COLUMN CONDENSER
- ④ STEAM FOR COLUMN

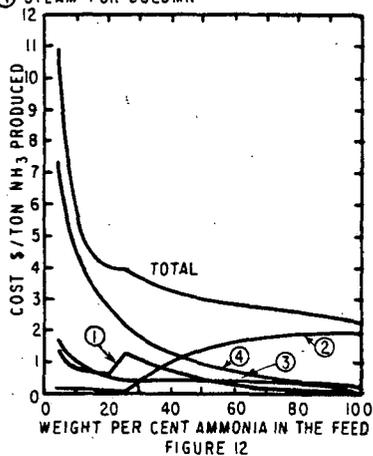


FIGURE 12

COMPARISON OF THE TOTAL UTILITY COSTS INVOLVED
IN PRODUCING ONE TON OF ANHYDROUS AMMONIA
FROM AN AMMONIA-WATER VAPOR FEED AT ATMOSPHERIC
PRESSURE BY MEANS OF METHODS I, II, III, AND IV

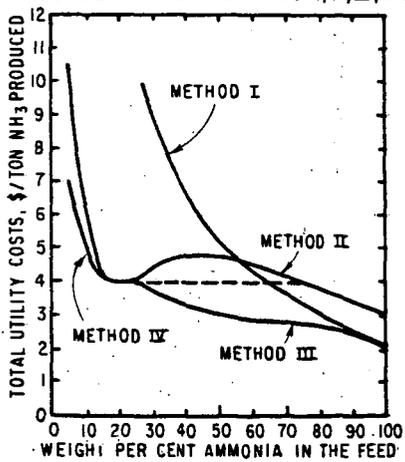


FIGURE 13