

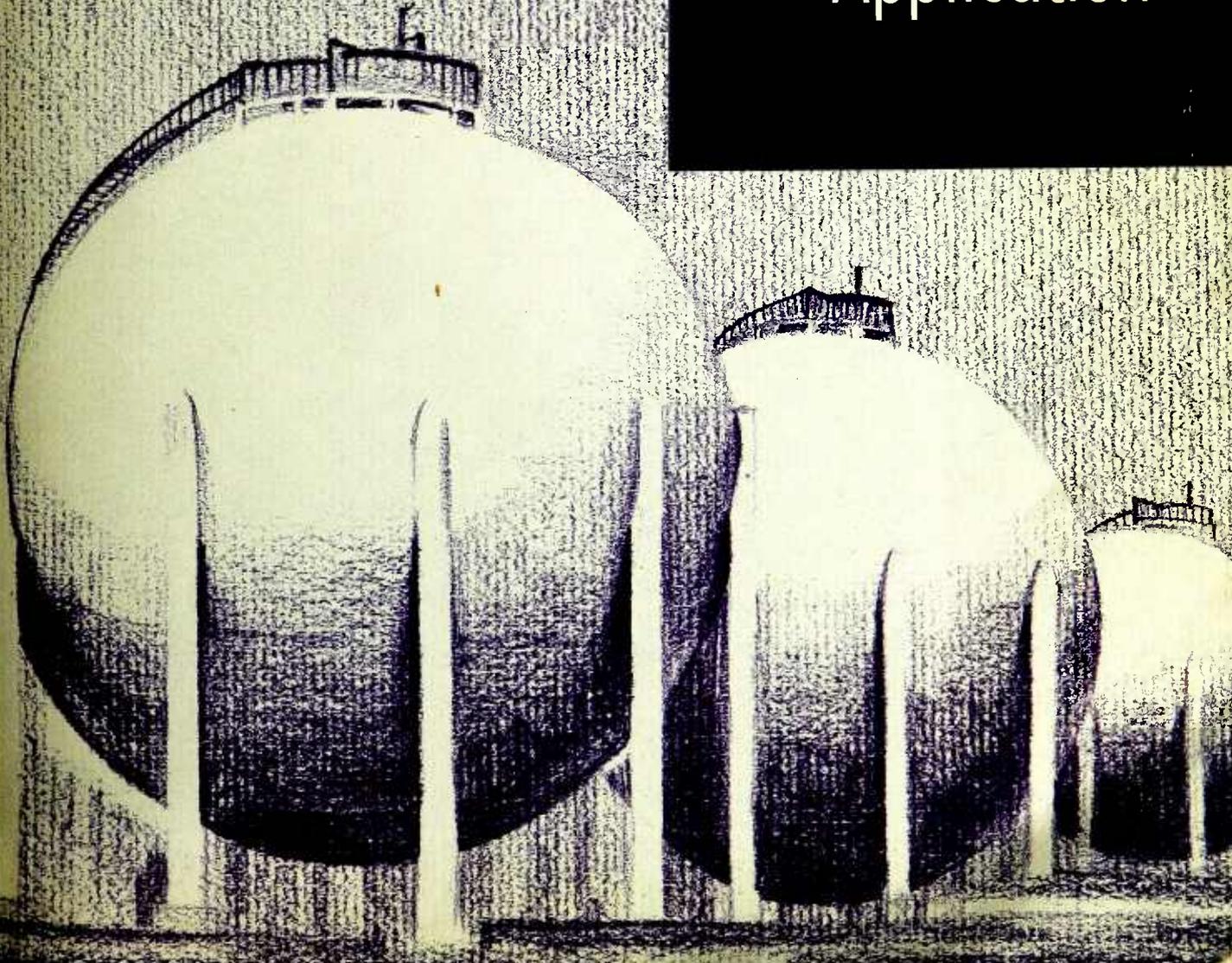
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U.S. DEPARTMENT OF AGRICULTURE
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LIQUID NITROGEN FERTILIZERS

For Direct
Application



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LIQUID NITROGEN FERTILIZERS For Direct Application

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Nitrogen fertilizers are applied as individual materials and as mixtures with carriers of one or more of the other primary plant-nutrient elements (phosphorus and potassium). The proportion of the total domestic consumption of fertilizer nitrogen used as separate materials was about 43 percent in 1900, 59 percent in 1920, and 63 percent in the year ended June 30, 1958.

The direct application of liquid materials as fertilizer carrying nitrogen as the only primary nutrient element has greatly increased in the United States since World War II. Such use of these liquids—comprising mostly anhydrous ammonia, aqua ammonia, and aqueous solutions of ammonium nitrate and (or) urea with or without ammonia—accounted for about 46 percent of the consumption of nitrogen in direct-application materials in the year ended June 30, 1958, as compared with only 8 percent in 1946–47. Liquids are also the principal form in which nitrogen is supplied to domestic manufacturers of mixed fertilizers. About 60 percent of the nitrogen in such fertilizers was derived from liquids in 1954 (14).³

Although not discussed in this publication, additional tonnages of other liquid fertilizers—phosphoric acid and aqueous solutions of poly-nutrient materials and mixtures—are used annually as direct-application materials. Scholl and

coworkers (168) reported consumption of 23,067 tons of phosphoric acid in 1957–58, an increase of 51 percent over the quantity consumed in 1953–54 (104).

Liquid nitrogen fertilizers have certain advantages over conventional solid fertilizers. Many of the liquids have a higher nitrogen content and cost less per pound of nitrogen. They can be applied accurately to the soil without dusting and are more adaptable to incorporation in the water of irrigation systems. Ease of handling is a major consideration. Liquid fertilizers are handled mechanically so that the lifting and carrying of heavy bags of fertilizer are eliminated. Liquid nitrogen fertilizers, however, are corrosive and require special application equipment and storage containers. Many of them must be handled in pressure equipment. A drop in temperature may cause salting out of some of the dissolved solids and subsequent clogging of equipment.

The purpose of this publication is to bring together information on the consumption, composition, and properties of liquid nitrogen materials; the processes and facilities for their manufacture; the methods, equipment, and safety precautions for their storage, transportation, and application; and the agronomic and economic considerations in their use.

EARLY DEVELOPMENTS

More than a century ago Liebig suggested the possibility of using the ammoniacal liquors from coal gas plants as a source of fertilizer nitrogen. In 1843 Bishop (43) compared the effects of ammoniacal water, potassium nitrate, sodium nitrate, and rape-dust on grassland in Scotland. The ammoniacal water scorched some of the grass and was a little slower than sodium nitrate in stimulating growth, but it produced a 25-percent greater grass yield than the other sources of nitrogen.

Lawrence (114) refers to a pamphlet printed in 1848 that cited many examples of farmers using ammonia liquor for fertilizing grassland. In 1852 Johnston (106, p. 248) wrote "To grassland this ammoniacal liquor may be applied with great advantage, by means of a water-cart—being previously diluted with from three to five times its bulk of water. If too strong it will burn up the grass at first, especially if the weather be dry; but, on the return of rain, the herbage will again spring up with increased luxuriance. On arable land it may be applied with profit to the young wheat or other corn by the water-cart . . ." In 1891 Shutt (173), of the Canada Experimental Farms, reported that some people had applied ammonia liquor, diluted with three times its bulk of water, directly to the soil with safety and profit. He emphasized it could be used with safety only

¹ Retired November 30, 1957.

² The authors gratefully acknowledge the valuable suggestions and assistance of K. D. Jacob in the preparation of the manuscript, and the assistance of C. W. Gantt, Jr., research agricultural engineer, in compiling information of application equipment.

³ Italic numbers in parentheses refer to Literature Cited, p. 37.

after careful experiments and previous dilution. According to McMillan (130), Mach found at the Agricultural Institute, Baden, early in the 20th century, that ammonia water was an effective source of fertilizer nitrogen which should be applied and plowed under about 2 weeks before seeding.

Marsden (136) and Lawrence (114) discuss the development of the use of gas (ammoniacal) liquor as a fertilizer in England. An attempt during the latter part of World War I to interest farmers in the use of gas liquor met with no success. The Shepton Mallet Gas Co. made a number of experiments with the liquor in 1931, and its experimental use as a source of nitrogen for market gardens was sponsored by the Tottenham Gas Co. in 1936. It was found satisfactory for cabbage, potatoes, beetroot, turnips, carrots, and asparagus. Successful tests were made later on grass, kale, and cereal crops. Beginning in 1950, a number of the gas companies or boards applied large quantities of gas liquor to the soil. One group applied 7 million gallons from 1950 to 1955 and a second group applied 5½ million gallons in 1954. In 1952 the British Government recognized gas liquor as a nitrogenous fertilizer and granted a subsidy for its use.

The fertilizing value of ammonia liquor has also been demonstrated in a number of other foreign countries. Among these are Czechoslovakia (113), Italy (74), Germany (41, 52, 156), Japan (101), Poland (55), and U.S.S.R. (110).

Experiments were initiated in 1949 in France and Algeria on the use of anhydrous ammonia as a fertilizer material. Gros (92) reported that in France anhydrous ammonia, placed about 6 inches below the surface of the soil, produced about 3 percent more sugar beets per acre and gave larger yields of bigger and better appearing tubers than mineral fertilizers. Rebour (158) found that the addition of anhydrous ammonia to irrigation water in Algeria adversely affected the permeability of the soil and caused some loss of humus. According to Hunter and Jarvis (99), the first record of the fertilizer use of ammonia gas in Britain was in 1953. They showed that ammonia injected 4 inches into the soil was as effective as ammonium sulfate in promoting the growth of kale. They also showed that the growth of pasturage was promoted by ammonia gas but that response might be slower than with ammonium sulfate. Mulder (144) found the delayed response to anhydrous ammonia to be objectionable under the growing conditions encountered in the Netherlands.

As reported in 1931, the early work in this country on the use of aqua ammonia as a source of fertilizer nitrogen was carried out by Tiedjens and Robbins (187) with sand cultures in New Jersey. Aqua ammonia was found to be an ideal source of nitrogen under many conditions and a better source than either ammonium sulfate or

calcium nitrate for tomatoes and soybeans. Experiments by Beaumont and Larsinos (35) in Massachusetts showed that surface applications of aqua ammonia did not impair germination or stand of a number of crops but did burn the foliage of established grass sod. The injury was confined to the portion of the plant above ground and was temporary. Aqua ammonia proved only about 70 percent as effective a source of nitrogen as ammonium sulfate or sodium nitrate. Pot tests reported by Chapman (58) in 1936 showed that ammonium hydroxide applications gave significant increases in the growth of sudangrass on two calcareous soils in California and was slightly toxic on a third. In 1943 Andrews and others (27) applied aqua ammonia to field crops, but no response data were given. The following year MacIntire (128) and coworkers found that surface applications of aqua ammonia at rates up to 50 pounds of nitrogen per acre were comparable to equivalent quantities of ammonium nitrate and ammonium sulfate in promoting the growth of sudangrass on two typical acid Tennessee soils.

Experimental work was started in 1931 (1) on the application of anhydrous ammonia to the soil in irrigation water. The first commercial application was made the next year on California citrus (171). No ammonia toxicity was observed by Waynick (200) either on citrus trees or on a wide variety of field crops after 3 years of experiments with anhydrous ammonia applied in irrigation water. Rosenstein (161) found in 1936 that irrigation water containing ammonia was a satisfactory source of nitrogen for more than 20 California crops. This method of applying anhydrous ammonia to the soil was given the trade name "Nitrojection" in the far West (116, 117, 118).

Andrews and others (27) stated that J. O. Smith injected anhydrous ammonia directly into the soil in Mississippi in 1930 but gave no indication as to the results he obtained. Study of soil injection of anhydrous ammonia was begun in California shortly after application of this fertilizer in irrigation water had gained acceptance. Injection proved feasible (116, 117, 118), and the first commercial application was made in California (171) in 1939. A patent (115), covering the method of application, was granted in 1942 and the term "Nitrojection" was applied to the method on the west coast (116, 117, 118). Direct application of anhydrous ammonia was limited until supplies became plentiful after World War II. Publication in 1947 of the findings of Andrews (22) and Andrews, Edwards, and Hammons (25, 26) in Mississippi, coupled with shortage of solid forms of nitrogen, created a market for anhydrous ammonia fertilizer. The development led to further research in Mississippi (23, 24, 27).

Limited quantities of ammoniacal solutions of ammonium nitrate and (or) urea have been used for direct application to the soil. In 1947 Hanway,

Luebs, and Rhoades (95) applied an ammonia-ammonium nitrate-water solution below the surface of the soil in a winter wheat experiment in Nebraska. The present writers have personal knowledge that a similar type of solution was shipped at about the same time into both Arizona and California for application in irrigation water. Such solutions are applied commercially in irrigation water or injected beneath the surface of the soil with specially designed equipment.

The possibility of using aqueous solutions of nitrogen materials as fertilizer has long been recognized. In 1845 Boussingault (47, p. 255) stated that Davy had found that an aqueous solution of

ammonium carbonate favored the growth of wheat. Research since then has shown that nitrogen fertilizer materials applied in aqueous solutions or as solids are equally effective in promoting crop growth. The development of aqueous solutions reduced material processing time and supplied some of the unsatisfied demand for fertilizer nitrogen.

Aldrich and coworkers (16) reported in 1953 that field experiments showed nitric acid and nitrogen dioxide compared favorably with conventional fertilizer nitrogen materials as sources of nitrogen. However, the use of these materials as fertilizer has never developed.

CONSUMPTION OF LIQUID NITROGEN MATERIALS

Solids were the only commercial source of direct application nitrogen until in the 1930's when liquid sources were first used. Little information is available on the consumption of liquid sources of fertilizer nitrogen previous to 1946-47.

Separate materials applied directly to the soil accounted for over 40 percent (table 1) of the 783,588 tons of nitrogen consumed in 1946-47, with less than 8 percent of the direct application nitrogen in liquid form. Liquid products supplied almost 20 percent of the nitrogen in separate materials in 1951-52 and more than 45 percent in 1957-58.

TABLE 1.—Consumption of fertilizer nitrogen in short tons and the portions used for direct application in single nutrient liquids and in all separate materials, years ended June 30, 1947-58¹

Year ended June 30—	Total consumption ²	Portion consumed in—	
		Single nutrient liquids	All separate materials
	Tons N	Percent	Percent
1947.....	783,588	3.2	40.3
1948.....	856,719	4.8	42.4
1949.....	919,946	6.3	44.3
1950.....	1,005,524	7.7	50.7
1951.....	1,236,977	8.7	52.8
1952.....	1,422,160	10.7	54.4
1953.....	1,637,056	12.2	55.5
1954.....	1,847,416	18.3	57.9
1955.....	1,960,536	19.1	59.0
1956.....	1,933,342	22.8	58.8
1957.....	2,135,287	24.5	60.5
1958.....	2,284,359	28.6	62.6

¹ United States and Territories.

² Data for 1947-54, from Mehring, Adams, and Jacob (139, p. 16); for 1955-58, from Scholl and others (166, 167, 168).

Table 2 shows that the consumption of nitrogen in the liquid nitrogen products used for direct application increased from 1,230 tons in 1934 to 652,348 tons in 1957-58. The increase has been continuous since 1942, with the greatest increases occurring in recent years. The consumption in 1957-58 was more than six times that in 1950-51; about one-fourth of the increase took place in 1953-54.

Anhydrous ammonia was the only liquid nitrogen product used commercially for direct applica-

tion until 1946, when aqua ammonia and other nitrogen solutions came into commercial use. Nitrogen in the form of anhydrous ammonia accounted for more than 85 percent of the direct-application nitrogen applied annually in liquid form until 1952-53. The relative proportion of nitrogen in this form started to decline in 1952-53 and was only 71 percent in 1956-57. In spite of the percentage decreases, the consumption of nitrogen supplied by anhydrous ammonia has increased annually since 1942.

Nitrogen solutions accounted for 27 percent of the nitrogen applied to the soil in liquid form in 1957-58. Aqua ammonia supplied annually less than 50 percent of the nitrogen applied to the soil in nitrogen solutions until 1954-55. The aqua

TABLE 2.—Consumption in short tons, as separate materials, of liquid nitrogen fertilizer products, calendar years 1934-46, and years ended June 30, 1947-58¹

Year	Anhydrous ammonia ²	Nitrogen solutions ³		Total
		Aqua ammonia	Other solutions	
	Tons N	Tons N	Tons N	Tons N
Calendar year:				
1934.....	1,230	0	0	1,230
1935.....	2,050	0	0	2,050
1936.....	3,280	0	0	3,280
1937.....	3,280	0	0	3,280
1938.....	3,280	0	0	3,280
1939.....	3,280	0	0	3,280
1940.....	4,100	0	0	4,100
1941.....	5,740	0	0	5,740
1942.....	1,230	0	0	1,230
1943.....	5,740	0	0	5,740
1944.....	10,660	0	0	10,660
1945.....	14,350	0	0	14,350
1946.....	16,400	19	804	17,223
Year ended June 30—				
1947.....	22,397	78	2,815	25,290
1948.....	35,556	1,095	4,688	41,339
1949.....	53,789	1,275	2,972	58,036
1950.....	70,123	2,340	5,157	77,620
1951.....	97,107	4,158	6,351	107,616
1952.....	137,983	4,252	10,027	152,262
1953.....	178,074	6,387	14,933	199,394
1954.....	287,155	22,600	28,804	338,559
1955.....	290,337	46,617	38,362	375,316
1956.....	344,317	62,510	34,493	441,320
1957.....	371,668	76,844	75,241	523,753
1958.....	479,109	73,342	99,897	652,348

¹ United States and Territories.

² 1934-46, 82 percent of estimated ammonia consumed as separate material reported by Mehring, Adams, and Jacob (139, p. 22); 1947-55, Adams and Scholl (15); 1956-58, Scholl and others (166, 167, 168).

³ 1946-54, unpublished data from U.S. Department of Agriculture fertilizer consumption surveys; 1955-58, Scholl and others (166, 167, 168).

ammonia was the source of 55 and 64 percent in 1954-55 and 1955-56, respectively, but only 50 percent in 1956-57. Only 42 percent of the nitrogen in nitrogen solutions was in the form of aqua ammonia in 1957-58.

Data for nitrogen applied directly to the soil in the form of anhydrous ammonia are given by

States and regions in table 3. The greatest tonnages have been used annually in the East South Central, West North Central, West South Central, and Pacific States. Use of anhydrous ammonia in the States along the Atlantic Coast and in the mountain area has not developed as rapidly as in the other regions. Anhydrous ammonia was used

TABLE 3.—Nitrogen, in short tons, applied to the soil as anhydrous ammonia, by States and Territories, years ended June 30, 1947-58¹

State and region	1947	1948	1949	1950	1951	1952	1953	1954	1955	1956	1957	1958
	Tons N	Tons N	Tons N	Tons N	Tons N	Tons N	Tons N	Tons N	Tons N	Tons N	Tons N	Tons N
Connecticut.....							5	2	11	2	0	0
New England.....												
New York.....							1	170	21	198	459	696
New Jersey.....					21	126	448	263	319	214	421	297
Pennsylvania.....							293	142	505	474	480	572
Delaware.....							22	174	195	159	25	41
Maryland.....					7	167	140	371	524	333	339	434
West Virginia.....								3	69	0	0	0
Middle Atlantic.....						28	315	1,056	1,128	1,633	1,378	2,040
Virginia.....							113	43	383	689	910	605
North Carolina.....								360	1,159	2,930	6,934	6,482
South Carolina.....								117	408	453	678	1,395
Georgia.....				1,002	1,360	2,196	4,005	4,872	5,549	6,225	6,899	9,565
Florida.....						151	0	572	371	892	1,418	2,622
South Atlantic.....				1,002	1,473	2,750	5,664	9,052	13,133	13,783	17,914	20,669
Ohio.....							895	1,789	2,388	2,479	1,840	2,352
Indiana.....				20	168	521	1,358	7,090	8,734	9,033	8,230	15,234
Illinois.....				43	1,065	3,973	16,408	23,582	14,215	15,246	12,091	20,842
Michigan.....						8	12	519	1,178	1,305	1,451	2,963
Wisconsin.....								558	1,597	2,311	2,723	4,206
East North Central.....				63	1,241	5,401	20,632	35,835	29,044	30,317	28,359	46,921
Minnesota.....							599	4,823	12,704	11,243	10,265	16,069
Iowa.....				43	0	505	4,097	17,252	14,681	8,639	12,322	14,872
Missouri.....				1,662	2,832	7,306	10,311	18,219	12,297	12,757	12,611	17,668
North Dakota.....							19	25	110	84	193	456
South Dakota.....							213	1,113	1,391	1,328	537	1,128
Nebraska.....					1,071	1,495	7,631	20,741	18,691	29,682	37,362	56,266
Kansas.....				41	21	676	3,564	7,419	6,997	6,765	6,285	7,751
West North Central.....				1,746	3,924	9,982	26,434	69,592	66,871	70,498	79,575	114,200
Kentucky.....				139	293	674	517	1,080	653	1,347	1,803	2,576
Tennessee.....		43	1,037	2,800	1,478	3,211	2,802	5,386	3,754	9,877	7,332	4,466
Alabama.....			192	618	1,138	2,427	1,670	2,137	1,888	2,411	2,871	3,466
Mississippi.....	1,847	10,555	22,495	24,487	21,517	22,737	22,198	37,215	33,506	37,001	35,161	32,046
East South Central.....	1,847	10,598	23,724	28,044	24,426	29,049	27,187	45,818	39,801	50,636	47,167	42,554
Arkansas.....		1,130	3,524	5,420	7,309	7,075	9,279	16,839	12,336	18,914	14,665	17,547
Louisiana.....		1,458	5,415	6,409	12,024	15,703	13,140	18,946	19,504	20,944	20,439	22,275
Oklahoma.....			21	43	23	71	560	1,410	1,473	1,331	1,091	1,202
Texas.....			140	214	3,192	14,312	15,190	20,833	22,297	34,144	50,696	73,856
West South Central.....		2,588	9,100	12,086	22,548	37,161	38,169	58,028	55,610	75,333	86,891	114,880
Montana.....									185	893	1,612	1,292
Idaho.....									3,251	3,688	2,497	5,043
Wyoming.....									169	739	915	823
Colorado.....									2,164	2,146	2,952	4,841
New Mexico.....									3,737	3,711	4,483	3,849
Arizona.....									8,162	11,845	13,400	17,406
Utah.....									1,375	1,495	1,029	1,714
Nevada.....									8	11	29	133
Mountain ²	(3)	(3)	(3)	(3)	(3)	(3)	(3)	(3)	19,051	24,528	26,917	35,101
Washington.....									15,015	15,610	18,995	30,357
Oregon.....									5,800	4,395	4,945	6,487
California.....									42,270	56,194	58,439	65,266
Pacific ²	20,550	22,370	20,961	27,176	43,057	51,245	56,788	67,120	63,085	76,199	82,379	102,110
Continental U.S.....	22,397	35,556	53,785	70,117	96,697	135,903	175,935	286,575	288,239	342,674	370,926	478,475
Hawaii.....			4	6	410	1,048	1,097	580	0	0	0	0
Puerto Rico.....						1,032	1,042	0	2,098	1,643	742	634
Territories.....			4	6	410	2,080	2,139	580	2,098	1,643	742	634
Total.....	22,397	35,556	53,789	70,123	97,107	137,983	178,074	287,155	290,337	344,317	371,668	479,109

¹ Consumption not reported for States omitted; 1947-55, Adams and Scholl (13); 1956-58, Adams (10, 12).

² Data for individual States omitted prior to 1955 to avoid divulging private business.

³ Total included with the Pacific total.

in 1954-55 in Puerto Rico and all the States in each region except New England, where it was used only in Connecticut. No consumption was reported in 1956-57 in any of the New England States nor in West Virginia. It was used in

Hawaii from 1948-49 through 1953-54, but since then consumption has not been reported.

The quantity of nitrogen applied to the soil in the form of nitrogen solutions, as shown in table 4, has increased annually since 1948-49 to a total

TABLE 4.—Nitrogen, in short tons, applied to the soil as nitrogen solutions, by States and Territories, years ended June 30, 1947-58¹

State and region	1947	1948	1949	1950	1951	1952	1953	1954	1955	1956	1957	1958
	Tons N	Tons N	Tons N	Tons N	Tons N	Tons N	Tons N	Tons N	Tons N	Tons N	Tons N	Tons N
Maine.....												67
New Hampshire.....												67
Vermont.....										(²)	44	43
Massachusetts.....											4	3
Connecticut.....									1	2	(²)	93
New England.....									11	18	97	273
New York.....		48	0	0	0	0	24	136	311	269	387	483
New Jersey.....							42	108	194	181	128	113
Pennsylvania.....							22	60	172	521	106	193
Delaware.....						8	33	389	201	228	178	248
District of Columbia.....									1	0	0	0
Maryland.....							135	106	517	322	335	360
West Virginia.....										5	0	0
Middle Atlantic.....		48	0	0	0	8	256	799	1,396	1,526	1,134	1,397
Virginia.....						20	93	15	744	974	1,860	2,590
North Carolina.....						70	300	1,047	1,960	3,699	12,278	11,795
South Carolina.....							41	107	401	1,206	3,482	4,412
Georgia.....							87	43	404	424	2,405	3,592
Florida.....		28	0	2	354	140	40	114	97	581	1,742	1,637
South Atlantic.....		28	0	2	354	317	498	1,326	3,606	6,884	21,767	24,026
Ohio.....						64	232	747	681	981	1,421	1,686
Indiana.....					14	518	1,369	1,930	2,394	2,049	6,372	7,636
Illinois.....						1,053	2,061	1,798	3,190	2,212	1,640	5,533
Michigan.....								101	308	409	1,968	1,639
Wisconsin.....								1	104	129	790	1,793
East North Central.....					14	1,635	3,663	4,680	6,702	6,079	12,191	18,287
Minnesota.....							1,041	1,752	3,467	2,259	4,227	5,813
Iowa.....						36	804	3,354	4,389	2,362	3,764	6,726
Missouri.....						197	573	2,290	1,320	1,649	3,281	4,266
North Dakota.....									58	26	9	12
South Dakota.....								70	162	129	13	313
Nebraska.....						23	565	5,566	5,414	4,427	7,442	13,843
Kansas.....							295	94	134	260	81	304
West North Central.....						256	3,278	13,126	14,944	11,112	18,817	31,277
Kentucky.....						36	27	187	62	158	445	502
Tennessee.....								13	0	0	16	38
Alabama.....						140	0	0	268	211	56	226
Mississippi.....	12	131	120	219	0	0	0	0	0	125	2,310	2,240
East South Central.....	12	131	120	219	0	176	27	200	330	494	2,827	3,006
Arkansas.....									6	274	1,875	2,363
Louisiana.....	62	572	291	199	268	287	360	496	1,029	657	1,740	2,654
Oklahoma.....											45	57
Texas.....				44	39	147	458	795	1,335	1,920	2,016	3,846
West South Central.....	62	572	291	243	307	434	818	1,291	2,370	2,851	5,676	8,920
Montana.....										33	119	158
Idaho.....									380	710	1,978	2,985
Wyoming.....										7	3	1
Colorado.....						4	0	35	114	303	316	474
New Mexico.....		18	100	148	153	0	161	0	0	0	0	375
Arizona.....	52	205	222	712	1,018	2,259	2,124	4,046	3,797	3,088	2,895	3,106
Utah.....								3	(²)	9	87	49
Nevada.....								8	51	8	28	108
Mountain.....	52	223	322	860	1,171	2,263	2,293	4,135	4,300	4,178	5,494	7,256
Washington.....	3	0	0	0	0	0	19	783	4,452	5,853	8,761	12,834
Oregon.....							23	53	891	2,640	8,961	7,425
California.....	2,764	4,781	3,514	6,173	8,663	9,187	10,445	20,590	37,142	44,609	51,578	52,661
Pacific.....	2,767	4,781	3,514	6,173	8,663	9,187	10,487	21,426	42,485	53,162	69,300	72,920
Continental U.S.....	2,893	5,783	4,247	7,497	10,509	14,276	21,320	46,983	76,144	86,304	137,303	167,362
Hawaii.....								3,023	8,480	10,059	13,962	4,996
Puerto Rico.....						3	0	1,398	355	640	820	881
Territories.....						3	0	4,421	8,835	10,699	14,782	5,877
Total.....	2,893	5,783	4,247	7,497	10,509	14,279	21,320	51,404	84,979	97,003	152,085	173,239

¹ Includes aqua ammonia; consumption has never been reported in Rhode Island; 1947-55, Adams and Scholl (19); 1956-58, unpublished data from U.S.

Department of Agriculture fertilizer consumption surveys.
² Less than 1 ton.

of 173,239 tons in 1957-58. The greatest annual increase in consumption over the previous year was 55,082 tons in 1956-57. No reports of consumption of nitrogen in this form in 1957-58 were received from Rhode Island, West Virginia, and the District of Columbia. Rhode Island is the only State where the use of nitrogen solutions has never been reported.

The largest quantities of nitrogen applied annually to soils as nitrogen solutions are used in the Pacific States. Annual consumption in this region amounted to more than 50 percent of the

total annual consumption in continental United States from 1946-47 to 1956-57, except in 1952-53, and 1953-54. Nitrogen solutions were used in the West North Central States for the first time in 1951-52. Starting in 1953-54 annual consumption in this region has ranked second to that in the Pacific States except in 1956-57, when the South Atlantic States took over second place. The first use of nitrogen solution in New England was in 1954-55; only token amounts were used in five States of this region in 1957-58.

CHARACTERISTICS OF LIQUID NITROGEN MATERIALS

As of August 1, 1957, 53 nitrogen solutions (11) were listed as available to the fertilizer trade in addition to anhydrous ammonia and aqua ammonia. Other solutions are now also listed, and some of the original solutions are being produced by additional companies. Some liquid nitrogen materials are used only for direct application, some for direct application and for making mixed fertilizers, and others—not discussed in this publication—are used only for the latter purpose.

Generally, each liquid nitrogen material is manufactured by more than one company and each company produces several different liquids. The products of one company are distinguished from those of another by a combination of the company name with "Nitrogen Solution," "Aqua Ammonia," or "Anhydrous Ammonia," or by trademark names registered in the U.S. Patent Office. The registered names in 1957 (11) were Amanol, Bay-Sol, Brea, Dixsol, Elephant, Feran, Lion, Nisol, Nitrana, Ortho, Phillips 66, Sodan, Sohio-gen, Spensol, Steamboat, U.A.S., Uramon, Uran, and Urana.

Liquid nitrogen materials can be classified arbitrarily on the basis of their vapor pressures (pounds-per-square-inch gage) at 104° F. into nonpressure (0 pound), low-pressure (0-19 pounds), medium-pressure (20-100 pounds), and high-pressure (above 100 pounds) liquids.

The nonpressure (NP) liquids are aqueous solutions of nitrogen salts and contain no neutralizing ammonia. The solutions contain one or two of the following sources of nitrogen—ammonium bisulfite, ammonium nitrate, calcium nitrate, urea. They are sold primarily for direct application to the soil.

Aqueous solutions of ammonia alone or with ammonium nitrate or urea, singly or in combination, comprise the low-pressure (LP) and medium-pressure (MP) liquids. The pressure solutions have been used for several decades for ammoniation of superphosphate and mixtures containing superphosphate. They have also been used for direct application in recent years, but this use has been limited almost exclusively to those containing approximately 41 percent or less nitrogen.

The more concentrated liquids can be used for the same purpose under favorable temperature conditions or after dilution.

Anhydrous ammonia is a high-pressure (HP) liquid and supplies the greatest tonnage of nitrogen applied to the soil in the form of liquid nitrogen materials.

A nomenclature system for nitrogen solutions has been suggested (8, 135) and has been adopted by some of the commercial producers. The proposed system includes in the following order: (1) The company trade name, (2) the percent total nitrogen with the percentage point omitted, and (3) in brackets, the percentage composition of ammonia, ammonium nitrate, urea, and any other significant source of nitrogen, all rounded off to the nearest whole number and in the sequence given. For example, a material labeled 403 [20-16-4] would be a nitrogen solution containing 40.3 percent total nitrogen, 20 percent ammonia, 16 percent ammonium nitrate, and 4 percent urea.

Compositions

The chemical composition, salting-out or crystallization temperature, and calcium carbonate equivalent of the listed commercial liquid nitrogen materials are given in table 5. The tabulated data are representative of each type of liquid and may vary slightly from the compositions reported by individual manufacturers. These variations are no greater than the variations in the composition of batches of the same type of solution produced by one company or by different companies.

Liquid nitrogen materials are comprised of anhydrous ammonia and water solutions of ammonia, ammonium salts, and urea singly or in combination. At present all contain ammoniacal nitrogen. Ammonium nitrate is the only salt supplying ammoniacal nitrogen in any of the solutions except NP-1 and MP-8. Ammonium bisulfite is the source in NP-1 and ammonium sulfate in MP-8. Urea supplies additional nitrogen in many of the solutions. Calcium nitrate is the source of some of the nitrogen in NP-3 and sodium nitrate supplies some in NP-6. Solutions LP-13, MP-8, -10, and -12 contain carbon dioxide.

TABLE 5.—Chemical composition and properties of liquid nitrogen materials available for fertilizer use, in 1959¹

Product			Composition				Nitrogen content				Salt- ing-out tem- per- ature	Calcium carbonate equiv- alent per 100 pounds of—			
Kind	Designation		Am- monia	Am- mon- ium nitrate	Urea	Water	Ammonia N		Nitrate N	Urea N		Total N	° F.	Lb.	Lb.
	Pressure	Suggested					Free	Com- bined								Material	Nitro- gen
Nonpressure liquids															
Aqueous solutions of nitrogen products.	(NP-1	85[0-0-0-60 ²]	Pct.	Pct.	Pct.	Pct.	Pct.	Pct.	Pct.	Pct.	Pct.	° F.	Lb.	Lb.	
	(NP-2	160[0-46-0]	40.0	45.7	-----	54.3	8.5	8.5	8.5	-----	8.5	-----	45.5	535	
	(NP-3	170[0-31-0-36 ³]	32.9	30.9	-----	54.3	8.0	8.0	16.0	-----	11	-----	28.8	180	
	(NP-4	175[0-50-0]	32.9	50.0	-----	50.0	5.4	11.6	17.0	-----	32	-----	11.3	66	
	(NP-5	190[0-54-0]	45.7	54.3	-----	45.7	8.7	8.8	17.5	-----	22	-----	31.5	180	
	(NP-6	200[0-48-0-20 ⁴]	32.0	47.5	-----	32.0	9.5	9.5	19.0	-----	34	-----	34.2	180	
	(NP-7	200[0-57-0]	42.7	57.3	-----	42.7	8.3	11.7	20.0	-----	58	-----	23.8	119	
	(NP-8	210[0-60-0]	40.0	60.0	-----	40.0	10.0	10.0	20.0	-----	42	-----	36.0	180	
	(NP-9	227[0-65-0]	35.0	65.0	-----	35.0	10.5	10.5	21.0	-----	51	-----	37.8	180	
	(NP-10	245[0-70-0]	30.0	70.0	-----	30.0	11.4	11.3	22.7	-----	-----	-----	40.9	180	
	(NP-11	280[0-40-30]	30.0	39.5	30.5	30.0	12.3	12.2	24.5	-----	-----	-----	44.1	180	
	(NP-12	300[0-42-33]	25.1	42.2	32.7	25.1	6.9	6.9	14.2	-----	-----	-----	50.4	180	
	(NP-13	320[0-44-35]	20.3	44.3	35.4	20.3	7.4	7.4	15.2	-----	-----	-----	36.0	180	
		-----	-----	-----	-----	7.7	7.8	16.5	-----	-----	-----	57.6	180		
Low-pressure liquids															
Aqua ammonia	LP-1	206[25-0-0]	25.0	-----	-----	75.0	20.6	-----	-----	-----	20.6	-103	37.1	180	
	(LP-2	370[17-67-0]	16.6	66.8	-----	16.6	13.6	11.7	11.7	-----	37.0	48	66.6	180	
	LP-3	410[19-72-0]	19.0	72.5	-----	8.5	15.6	12.7	12.7	-----	41.0	61	73.8	180	
Ammonia-ammoni- um nitrate solutions.	LP-4	410[22-65-0]	22.2	65.0	-----	12.8	18.3	11.4	11.3	-----	41.0	21	73.8	180	
	LP-5	410[24-60-0]	24.3	60.0	-----	15.7	20.0	10.5	10.5	-----	41.0	1	73.8	180	
	LP-6	410[26-56-0]	26.3	55.5	-----	18.2	21.6	9.7	9.7	-----	41.0	-25	73.8	180	
	LP-7	414[19-74-0]	19.0	74.0	-----	7.0	15.6	12.9	12.9	-----	41.4	64	74.5	180	
	LP-8	434[23-70-0]	23.0	70.0	-----	7.0	18.9	12.2	12.3	-----	43.4	32	78.1	180	
Ammonia-urea solu- tions.	LP-9	440[24-70-0]	23.8	69.8	-----	6.4	19.6	12.2	12.2	-----	44.0	26	79.2	180	
	LP-10	448[25-69-0]	25.0	69.0	-----	6.0	20.6	12.1	12.1	-----	44.8	6	80.6	150	
	LP-11	210[4-0-38]	4.3	-----	37.5	58.2	3.5	-----	17.5	-----	21.0	33	37.8	180	
Ammonia-ammonium nitrate-urea solu- tions.	LP-12	350[20-0-41]	19.6	-----	40.6	39.8	16.1	-----	18.9	-----	35.0	58	63.0	180	
	LP-13 ⁵	371[25-0-35]	25.0	-----	35.3	23.3	20.6	-----	16.5	-----	37.1	34	66.8	180	
Ammonia-ammonium nitrate-urea solu- tions.	LP-14	410[19-58-11]	19.0	58.0	11.0	12.0	15.6	10.1	10.2	5.1	41.0	7	73.8	180	
	LP-15	414[19-66-6]	19.0	65.6	6.0	9.4	15.6	11.5	11.5	2.8	41.4	35	74.5	180	
Medium-pressure liquids															
Ammonia-ammonium nitrate solutions.	(MP-1	440[28-60-0]	28.0	60.0	-----	12.0	23.0	10.5	10.5	-----	44.0	-36	79.2	180	
	MP-2	451[26-68-0]	26.0	68.0	-----	6.0	21.3	11.9	11.9	-----	45.1	-6	81.2	180	
	MP-3	452[30-59-0]	29.9	59.0	-----	11.1	24.6	10.3	10.3	-----	45.2	-27	81.4	180	
	MP-4	471[30-64-0]	30.0	64.0	-----	6.0	24.7	11.2	11.2	-----	47.1	-32	84.8	180	
	MP-5	490[34-60-0]	34.0	60.0	-----	6.0	28.0	10.5	10.5	-----	49.0	-51	88.2	180	
	MP-6	500[40-50-0]	39.6	50.0	-----	10.4	32.5	8.7	8.8	-----	50.0	-85	90.0	180	
	MP-7	508[43-45-0]	42.6	45.0	-----	12.4	35.0	7.9	7.9	-----	50.8	-96	91.4	180	
	MP-8 ⁶	425[27-0-39-10 ⁷]	27.1	-----	38.8	15.1	22.3	2.1	-----	18.1	-----	42.5	20	82.5	194
	MP-9	453[31-0-43]	30.6	-----	43.1	26.3	25.2	-----	20.1	-----	45.3	46	81.5	180	
	Ammonia-urea solu- tions.	MP-10 ⁸	453[30-0-43]	30.5	-----	43.3	17.6	25.1	-----	20.2	-----	45.3	34	81.5	180
MP-11		454[37-0-32]	36.8	-----	32.5	30.7	30.3	-----	15.2	-----	45.4	16	81.8	180	
MP-12 ⁹		455[37-0-32]	36.8	-----	32.5	24.8	30.3	-----	15.2	-----	45.5	5	81.9	180	
MP-13		460[31-0-44]	31.1	-----	43.8	25.1	25.6	-----	20.4	-----	46.0	41	82.8	180	
MP-14		460[37-0-33]	37.3	-----	32.9	29.8	30.7	-----	15.3	-----	46.0	1	82.8	180	
Ammonia-ammonium nitrate-urea solu- tions.	MP-15	430[20-68-6]	20.0	68.0	6.0	6.0	16.4	11.9	11.9	2.8	43.0	14	77.4	180	
	MP-16	440[22-66-6]	22.0	66.0	6.0	6.0	18.1	11.5	11.6	2.8	44.0	-17	79.2	150	
	MP-17	440[28-40-15]	28.0	40.0	15.0	17.0	23.0	7.0	7.0	7.0	44.0	1	79.2	180	
	MP-18	444[24-56-10]	24.5	56.0	10.0	9.5	20.2	9.8	9.8	4.6	44.4	-15	79.9	180	
	MP-19	444[25-55-10]	25.0	55.0	10.0	10.0	20.6	9.6	9.6	4.6	44.4	-20	79.9	180	
	MP-20	444[26-50-12]	26.0	50.0	12.0	12.0	21.3	8.7	8.8	5.6	44.4	-7	79.9	180	
	MP-21	452[30-51-6]	29.9	51.0	6.0	13.1	24.6	8.9	8.9	2.8	45.2	-8	81.4	180	
	MP-22	455[26-45-18]	26.0	45.0	18.0	11.0	21.3	7.9	7.9	8.4	45.5	15	81.9	180	
	MP-23	490[33-45-13]	33.0	45.0	13.2	8.8	27.1	7.9	7.9	6.1	49.0	-13	88.2	180	
	MP-24	491[34-43-13]	34.0	43.0	13.0	10.0	28.0	7.5	7.5	6.1	49.1	-5	88.4	180	
MP-25	495[37-40-11]	37.0	40.0	11.0	12.0	30.4	7.0	7.0	5.1	49.5	-----	89.1	180		
High-pressure liquids															
Anhydrous ammonia	HP-1	822[100-0-0]	99.9	-----	-----	-----	82.2	-----	-----	-----	82.2	-----	148.0	180	

¹ Each product represents one or more similar commercial products; slight variations occur in the published data for similar liquids.

² Estimated to contain 60 percent ammonium bisulfite.

³ Contains 36.2 percent calcium nitrate.

⁴ Contains 20.5 percent sodium nitrate.

⁵ Contains 8.4 percent carbon dioxide and 8.0 percent formaldehyde.

⁶ Contains 9.0 percent carbon dioxide and 10.0 percent ammonium sulfate.

⁷ Contains 10.0 percent ammonium sulfate.

⁸ Contains 8.6 percent carbon dioxide.

⁹ Contains 5.9 percent carbon dioxide.

Anhydrous ammonia is often diluted to produce the low-pressure aqua ammonia (LP-1), which does not require the high-pressure storage and application equipment for the deep-placement application necessary for the anhydrous material. LP-1 is representative of a number of grades of commercial aqua ammonia.

The nitrogen content of the liquid nitrogen fertilizers ranges from 8.5 percent in NP-1 to 82.2 percent in HP-1. The nonpressure solutions, with two exceptions, contain less than 30 percent nitrogen whereas the low-pressure solutions, except LP-1 and LP-11, contain between 30 and 45 percent. The medium-pressure liquids, with two exceptions, contain 44.0 percent or more nitrogen.

Chemical Properties

A number of chemical properties are important to the use of liquid nitrogen fertilizers. The liquids are corrosive, many support combustion, and some may form explosive mixtures with oxygen. Other important properties are crystallization temperature, physiological acidity developed in the soil, and forms of nitrogen—ammoniacal, nitrate, and urea-nitrogen.

Most of the common metals are not affected by dry ammonia, but the presence of moisture will cause the ammonia to react rapidly with copper, brass, zinc (galvanized equipment), and many alloys, especially those containing copper (62). Iron and steel are not affected by moist ammonia, and equipment made of these materials can be used with anhydrous and aqua ammonia.

The other solutions can also be handled in ordinary steel, but corrosion occurs and shortens the life of the equipment (60). Equipment made of aluminum, of many of the essentially copper-free aluminum alloys, or of certain stainless steels is recommended for solutions containing dissolved nitrogen salts (147). Vreeland and Kalin (198) studied the corrosion of metals in solutions NP-8 and LP-4 by partially immersing 1-inch by 2-inch specimens in the solution being tested. Each specimen was tested separately. The corrosion rates, as calculated from the weight losses, are given in table 6. They indicate that chromium stain-

less steel, type 405, nickel stainless steel, type 304, and aluminum alloy, type 3003-H14, should be suitable for liquid nitrogen fertilizer containers.

Ammonium thiocyanate is used generally as a corrosion inhibitor in liquid nitrogen solutions. At concentrations greater than 0.1 percent by weight, the corrosion of cold-rolled, mild steel at 86° F. is only about 0.5 percent the uninhibited rate. The corrosion rate is further reduced by the addition of sodium arsenite (93). Other materials belonging to the general class of compounds containing divalent sulfur linked to carbon (38, 39, 111), other trivalent arsenic compounds (37), and sodium dichromate (36) have been suggested for reducing corrosion.

Attempts have also been made to combat corrosion by coating equipment with natural or synthetic rubber, glass, suitable plastic material, and corrosion-resistant metal. Rubber containers with capacities up to 15,000 gallons are also available, as well as rubber liners for metal tanks.

Anhydrous ammonia and its aqueous solutions present fire and explosion hazards (66, 131, 133, 145, 147, 149). Ammonia-air mixtures containing 16 to 25 percent ammonia by volume and ammonia-oxygen mixtures containing 15 to 79 percent ammonia will explode when ignited. The explosive range is broadened by elevated temperatures and pressures higher than atmospheric. The presence of oil or other combustible materials increases the hazard. Mercury forms explosive compounds with ammonia and accelerates the corrosion of aluminum containers.

Solutions containing ammonium nitrate, a vigorous oxidizing agent, are substantially nonhazardous so long as the nitrate remains in solution. The solid salt, however, presents serious fire and explosion hazards (71, 132, 169), especially when in contact with combustible materials. The presence of urea in the solutions does not add to either of these hazards, but sodium nitrate contributes to the fire risk.

Anhydrous ammonia has been handled to a limited extent in butane and propane tanks, although hydrocyanic acid has been reported to be formed when mixtures of butane or propane and ammonia are burned (25). This is a controversial subject (191) that has not been settled, and every effort should be made to avoid the possibility of danger. When ammonia is mixed rapidly with a strong inorganic acid, the mixture boils and may overflow or rupture the container.

The salting-out temperature is the temperature at which crystals begin to form in the liquid. It is one of the important characteristics to be considered in selecting a liquid nitrogen fertilizer. Liquids with salting-out temperatures above prevailing air temperatures will salt out and cause equipment failure and uneven distribution. Particular attention must be paid to this factor during the changing seasons. Anhydrous and aqua

TABLE 6.—Corrosion rates of metals in nitrogen solutions¹

Metal	Corrosion rate ² (mils penetration per month) for—	
	NP-8 ³	LP-4 ⁴
Carbon steel.....	0.11	1.6
Chromium stainless steel:		
Type 502 (5.2 percent Cr).....	< .01	1.5
405 (12.5 percent Cr).....	< .01	(⁵) < .01
430 (17.1 percent Cr).....	< .01	
Nickel stainless steel:		
Type 304 (9.0 percent Ni, 18.9 percent Cr).....	< .01	< .01
316 (12.9 percent Ni, 18.0 percent Cr).....	< .01	(⁵) < .01
Aluminum alloy, type 3003-H14 (1.15 percent Mn).....	< .01	< .01

¹ Data from Vreeland and Kalin (198).

² Calculated from weight loss.

³ At 100° F. for 28 days.

⁴ At 100° F. for 14 days.

⁵ Not tested.

ammonia, solutions LP-1 and LP-6, and some of the medium-pressure solutions can be applied any time it is possible to work the soil. Solutions with high salting-out temperatures, such as NP-6, NP-8, and LP-7, cannot be recommended for use during cold weather unless they are diluted to prevent salting out.

The effect of dilution of some typical nitrogen solutions is given in table 7. The addition of

water depresses the salting-out temperature in each case. The depression is continuous with dilution in the examples given, and in three cases the addition of 15 gallons of water to 100 gallons of solution reduces the salting-out temperature to the freezing point of water or below. The lower salting-out temperature increases the area and widens the temperature range over which a solution can be used.

TABLE 7.—Effect of dilution on the nitrogen content and salting-out temperatures of typical nitrogen fertilizer liquids¹

Product designation	Original liquid		3 gallons of water added to 100 gallons of liquid		5 gallons of water added to 100 gallons of liquid		10 gallons of water added to 100 gallons of liquid		15 gallons of water added to 100 gallons of liquid	
	Nitrogen content	Salting-out temperature	Nitrogen content	Salting-out temperature	Nitrogen content	Salting-out temperature	Nitrogen content	Salting-out temperature	Nitrogen content	Salting-out temperature
	Percent	° F.	Percent	° F.	Percent	° F.	Percent	° F.	Percent	° F.
NP-6.....	20.0	58	19.6	54	19.4	51	18.7	44	18.1	36
NP-8.....	21.0	51	20.6	48	20.2	45	19.5	38	18.8	32
NP-13.....	32.0	32	31.2	24	30.8	21	29.8	12	28.8	5
LP-2.....	37.0	56	36.1	50	35.6	48	34.2	42	33.0	37
LP-4.....	41.0	21	39.8	19	39.2	18	37.7	16	36.2	15

¹ Data from U.S. Department of Agriculture (193).

The liquid nitrogen fertilizers are physiologically acid and leave an acid residue in the soil. The potential decrease in soil pH resulting from the use of these liquids is evaluated in terms of the pounds of calcium carbonate necessary to neutralize the resulting acid residue (154). The general requirement, as shown in table 5, is 180 pounds of calcium carbonate per 100 pounds of nitrogen applied to the soil.

Physical Properties

Physical properties of liquid nitrogen fertilizers are given in table 8. The tabulated properties include the vapor pressures at four different temperatures, the temperature at which the gage pressure becomes zero, specific gravity, the weight of a gallon of liquid, the weight of nitrogen con-

tained therein, and the volume of liquid per 100 pounds of nitrogen. Additional properties of anhydrous ammonia are given in table 9. Further information on the properties of nitrogen solutions have been reported by Shultz and Elmore (172) and Worthington, Datin, and Schutz (201). The former determined the vapor pressures of experimental ammonia-ammonium nitrate-water solutions and the partial pressures of the ammonia and water at 10° and 35° C. Worthington and coworkers reported data on the solubilities, vapor pressures, and densities of ammonia-ammonium nitrate-water and ammonia-urea-water solutions in the ranges of 0 to 65 percent ammonia, 0 to 75 percent ammonium nitrate, and 0 to 65 percent urea.

TABLE 8.—Physical properties of liquid nitrogen materials available for fertilizer use in 1959¹

Kind	Product Designation	Nitrogen content	Vapor pressure (gage) at—				Temperature at which gage pressure is 0	Specific gravity at 60° F.	Weight of solution per gallon at 60° F.	Weight of nitrogen per gallon at 60° F.	Volume per 100 pounds of nitrogen at 60° F.
			60° F.	90° F.	104° F.	120° F.					
			Pressure	Suggested	Percent	P.s.i.					
Nonpressure liquids											
Aqueous solutions of nitrogen products.	NP-1	85[0-0-60]	8.5	-----	-----	-----	-----	1.28	10.67	.91	109.9
	NP-2	160[0-46-0]	16.0	-----	-----	-----	-----	1.208	10.07	1.61	62.1
	NP-3	170[0-31-0-36]	17.0	-----	-----	-----	-----	² 1.499	³ 12.50	³ 2.15	³ 46.5
	NP-4	175[0-50-0]	17.5	-----	-----	-----	-----	1.225	10.22	1.79	55.9
	NP-5	190[0-54-0]	19.0	-----	-----	-----	-----	1.254	10.46	1.99	50.3
	NP-6	200[0-48-0-20]	20.0	-----	-----	-----	-----	1.410	11.76	2.35	42.6
	NP-7	200[0-57-0]	20.0	-----	-----	-----	-----	² 1.263	³ 10.53	³ 2.11	³ 47.4
	NP-8	210[0-60-0]	21.0	-----	-----	-----	-----	1.287	10.73	2.25	44.4
	NP-9	227[0-65-0]	22.7	-----	-----	-----	-----	1.307	10.90	2.47	40.5
	NP-10	245[0-70-0]	24.5	-----	-----	-----	-----	⁴ 1.346	11.23	2.75	36.4
	NP-11	280[0-40-30]	28.0	-----	-----	-----	-----	1.278	10.66	2.98	33.6
	NP-12	300[0-42-33]	20.0	-----	-----	-----	-----	1.300	10.84	3.25	30.8
	NP-13	320[0-44-35]	32.0	-----	-----	-----	-----	1.327	11.07	3.54	28.2

See footnotes at end of table.

TABLE 8.—Physical properties of liquid nitrogen materials available for fertilizer use in 1959¹—Continued

Product			Nitro- gen con- tent	Vapor pressure (gauge) at				Tem- per- ature at which gauge pres- sure is 0	Specific gravity at 60° F.	Weight of solu- tion per gallon at 60° F.	Weight of nitro- gen per gallon at 60° F.	Volume per 100 pounds of nitro- gen at 60° F.
Kind	Designation			60° F.	90° F.	104° F.	120° F.					
		Pressure	Suggested									
Low-pressure liquids												
			<i>Percent</i>	<i>P.s.i.</i>	<i>P.s.i.</i>	<i>P.s.i.</i>	<i>P.s.i.</i>	<i>°F.</i>		<i>Pounds</i>	<i>Pounds</i>	<i>Gallons</i>
Aqua ammonia.....	LP-1	206[25-0-0]	20.6	-9	-3	2	8	99	0.911	7.60	1.56	64.1
	LP-2	370[17-67-0]	37.0	-9	-3	1	7	101	1.182	9.86	3.65	27.4
	LP-3	410[19-72-0]	41.0	-6	2	7	15	86	1.194	9.96	4.08	24.5
	LP-4	410[22-65-0]	41.0	-5	5	10	19	79	1.139	9.50	3.89	25.7
	LP-5	410[24-60-0]	41.0					70	1.100	9.17	3.76	26.6
Ammonia—ammonium nitrate solutions.	LP-6	410[26-56-0]	41.0	-3	8	17	29	68	1.078	8.99	3.69	27.1
	LP-7	414[19-74-0]	41.4	-3	3	8	18	78	1.186	9.89	4.09	24.4
	LP-8	434[23-70-0]	43.4			18			1.16	9.67	4.20	23.8
	LP-9	440[24-70-0]	44.0	-2	10	18	29	67	1.147	9.56	4.21	23.8
	LP-10	448[25-69-0]	44.8	0	9	17	29	60	1.124	9.37	4.20	23.8
	LP-11	210[4-0-38]	21.0			0			1.085	9.05	1.90	52.6
Ammonia—urea solutions.....	LP-12	350[20-0-41]	35.0	-5	3	9	18	81	1.020	8.51	2.98	33.6
	LP-13	371[25-0-35]	37.1	-2	10	17	24	65	1.05	8.76	3.25	30.8
Ammonia—ammonium nitrate—urea solutions.	LP-14	410[19-58-11]	41.0	-6	4	10	18	80	1.161	9.68	3.97	25.2
	LP-15	414[19-66-6]	41.4			13			1.178	9.82	4.06	24.6
Medium-pressure liquids												
A ammonia—ammonium nitrate solutions.	MP-1	440[28-60-0]	44.0	1	15	25	39	57	1.083	9.03	3.97	25.2
	MP-2	451[26-68-0]	45.1	0	13	24	36	60	1.124	9.37	4.23	23.6
	MP-3	452[30-59-0]	45.2	⁴ 4	⁵ 20	26	⁵ 55	⁵ 54	1.070	8.92	4.03	24.8
	MP-4	471[30-64-0]	47.1	5	22	30	46	47	1.095	9.13	4.30	23.3
	MP-5	490[34-60-0]	49.0	10	32	50	71	39	1.044	8.71	4.27	23.4
	MP-6	500[40-50-0]	50.0			58			.992	8.26	4.13	24.2
	MP-7	508[43-45-0]	50.8	24	53	72	99	6	.984	8.21	4.17	24.0
	MP-8	425[27-0-39-10]	42.5	15					1.13	9.42	4.00	25.0
Ammonia—urea solutions.....	MP-9	453[31-0-43]	45.3	13	32	48	65		.973	8.11	3.67	27.2
	MP-10	453[30-0-43]	45.3	16	40	55	74	28	1.06	8.84	4.00	25.0
	MP-11	454[37-0-32]	45.5	15	40	57	79	29	.927	7.73	3.52	28.4
	MP-12	455[37-0-32]	45.5	23	53	71	96	10	.99	8.26	3.76	26.6
	MP-13	460[31-0-44]	46.0	13	36	51	70	31	.972	8.11	3.73	26.8
	MP-14	460[37-0-33]	46.0	19	42	60	82	22	.927	7.73	3.56	28.1
	MP-15	430[20-68-6]	43.0	1	14	22	31	57	1.165	9.72	4.18	23.9
	MP-16	440[22-66-6]	44.0	4	18	27	36	54	1.149	9.57	4.21	23.8
	MP-17	440[28-40-15]	44.0	3	18	27	45	52	1.052	8.77	3.86	25.9
	MP-18	444[25-56-10]	44.4	-1	12	22	35	62	1.108	9.24	4.10	24.4
Ammonia—ammonium nitrate—urea solutions.	MP-19	444[25-55-10]	44.4	1	13	22	34	55	1.111	9.26	4.11	24.3
	MP-20	444[26-50-12]	44.4	1	15	24	37	54	1.081	9.01	4.00	25.0
	MP-21	452[30-51-6]	45.2	⁵ 8	⁵ 19	27	⁵ 50	⁵ 56	1.057	8.82	3.99	25.1
	MP-22	455[26-45-18]	45.5	3		28	42	56	1.089	9.08	4.13	24.2
	MP-23	490[33-45-13]	49.0	12	34	50	69	35	1.034	8.62	4.22	23.7
	MP-24	491[34-43-13]	49.1	12		52	74	35	1.012	8.44	4.14	24.2
	MP-25	495[37-40-11]	49.5			60			1.039	8.66	4.29	23.3
High-pressure liquids												
Anhydrous ammonia.....	HP-1	822[100-0-0]	82.2	92	166	211	276	-28	0.618	5.15	4.23	23.6

¹ Each product represents one or more similar commercial products; slight variations occur in the published data for similar liquids.

² At 68° F./60° F.

³ At 68° F.

⁴ At 70° F.

⁵ Estimated by producer.

TABLE 9.—Physical properties of anhydrous ammonia¹

Boiling point at 1 atmosphere.....	-28° F.
Melting point at 1 atmosphere.....	-107.9° F.
Critical temperature.....	271.4° F.
Critical pressure.....	1,657 p.s.i.a.
Vapor density at -28° F., 1 atmosphere.....	0.0555 lb./cu. ft.
Liquid density at -28° F., 1 atmosphere.....	42.57 lb./cu. ft.
Specific volume of vapor at 32° F., 1 atmosphere.....	20.78 cu. ft./lb.
Range of explosive ammonia-air mixtures.....	16-25 percent NH ₃ , by volume
Ignition temperature (iron bomb).....	1,204° F.
Specific heat, Cp (1 atmosphere, 60° F.).....	0.52 B.t.u./lb./° F.
Solubility in water at 1 atmosphere and 32° F.....	0.899 g. NH ₃ /g. water
68° F.....	0.518 g. NH ₃ /g. water
104° F.....	0.338 g. NH ₃ /g. water
140° F.....	0.238 g. NH ₃ /g. water

¹ Data from Nitrogen Division, Allied Chemical & Dye Corp. (149).

The gage pressures of the commercial liquid nitrogen fertilizers cover a range of -9 pounds per square inch at 60° F. to 276 pounds at 120°. The gage pressures are 0 or below at 60° for all the low-pressure solutions and 0 or above for all the medium- and high-pressure liquids, except solution MP-18. All the liquid nitrogen fertilizers have gage pressures of 0 or above at 104°. Solutions LP-2 and LP-11 are the only liquids with a vapor pressure of 0 at a temperature over 100°. The temperature of liquid HP-1 must drop to -28° before the gage pressure is reduced to 0.

Anhydrous ammonia has the lowest specific gravity and is the most concentrated of any of the liquid nitrogen materials. However, three solutions—MP-4, -5, and -25—contain more nitrogen per gallon than anhydrous ammonia.

The weight of nitrogen per gallon is one of the important characteristics of the various liquid nitrogen materials. A 100-gallon liquid anhydrous ammonia container, which in practical use should not be filled to more than 90 percent of capacity, has a carrying capacity of 381 pounds of nitrogen. The same size tank has a carrying capacity of 354 pounds of nitrogen in the form of solution NP-13 and over 400 pounds of nitrogen in several LP and MP solutions. The tanks and metering devices for these solutions are much lighter and less costly than those required for anhydrous ammonia. Because of the difference in weight of equipment, the weight of nitrogen carried per pound of loaded equipment will be greater for some solutions than for anhydrous ammonia.

Physiological Properties

The ammonia in any of the liquid nitrogen fertilizers is a health hazard, but undue exposure to an atmosphere seriously contaminated with ammonia is unlikely because of its pungent odor and suffocating effect. The physiological effects and remedial treatments have been discussed in many publications, including those of the Manufacturing Chemists' Association, Inc. (131, 133) and various ammonia producers (61, 75, 149, 153, 180).

The magnitude of the hazard is commensurate with the ammonia concentration of the liquid nitrogen fertilizer. The critical concentrations are given in table 10. The symptoms resulting from exposure to ammonia gas may be nausea, vomiting, pain in the throat and abdomen, weak and rapid pulse, convulsions, burning of the eyes, and coughing.

TABLE 10.—Critical gaseous ammonia concentrations¹

Concentration (parts per million)	Effects on unprotected worker	Exposure period
50.....	Least detectable odor.....	Permissible for 8-hour working exposure.
100.....	No adverse effects for average unprotected worker.	
400.....	Causes irritation of throat.....	Ordinarily no serious results following infrequent short exposures (less than 1 hour).
700.....	Causes irritation of eyes.....	No exposure permissible (may be fatal after short exposure—less than half an hour).
1,720.....	Causes convulsive coughing.....	
5,000 to 10,000..	Causes respiratory spasm, strangulation, asphyxia.	No exposure permissible, rapidly fatal.

¹ Data from Manufacturing Chemists' Association, Inc. (133).

Ammonia gas dissolves readily in the perspiration of the body and causes a caustic burn that varies in severity with the concentration of ammonia and the length of time of exposure. A 2-percent concentration is generally the maximum tolerated by the skin for more than a few seconds. Liquid anhydrous ammonia produces severe burns on contact with the skin, caused not only by its caustic action but also by the freezing

effect produced by the rapid evaporaton of the liquid.

Employees working where ammonia hazards exist should be fully informed of the dangers and instructed in the precautions to be taken and in first aid treatment. They should be provided with approved gas masks, rubber hats, suits, gloves, and boots and should wear cotton garments under the rubber clothing. Easily accessible safety showers and bubble fountains should be available.

A person overcome or burned by ammonia should be placed under the care of a physician. Immediately apply artificial respiration if asphyxiation has occurred. When breathing is weak, administer oxygen or mixtures of oxygen with 5 percent or less of carbon dioxide. Never try to give anything by mouth to an unconscious person. When skin is exposed to ammonia, wash the affected areas repeatedly with water and follow with an application of 2 percent boric acid or acetic acid solution, lemon juice, or vinegar. More water is then applied. Eyes injured with ammonia should be immediately flooded with water or 2 percent boric acid solution. This should be continued for at least 15 minutes, after which 2 or 3 drops of an aqueous topical anesthetic can be applied. When throat and internal exposure occurs, have the victim drink large quantities of water followed by harmless weak acid solutions such as lemonade and dilute vinegar. If ammonia has been swallowed, administer a demulcent such as raw egg, milk, cream, barley water, or olive oil.

The ammonium nitrate in liquid nitrogen fertilizers is also toxic to humans. Van Arsdell (196) states that ingestion of ammonium nitrate severely irritates the stomach and may produce death within 20 minutes to 5 hours. Ingested nitrate should be diluted immediately with large quantities of water and the stomach should be thoroughly washed. Starch and flour water, milk, and egg white may be swallowed to absorb some of the free nitrate ions.

Liquid nitrogen fertilizers, because of their ammonia, ammonium nitrate, and urea contents, may be toxic to livestock. Animals will lick up excess solutions left on application equipment and the salts left after evaporation of the solutions.

Boyd, McLachlan, and Perry (49) have shown that ammonia poisoning may be fatal to animals. It is associated with a series of complex changes in the chemistry of the body and particularly of the respiratory tract.

Nitrate poisoning of cattle, sheep, and horses may occur when they have access to nitrate fertilizer, which is quite palatable, especially to cattle (42). The ingested nitrate is reduced to the highly toxic nitrite by bacterial or enzymatic action within the digestive tract of the animal. The nitrite prevents the red blood cells from carrying oxygen to the tissues by changing the oxy-

hemoglobin to methemoglobin. Immediate intravenous injection of methylene blue helps to counteract the effect of the nitrite by converting the methemoglobin into hemoglobin.

Osebold (152) reported two cases of urea poisoning in cattle resulting from ingestion of urea fertilizer and other cases in which the cattle were fed

portions of poorly mixed grain rations with high urea concentrations. Chronic organic dysfunctions were detected in some cases. Reports of urea toxicity to sheep have also been received (78). The danger is alleviated when the animal has access to water and can quickly excrete the excess urea.

MANUFACTURING PROCESSES AND FACILITIES

Aside from a small quantity of aqua ammonia obtained as a byproduct of coke manufacture (67, 159, 184), the domestic output of liquid nitrogen materials is based on ammonia manufactured by the direct synthesis process. The ammonia, in turn, is the parent compound of the other nitrogenous constituents.

Synthetic ammonia is produced by a catalyzed reaction between nitrogen and hydrogen at elevated temperatures and pressures (67, 83, 143, 159, 184, 195). The hydrogen is produced principally by reactions of steam and air with carbonaceous materials such as coke, fuel oil, natural gas, and oil-refinery gas. Other ways in which hydrogen is obtained include recovery from coke-oven and petroleum-refining gases—as a byproduct of caustic soda-chlorine manufacture—and by electrolysis of water.

Air is essentially the sole source of the nitrogen used in the production of synthetic ammonia. The nitrogen is obtained from (1) the producer gas-water gas reaction, (2) direct combustion of air, (3) flue gas, (4) fractionation of liquid air, and (5) the nitrogen-rich tail gas from ammonia oxidation plants.

The first commercial process for producing synthetic ammonia was the Haber-Bosch process, which went into commercial operation in Germany in 1913. The synthesis takes place at a pressure of 200 atmospheres and a temperature of 1022° F. (550° C.) over a promoted iron catalyst. Many of the processes developed since 1913 for the production of synthetic ammonia are based on the Haber-Bosch process.

The processes used in the United States and Canada employ the promoted iron catalyst and are characterized primarily by differences in the operating temperatures and pressures. Table 11

TABLE 11.—Synthetic ammonia production processes ¹

Process	Operating		
	Pressure	Temperature	
		Atm.	° F.	° C.
American.....	300	887	475
Casale.....	400	752	400
Fausser.....	250	752-932	400-500
General Chemical.....	200	932	500
L'Air Liquid.....	950-1,000	896-932	480-500
Modified Casale.....	820	977-1,022	525-550
Mont Cenis.....	100-200	752-797	400-425
M. W. Kellogg.....	300	932	500
Nitrogen Engineering Corp.....	300	977	510-525

¹ Data from Taylor (184, p. 46).

lists the various processes and some of the characteristics of each.

The reported annual productive capacity of the 22 anhydrous ammonia plants in the United States in August 1950 was 1,655,000 tons of nitrogen (table 12). There were no plants in either the New England or Mountain States and only one each in the South Atlantic and West North Central States. Six plants with a productive capacity of 462,000 tons of nitrogen were located in the West South Central States. Expansion in a little over 9 years increased the number of plants (in existence or under construction) to 59 and the annual productive capacity to 4,246,000 tons of nitrogen. At least 1 plant is located in each region. In the West South Central States, 12 plants have a productive capacity of 1,141,000 tons of nitrogen.

TABLE 12.—Number and estimated annual productive capacity of domestic anhydrous ammonia plants August 1950, and of plants existing or under construction January 1, 1960, by regions

Region	August, 1950 ¹		January 1, 1960 ²	
	Plants	Productive capacity	Plants	Productive capacity
	Number	1,000 short tons N	Number	1,000 short tons N
New England.....			1	36
Middle Atlantic.....	4	371	9	582
South Atlantic.....	1	240	3	459
East North Central.....	3	184	7	574
West North Central.....	1	140	6	407
East South Central.....	3	145	7	429
West South Central.....	6	462	12	1,141
Mountain.....			3	83
Pacific.....	4	113	11	535
Total.....	22	1,655	59	4,246

¹ Based on Taylor (184, p. 46).

² Derived from table 13.

Figure 1 and table 13 show that the productive facilities are rather evenly divided between the eastern and western parts of the country; 27 plants with a productive capacity of 2,080,000 tons of nitrogen are situated east of the Mississippi River and 32 with a capacity of 2,166,000 tons lie west of the river. All but two of the plants are privately operated. The plant at Wilson Dam, Ala., is operated by the Government. The Morgantown, W. Va., plant is Government-owned and had been leased and operated by a private company until July 15, 1959, when the lessee turned it back to the Government.

TABLE 13.—Domestic anhydrous ammonia manufacturing plants existing or under construction, January 1, 1960

Company and location	Estimated annual capacity	Company and location	Estimated annual capacity
	1,000 short tons N ¹		1,000 short tons N ¹
1. Allied Chemical Corp., Hopewell, Va.	329	32. Northern Chemical Industries Inc., Searsport, Maine	36
2. Allied Chemical Corp., Omaha, Nebr.	62	33. Olin-Mathieson Chemical Corp., Lake Charles, La.	90
3. Allied Chemical Corp., South Point, Ohio	263	34. Olin-Mathieson Chemical Corp., Niagara Falls, N.Y.	5
4. American Cynamid Co., New Orleans, La.	44	35. Pennsylvania Salt Manufacturing Co., Portland, Oreg.	12
5. Apache Powder Co., Benson, Ariz.	8	36. Pennsylvania Salt Manufacturing Co., Wyandotte, Mich.	26
6. Armour Agricultural Chemical Co., Crystal City, Mo.	58	37. Petroleum Chemicals, Inc., Lake Charles, La.	82
7. Atlantic Refining Co., Philadelphia, Pa.	29	38. Phillips Chemical Co., Etter, Tex.	158
8. California Ammonia Co., Lathrop, Calif.	230	39. Phillips Chemical Co., Port Adams, Tex.	158
9. Calumet Nitrogen Products Co., Hammond, Ind.	86	40. Phillips Pacific Chemical Co., Kennewick, Wash.	60
10. Coastal Chemical Co., Paseagoula, Miss.	245	41. Rohm & Haas, Deer Park, Tex.	40
11. Collier Carbon and Chemical Corp., Brea, Calif.	74	42. St. Paul Ammonia Products, Inc., Pine Bend, Minn.	58
12. Columbla-Southern Chemical Corp., Natrium, W. Va.	27	43. Shell Chemical Co., Pittsburg, Calif.	97
13. Commercial Solvents Corp., Sterlington, La.	115	44. Shell Chemical Co., Ventura, Calif.	66
14. Cooperative Farm Chemicals Assoc., Lawrence, Kans.	52	45. Smith-Douglas Co., Inc., Pasadena, Tex.	33
15. Deere and Co., Pryor, Okla.	54	46. Sohio Chemical Co., Lima, Ohio.	86
16. Dow Chemical Co., Freeport, Tex.	74	47. Southern Nitrogen Co., Inc., Savannah, Ga.	72
17. Dow Chemical Co., Midland, Mich.	20	48. Southwest Agrochemical Corp., Chandler, Ariz.	217
18. Dow Chemical Co., Pittsburg, Calif.	6	49. Spencer Chemical Co., W. Henderson, Ky.	61
19. E. I. du Pont de Nemours & Co., Belle, W. Va.	191	50. Spencer Chemical Co., Pittsburg, Kans.	144
20. E. I. du Pont de Nemours & Co., Niagara Falls, N.Y.	8	51. Spencer Chemical Co., Vicksburg, Miss.	58
21. E. I. du Pont de Nemours & Co., Gibbstown, N.J.	250	52. Standard Oil Co. of California, Richmond, Calif.	86
22. Escambia Chemical Corp., Pensacola, Fla.	58	53. Sun Oil Co., Marcus Hook, Pa.	90
23. Food Machinery & Chemical Corp., Charleston, W. Va.	18	54. Tennessee Valley Authority, Wilson Dam, Ala.	74
24. W. R. Grace and Co., Memphis, Tenn.	72	55. Texaco Inc., Lockport, Ill.	52
25. Hercules Powder Co., Louisiana, Mo.	33	56. U.S. Government, Morgantown, W. Va.	164
26. Hercules Powder Co., Hercules, Calif.	41	57. U.S. Industrial Chemicals Co., Tuseola, Ill.	41
27. Hooker Electrochemical Co., Tacoma, Wash.	19	58. U.S. Steel Corp., Geneva, Utah.	58
28. Ketona Chemical Corp., Ketona, Ala.	39	59. Valley Nitrogen Producers, Helm, Calif.	44
29. Mississippi Chemical Corp., Yazoo City, Miss.	80		
30. Monsanto Chemical Co., El Dorado, Ark.	173		
31. Monsanto Chemical Co., Luling, La.	120		
		Total	4,246

¹ Unless otherwise noted, calculated from data in Chemical Statistics Handbook (134). ² Estimated.



FIGURE 1.—Anhydrous ammonia manufacturing plants, January 1, 1960.

Aqua ammonia is produced by mixing anhydrous ammonia with water or as a byproduct of coke plants. The anhydrous ammonia, in many cases, is shipped out to large-scale conversion plants for quantity production of aqua ammonia or to smaller plants where aqua ammonia is prepared for local use. As it is unloaded from tank cars the anhydrous ammonia can be piped directly through a converter into aqua ammonia storage (188), thereby eliminating the need for high-pressure storage facilities. Aqua ammonia also is produced at some ammonia-synthesis plants.

The other pressure liquids are prepared by adding anhydrous ammonia to aqueous solutions of the salts. The ammonium nitrate is formed by neutralizing nitric acid with ammonia (162, pp. 412-413) and the urea is manufactured by reacting carbon dioxide with ammonia in the liquid

phase under greatly elevated pressure and temperature (64, 189). The aqueous solutions of the salts are blended with anhydrous ammonia under pressure and then passed through coolers to storage. Pressure storage containers are used to prevent loss of ammonia. The carbon dioxide contents of solutions LP-13, MP-8, -10 and -12 are due to the use of urea solutions from which dissolved CO₂ had not been completely removed.

The nonpressure liquids are aqueous solutions of solid nitrogen materials. They may be solutions withdrawn at some stage during the production of the material, diluted or blended mixtures of such solutions, or the solid materials dissolved in water. Seven of the listed solutions (table 5) are fundamentally dilutions of the 83 percent ammonium nitrate solution withdrawn from the process following neutralization of nitric acid with ammonia.

SAFETY REGULATIONS AND PRECAUTIONS

Safety regulations are based primarily on the use of anhydrous ammonia. Many of the regulations are applicable to the pressure solutions, but none of them apply to the nonpressure solutions. No specific recommendations have been made on the basis of the salts in the solutions, but applicable precautions, based on the inherent hazards of ammonium nitrate as described by Davis (71), should be observed.

Regulations and suggestions for the safe handling of liquid nitrogen fertilizers have been formulated by the Interstate Commerce Commission (194), the Compressed Gas Association, Inc. (62), the National Safety Council (145), the Agricultural Ammonia Institute (15, 50), and many State and local authorities. A list of the State agencies having jurisdiction over the storage and handling of liquid nitrogen fertilizers is given in the appendix. Many nitrogen fertilizer manufacturers have published brochures containing suggestions for handling the liquids (61, 75, 147, 148, 149, 153, 176, 177, 180, 185).

The Interstate Commerce Commission classifies anhydrous ammonia as a nonflammable compressed gas. It must be packaged in ICC specification containers; all ICC Regulations regarding loading, handling, and labeling must be followed. Each container (including tank cars) should carry an identifying label or stencil. Tank cars must be stenciled to show ICC class No. 105A-300 and must carry the ICC "Dangerous" placard when loaded. Each cylinder must carry the ICC green label of nonflammable compressed gas, the name of the owner, serial number, test date, and ICC specification number. Also the Manufacturing Chemists' Association (133) describes a warning label that is recommended for use on each container in addition to any labels required by statutes, regulations, or ordinances. Although

the ICC Regulations apply specifically to interstate movement of ammonia, many States have adopted them for intrastate shipments as well.

The Interstate Commerce Commission does not regulate shipments of any of the other liquid forms of fertilizer nitrogen. Aqua ammonia, however, is usually shipped in ICC specification containers, and it is recommended that the containers carry a warning label (131). The tank cars usually comply with ICC specification 103 or 103A and steel drums are labeled ICC specification 5 or 5A.

Tanks for storing anhydrous and aqua ammonia should be fabricated in accordance with the American Society of Mechanical Engineers code for unfired pressure vessels (19). Underground containers for anhydrous ammonia should have a minimum design working pressure of 250 pounds per square inch and aboveground containers should be designed for 265 pounds per square inch working pressure.

State and local ordinances generally specify that anhydrous ammonia storage tanks shall not be located in densely populated areas or within certain fixed distances—50 to 200 feet—from a dwelling, an important building, railroad, or public highway. Buildings, in which tanks are located, must have openings at the top for natural ventilation. A tank located outside a building should be shaded or painted a light color to reduce heat absorption from the sun. Howell (98) states that the pressure exerted by anhydrous ammonia in a 110-gallon tank painted white was approximately 40 pounds lower throughout the summer than in a similar tank painted aluminum. Tucker and Dyer (192) show that the maximum pressure exerted by ammonia in tanks painted white was approximately 90 pounds lower than in rusted tanks at air temperatures of 104° to 108° F.

Some States require that the words "DANGER—AMMONIA" be printed on both sides and ends of the tank in red letters at least 6 inches high.

Aqua ammonia and the other pressure solution containers should be designed for a working pressure of not less than the vapor pressure of the contained solution at 115° F. The tanks for aqua ammonia should have a minimum working pressure of 100 pounds per square inch. Tanks for the pressure and nonpressure solutions, when pressure is used to transfer the solution, should be designed for a 30- to 35-pound-per-square-inch working pressure, in accordance with the code for unfired pressure vessels. The nonpressure solutions can be stored in nonpressure tanks or open containers when the solution is transferred by pumps or gravity.

Valves (70) and accessory equipment for tanks must be approved for the liquid to be handled. Tanks should be equipped with spring-loaded or equivalent type safety relief valves, with direct communication to the vapor space of the container. The valves should be vented to the open air away from the container. Loading and un-

loading operations should be protected by excess-flow and backflow check valves. Fittings for truck and trailer tanks should be installed in the rear end of the container and should be protected by a heavy permanent fixture. The container should be equipped with baffle plates to eliminate surging of the liquid.

Liquid nitrogen fertilizer equipment, tanks, and lines should be thoroughly washed and purged before repairing (85). Flammable air-ammonia mixtures may be formed and ignited during welding or cutting. The high temperatures of these operations decompose any residual ammonium nitrate. The reaction is exothermic and potentially explosive.

Spilled ammonium nitrate and sodium nitrate solutions should be cleaned up immediately, as the salts, like nitrates in general, present a fire hazard. Spontaneous combustion may occur when organic material containing nitrates comes in contact with hot surfaces such as steam pipes. Wooden floors impregnated with ammonium nitrate will ignite readily when exposed to heat, and the oxygen supplied by the nitrate will support combustion.

MARKETING AND DISTRIBUTION

The marketing of liquid nitrogen fertilizers does not follow a fixed pattern. Producers may sell to fertilizer manufacturers, bulk distributors, a group of consumers, or to the ultimate consumer. The bulk distributor sells to the consumer. The liquids may be sold to the farmer on a delivered-to-the-farm or applied-to-the-soil basis.

Anhydrous ammonia generally moves from the primary producer to fertilizer manufacturers or bulk distribution facilities. The manufacturers use it in the production of mixed fertilizers and seldom sell ammonia for direct application. Bulk distribution centers provide supplementary off-season storage for the producer and enable the distributor to have a supply available when needed. Distribution facilities are financed privately, by primary producers, or by cooperative associations. Those financed by the primary producers are operated by the company or leased to independent operators. Leases are so arranged that the producer is assured of ammonia outlets and the distributor has the assurance of a supplier.

Some ammonia is moved from the producing plant to the field in company-owned equipment and applied to the soil by company personnel (183). The ammonia is sold on an applied basis rather than on an f.o.b. plant basis. Essentially, all the ammonia sold by one producer for direct application is marketed as aqua ammonia (4).

Aqua ammonia may be made at the ammonia-production plant or from anhydrous ammonia shipped to local conversion stations. Otherwise,

the pattern of its marketing and distribution is about the same as that of anhydrous ammonia.

The movement of the other liquid nitrogen materials follows much the same pattern as that of anhydrous ammonia except for the fact that established fertilizer mixing plants often replace other distribution facilities or are an intermediary between the producer and distributor. As the use of liquid nitrogen fertilizers develops, there is a tendency for a greater percentage of the liquids to go directly from the producer to bulk distributors.

Probably any of these liquids can be purchased from a primary producer by a farmer or group of farmers having storage facilities for a carload or more of the product. Such purchases can be made during the slack season and at off-season prices. The privately owned storage tank is located in some cases at a bulk distribution plant rather than on the farm. The distributor charges a small fee for maintaining the equipment, for assuring the farmer of an adequate supply of liquid fertilizer when needed, and for transferring the liquid to the farmer's equipment.

These liquids are applied to the soil by custom applicators or by the farmer. According to Lowe (122) custom application has been used to develop new market areas. This method is still one of the principal means of applying liquid nitrogen fertilizer on farms, but Smith (174) states that there is a distinct trend among farmers having more than 200 acres of cropland to purchase or rent an applicator.

The operator of a custom application service provides over-the-road transport and field tanks and application equipment. He contracts with the farmer to fertilize his fields at the desired time and rate of application. Bulk distributors often supply the custom service. The cost of this service depends on the method of application—whether the liquid is applied on the soil, below the surface of the soil, or in irrigation water—and on the texture of the soil. The cost of application in some cases is included in the price of the nitrogen.

In the trend away from custom application, a farmer or a group of farmers may purchase or rent an applicator. The distributor then may service the equipment and supply the fertilizer to farm-storage facilities or provide it in small tanks that are left on the farm until empty. The

empty tanks are picked up for servicing and refilling by the bulk distributor. The farmer saves some cash expenditures and is able to apply his fertilizer at the most advantageous time. The distributor avoids the expense of a large inventory of applicators for limited seasonal use.

There are no Federal regulations covering the sale of fertilizer, but there are State fertilizer laws. Connor (63) summarizes the scope and the fee and labeling provisions of the fertilizer control statutes of each State. The statutes are enforced by State fertilizer control officials and, in general, govern labeling and tax and registration fees and prescribe plant nutrient standards for commercial fertilizers. For complete information on laws relating to the fertilizer industry, the manufacturer should consult the latest statutes of the several States in his marketing area.

STORAGE AND HANDLING

Storage

Anhydrous ammonia storage at producing points is provided usually by hortonspheres (fig. 2), with capacities ranging up to several hundred

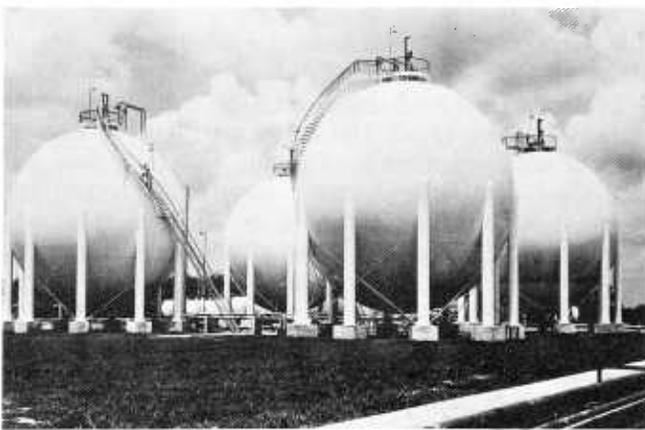


FIGURE 2.—Hortonspheres for the bulk storage of anhydrous ammonia. Courtesy of Lion Oil Co.

thousand gallons. Hortonspheres are used by a few bulk distributors. High-pressure cylinders and horizontal tanks (figs. 3 and 4) are also used for storage by some manufacturers and by most bulk distributors. Some anhydrous ammonia is stored by the producers in the form of aqua ammonia and regenerated for shipment.

The hortonspheres are large spherical tanks with moderately low working-pressure designs. They are provided with a refrigeration unit to guard against excessive pressure. As the ammonia vaporizes within the sphere, a compressor draws off the vapor, compresses it into a liquid, and returns it to the sphere. Insulated spheres are used in some cases.

Aqua ammonia is generally stored by the producers and bulk distributors in low-pressure,

vertical tanks. Small quantities can be kept in drums and carboys.

Storage at producing plants for nitrogen solutions containing ammonia, except aqua ammonia, is almost negligible. The solutions are blended and loaded directly into tank cars for shipment. Where storage is provided, several low-pressure or high-pressure horizontal tanks—depending on the vapor pressure of the solution—are favored because of the number of different solutions produced. The tanks enable the producer to stock different solutions and to fill orders for various types of solution immediately.

Permanent storage facilities for nitrogen solutions at bulk distribution centers consist of either 30,000-gallon pressure tanks or batteries of tanks with capacities as small as 6,000 gallons. The bulk distributor will also have portable tanks with capacities of 500 to 1,000 gallons. These are used to carry the solutions out to the field where they are left until emptied by the farmers. The portable tanks can be used for storage during the off season either on the farm or at the distribution center. Storage at bulk distribution centers is sometimes supplemented by farm storage. The most popular size of farm storage tank has a capacity of 1,000 gallons (147).

The nonpressure nitrogen solutions can be stored in vertical tanks. Some consideration has been given to sunken concrete tanks or cisterns for storing nonpressure solutions, but such storage is not commonly used.

The minimum storage capacity at a bulk plant should be about 12,000 gallons or large enough to receive a tank-car shipment before the storage facilities are completely empty. Optimum capacity should be adequate for storing a good proportion of the material that will be used for spring application. The storage required will depend on the length of the fertilizer season and the volume



FIGURE 3.—High-pressure storage and transfer tanks for anhydrous ammonia at a large bulk distribution plant. Courtesy of Mid-South Chemical Corp.

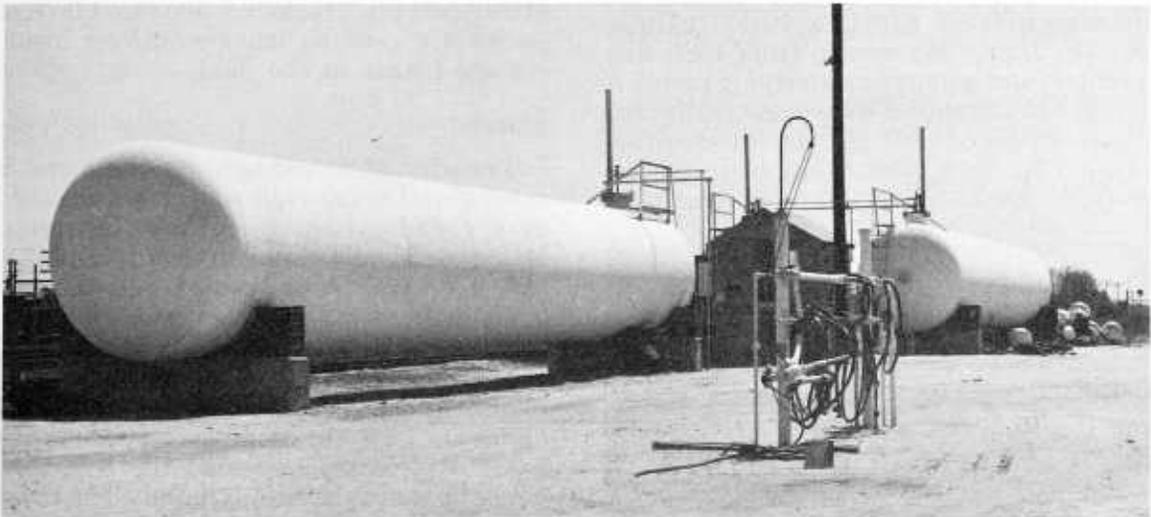


FIGURE 4.—Stationary 30,000-gallon tanks for storing anhydrous ammonia.

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of business handled by the company. Local storage is a prerequisite, since the producers do not have sufficient storage capacity nor are the railroads equipped to take care of the peak load in the spring. Also, during periods of nitrogen shortages, sales contracts have required that deliveries had to be accepted in equal periodic shipments over the year. Storage facilities can be filled during the off season when prices may be lower than during the fertilizer season.

Transportation

Anhydrous ammonia is transported in bulk and in cylinders. The major part moves out of producing plants in high-pressure, insulated tank cars with capacities of 10,000 gallons (149, 176, 177). Deliveries are also made in 6,800 gallon high-pressure tank trucks (177). Smaller trucks are used for movements between the bulk distributor and farmer. The essential equipment and proper use of trucks for transporting ammonia are discussed in some detail by Tucker (191).

Some producers of anhydrous ammonia ship a part of their output by water. The first bulk shipment by water was made in 1954 (3) in an ocean-going barge, which is shown in figure 5. The vessel has a capacity of 1,680 tons and the ammonia is carried in 7 under-deck and 2 on-deck tanks (7). Welded anhydrous ammonia barges (fig. 6) are also used. They are a hopper-type barge, in which a battery of six pressure tanks has a capacity of 400,000 gallons of anhydrous ammonia (6, 72).

Anhydrous ammonia used in irrigation water is trucked to the field in cylinders containing 25 to 150 pounds of ammonia. The cylinders are unloaded on the banks of the irrigation ditches and are ready for use when the water is turned in.

Producers normally ship aqua ammonia in tank cars with capacities of 6,000 to 10,000 gallons (148, 149, 176, 177). Movement from bulk distribution centers and ammonia conversion plants is by tank truck. Preference is shown, generally, for tanks with capacities of 1,000 gallons for over-the-road hauls, but in some cases tanks with 3 times this capacity are used. Water-borne tankers were



FIGURE 5.—Ocean-going barge for transporting anhydrous ammonia. Courtesy of Shell Chemical Corp.

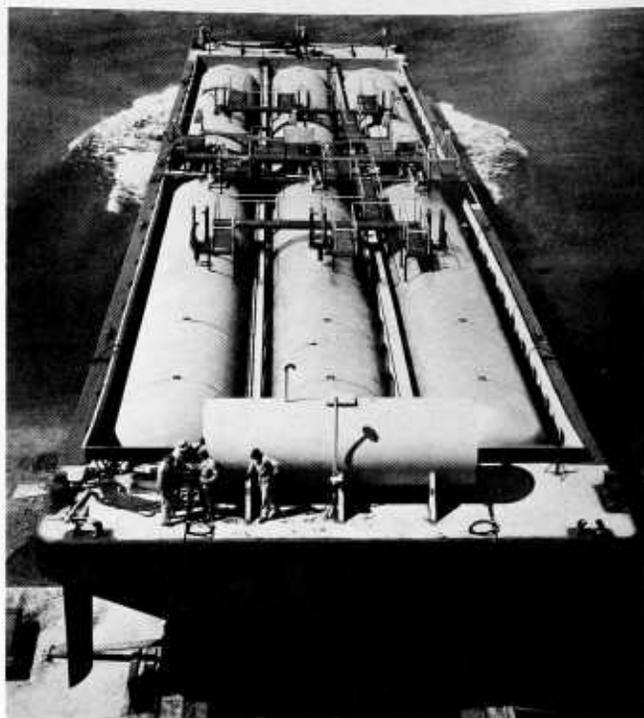


FIGURE 6.—Welded barge for transporting anhydrous ammonia. Courtesy of Ingalls Shipbuilding Corp.

first used in 1953 (2) for bulk shipments of aqua ammonia from California to Hawaii. The capacities of the tankers ranged from 5,000 to 42,000 gallons.

Producers commonly ship the nitrogen solutions containing dissolved salts in 10,000-gallon insulated tank cars. Some shipments are made in transport trucks carrying 1,000 to 3,000 gallons of solution. Low-pressure equipment is used except in the case of solutions with elevated vapor pressures. Such solutions require high-pressure tanks. Mobile supply trucks of 500- to 1,000-gallon capacity are used to move solutions from dealer's storage plants to the field.

Transfer

Transfer of anhydrous ammonia and the pressure solutions between containers should be made in a closed system to prevent loss of nitrogen. Many commercial brochures (61, 75, 147, 148, 149, 153, 180, 185) give layouts and descriptions of transfer systems for the various types of liquid nitrogen fertilizers.

Anhydrous ammonia is transferred at bulk plants by means of compressors, vaporizers, or under its own vapor pressure. Compressors are used to force the vapor of the receiver into the vapor space of the supply tank. The pressure differential forces the liquid ammonia into the receiver. The same result is achieved with a vaporizer that builds up the pressure differential through the application of heat to the liquid. The normal vapor pressure of the liquid is also used to transfer anhydrous ammonia.

Anhydrous ammonia is transferred in the field by connecting the tractor and delivery tanks with vapor-return and liquid delivery lines. The valves are opened on these lines and the pressure differential between the tanks is adjusted to approximately 10 pounds per square inch by regulating the opening in the vapor valve of the tractor tank. When the tractor tank is 85 to 90 percent full, a white fume escapes from the vapor line. Loading is then complete and the valves are closed.

Bulk transfer of nitrogen solutions is made by gravity, solution pumps, or compressed air. Gravity transfer is made through bottom outlet valves that should be screened to prevent clogging

of the tank outlet. Solution pumps are generally used for moving nonpressure solutions, but they can also be used with negligible losses of nitrogen for low-pressure solutions. Air pressure is the most popular means of moving nitrogen solutions despite the hazard of forming explosive air-ammonia mixtures.

The nitrogen solutions are transferred from transport or storage tanks to applicator tanks by hand pump, power takeoff pumps, and gravity or by means of the vapor pressure of the liquid. The vent valve of the applicator tank is open during filling and the appearance of a white fume at the vent indicates the tank is 85 to 90 percent full.

APPLICATION METHODS AND EQUIPMENT

Liquid nitrogen fertilizers are applied to the soil by subsurface and surface application and through sprinkler and surface irrigation. All these methods can be used for applying the non-pressure solutions. Ammonia and the pressure solutions generally are applied below the surface of the soil or through surface irrigation.

Subsurface applications are most effective on soils in good tilth. Liquids are applied in this manner as a preplant application and as a source of supplemental nitrogen for row crops.

Surface applications of nonpressure solutions can be made on stony soils with a minimum loss of nitrogen. Nitrogen can be applied to sod and close-growing crops by this method. Spray applications are particularly adapted to sandy soils and can be used for most major crops. This method of application is used also to feed plants through their leaves. Surface irrigation is an effective means of applying liquid nitrogen fertilizers to row crops, including truck crops, tree fruits, small fruits, and vineyards, growing on loams and clay loams.

Subsurface Application

Subsurface application is the principal method of applying the liquid nitrogen fertilizers characterized by a positive vapor pressure. Anhydrous ammonia and the pressure solutions are injected 4 to 8 inches below the surface of the soil to the sides of narrow furrows. The furrows are closed immediately after the application to minimize nitrogen losses by sealing in the gaseous ammonia. Nonpressure solutions can be applied in the same manner.

The basic application equipment consists of a tank, metering device, distributor manifold, hoses, and applicators. There are numerous types of equipment, and some of these have been described by Barr (32) and Andrews (25, 27). The three major assemblies used for applying anhydrous ammonia to the soil are (1) tractor mounted, (2) a trailing unit, and (3) a semimounted unit sup-

ported by both tractor and trailing unit. The units (fig. 7) consist essentially of a tank, metering mechanism, and soil tools. The soil openers are usually mounted on a cultivating-type tool bar with special soil-knife applicators. Figure 8 is a schematic drawing of this type of equipment, and the details of the applicator blade are shown in figure 9.

The liquid is forced from the regulator into a compact manifold fitted with orifices to apportion the liquid to the applicators. The applicator blades are steel and are usually curved forward so the toe of the blade is ahead of the shank. This facilitates the shedding of trash. The blades are either heat-treated or hard-surfaced to resist abrasion. Slip-on applicator boots are often used to prolong the life of the applicator knives or blades. On the back of each applicator is welded a small metal pipe through which the liquid passes into the soil. Small gas exit ports are located usually on the side of the metal pipes and close to the bottom of the cutting blade. The



FIGURE 7.—Anhydrous ammonia applicator mounted on a farm tractor.

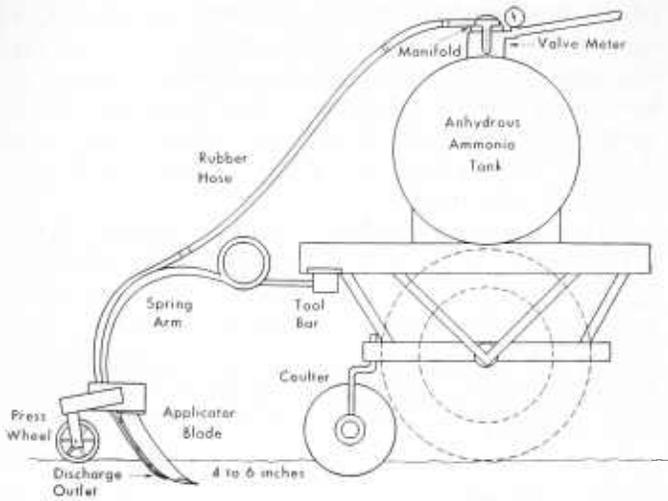


FIGURE 8.—Anhydrous ammonia applicator.

ports should not be so low that the wearing off of the knives would affect the discharge opening. The knives are attached to a tool bar with a shear pin or spring arm to prevent breakage if a resistant root or rock is encountered. Pasture applicators are often equipped with coulters ahead of the applicator knives to assist in penetration, to hold disturbance and dragging to a minimum, and to prevent clogging of the equipment. A press wheel or slide is usually located behind the

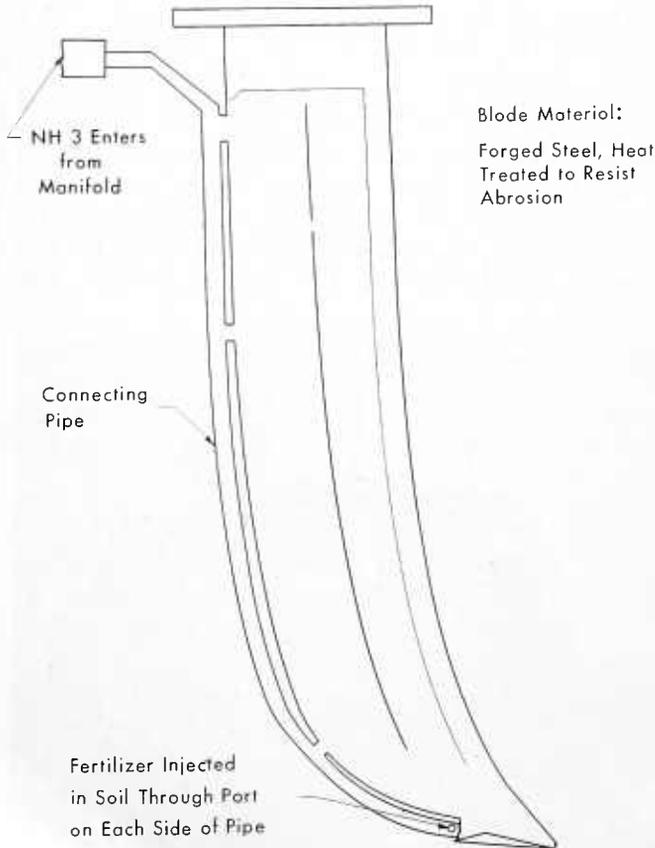
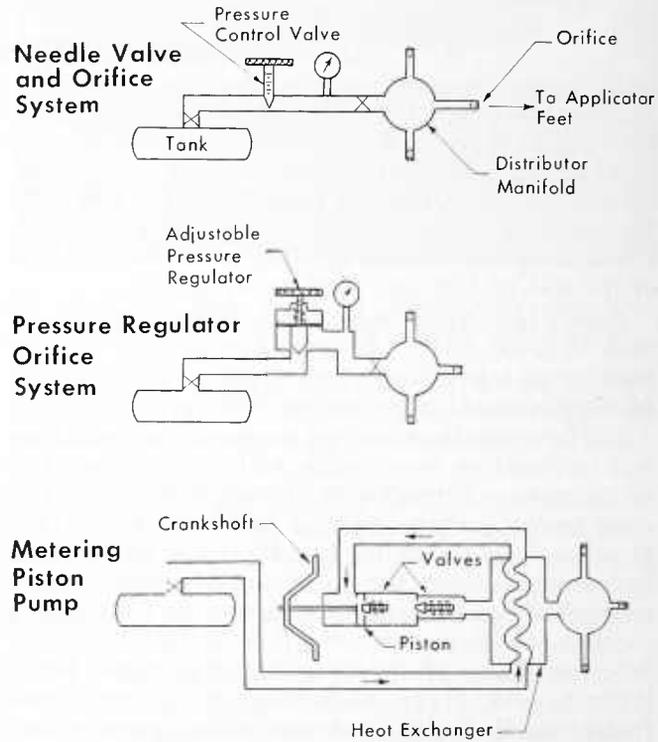


FIGURE 9.—Detail of applicator blade for anhydrous ammonia.

applicators to close the soil furrow or cut, thereby sealing in the ammonia.

The accurate metering of anhydrous ammonia requires it to be measured either as a liquid or as a gas (32). Erroneous measurements will occur if liquid-gas mixtures are metered. The practice is to measure ammonia as a liquid, and the devices currently used (fig. 10) fall into two systems—pressure and pump. Equipment should be calibrated with the same liquid, same size of hose and manifold, and same type of applicator knife or blade that will be used in the field. Calibration data and directions for any metering device are normally provided by the manufacturer.



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FIGURE 10.—Common methods of metering anhydrous ammonia.

The amount of liquid delivered by the pressure systems per linear unit of travel of the distributor is dependent on the gage pressure of the contained liquid, orifice size, static line pressure, and speed of the applicator rig. The rate of application for a given tractor speed is determined by the size of the orifice and the liquid pressure exerted. Barr (32) shows examples of these relations for one type of automatic control valve on implements of various widths. A uniform pressure and a constant speed of travel are necessary to maintain a uniform rate of application.

Methods of controlling the pressure are shown in the upper two drawings of figure 10. Pressure is controlled in the needle valve-orifice system by manually adjusting the valve as other factors vary. The automatic differential pressure regulator in the other system can be set in the morning

to deliver a given quantity of liquid per hour and will not have to be reset during the day.

The pump system for metering anhydrous ammonia consists of a variable stroke displacement pump and heat exchanger, as shown in the lower drawing of figure 10. The metering pump is driven from the rear axle of the tractor or from one of the wheels of a trailer applicator. The length of the stroke controls the quantity of liquid entering the distributor manifold. After a desired rate of application has been calibrated for a ground-driven displacement pump, the rate per acre is fairly constant, regardless of the speed or change of speed the rig may experience while in operation. The flow of liquid stops when the rig stops. The heat exchanger cools the outgoing ammonia and prevents it from vaporizing in the pump. The principal disadvantages of ground-driven metering are the relatively high initial cost and the expense of annual servicing, which is an essential requirement of this type of equipment.

The principles governing the application of anhydrous ammonia into the soil are also applicable to the application of both the low- and medium-pressure solutions. The solutions are forced into the distributor manifold and through the applicators by air compressors or solution pumps driven by a power takeoff or geared to the drive wheel of the tractor (fig. 11). A pressure-regulating valve between the compressor and the solution

tank maintains a constant pressure in the solution tank, regardless of the quantity of solution and changes of temperature in the system. This method provides a uniform discharge rate. It has the disadvantage that air pumped into a tank containing ammonia gas may form an explosive air-ammonia mixture, although the hazard involved is less than that connected with the gas chamber in the fuel tank of the tractor.

Pump equipment for the low- and medium-pressure solutions is the most varied and generally used of all types (142). A wide variety of pumps works on the tractor power takeoff—centrifugal, diaphragm, gear, piston, roller, and others. Most models allow liquid discharge when the pump stops and require a manually operated valve to shut off the flow. The gear pump is positive in its delivery and is durable when properly constructed. Diaphragm pumps are inexpensive, positive in action, and corrosion-proof. However, a certain amount of pulsation seems almost inevitable with this type of pump.

These pumps may give uniform discharge rates, but uniform application rates are not attained unless an unvaried ground speed is maintained in the field. Their successful adaptation to ground-driven equipment has been difficult.

The variable-stroke piston pump used for the application of anhydrous ammonia can be used for the application of other pressure solutions. The



FIGURE 11.—Application of aqua ammonia to the soil.

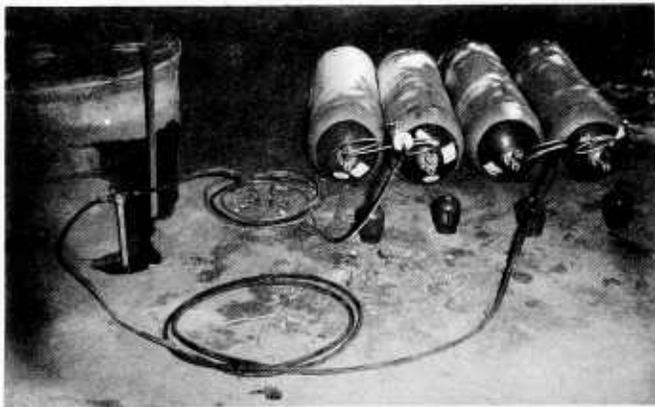
rate of application of this pump is uniform, regardless of throttle or gear changes of the prime mover of the field equipment, and its use is recommended for small fields or irregular terrains. Its use, however, is limited by its higher initial cost and greater corrosion hazards.

Surface Application

Liquid nitrogen fertilizers are applied to the soil in surface irrigation water and by various liquid-dispensing systems, including spray and sprinkler systems. Any of the liquids can be applied in flood and ditch irrigation water, whereas the nonpressure solutions are customarily the only ones applied in sprinkler irrigation water. Dilute aqua ammonia has been applied successfully by spray irrigation (157), and diluted low-pressure solutions have been dribbled onto the surface of the soil or into open furrows. Dilute solutions are also sprayed on the foliage of plants for the purpose of having the nitrogen absorbed through the leaves. If the solutions are too concentrated, they will burn the foliage unless washed off with fresh water.

Care must be taken in applying pressure liquids in irrigation water, as excessive quantities of nitrogen may be found near the water inlet on soils with high infiltration rates. The ammonia of the pressure solutions also causes objectionable calcium carbonate deposits on the pipes and valves of irrigation systems using hard water (109, 164). The deposits can be prevented by adding sodium hexametaphosphate to the irrigation water ahead of the point where the ammonia is introduced. Jordan (109) states that $1\frac{2}{3}$ ounces of dry hexametaphosphate will inhibit calcium carbonate deposition in 100 gallons of water of 1 grain hardness (17.1 p.p.m. of dissolved calcium).

Anhydrous ammonia is metered from cylinders into the irrigation water under its own pressure. The cylinders are laid horizontally on the ground adjacent to the head ditch or standpipe (fig. 12). The ammonia from a single cylinder or a manifold connecting two or three cylinders is measured into

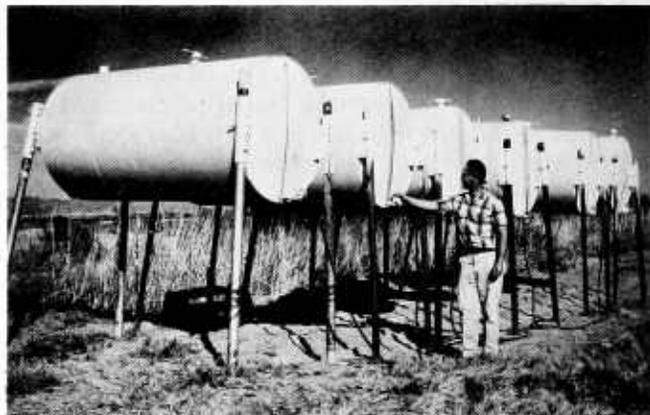


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FIGURE 12.—Application of anhydrous ammonia to irrigation water in California.

the irrigation water through a hose connected to a metering orifice. The rate of flow through the orifice is controlled by the orifice size and the ammonia pressure, which is regulated, in turn, by a control valve.

The pressure and nonpressure solutions can be added to surface irrigation water by gravity. The solutions are carried out to the fields in tanks equipped with extensible legs. The tanks are set up adjacent to the irrigation water, as shown in figure 13. A manually operated control valve regulates the flow of solution through a rubber hose into the water. Atmospheric pressure is maintained in the tank by venting it to the air. Nitrogen losses through the vent are negligible, even when pressure solutions are applied in this manner.



BN-12039

FIGURE 13.—Gravity application of nonpressure liquid nitrogen fertilizers to irrigation water.

Nonpressure nitrogen solutions are added to the water of sprinkler systems by two methods—gravity and differential pressure (147). In the gravity method a valve inlet is installed on the suction side of the water pump, and after irrigation begins the valve is opened sufficiently for the fertilizer solution to be drawn into the system. The differential pressure method requires a restricting orifice in the water pipeline. Valves are tapped into the pipe on each side of the orifice. The valve on the entrance side of the orifice is connected to a vent valve on the liquid fertilizer container, and the valve on the exit side of the orifice is connected to the discharge valve of the container. Water passing through the orifice builds up a pressure differential that draws the solution out of the tank. The desired withdrawal rate is obtained by adjusting both valves.

Nonpressure solutions are applied directly to the soil through spray booms. The solutions can be fed to the boom by many of the metering systems used in subsurface application and by gravity.

A simple, open-gravity system will have a relatively uniform liquid pressure at the discharge nozzle or orifice if the discharge opening of the tank is at least 4 feet above the orifice. Gravity kits have four or more orifice sizes for different

discharge rates (5). After an orifice has been selected, the final adjustment of the rate of application is made by varying the tractor speed with the throttle. A float chamber between the supply tank and the discharge orifices may be used to maintain a constant hydraulic head independent of the amount of liquid in the tank. The principle is similar to that of the float chamber in a cream separator.

Futral and others (88) describe a closed-gravity system that eliminates fluctuations in the rate of liquid flow caused by changes in the height of liquid in the container. A representative layout consists of a closed container with an air-intake pipe open to the air at the top of the container and extending down to a point near the bottom. The liquid is drawn from the bottom of the tank through a cutoff valve in line with a needle valve or orifice that regulates the rate of flow. The hydrostatic pressure at the needle valve is the pressure exerted by the height of liquid from the orifice to the bottom of the intake pipe.

In the early 1940's, a metering hose pump was adapted to the application of nonpressure liquids at the University of Tennessee (170). Pump modifications worked out by ARS research engineers in 1953 and 1954 led to commercial production of the pump for farm use (90, 91). The pump (figs. 14 and 15) consists essentially of a 4-bar rotating reel with a series of flexible hoses mounted on the reel in the form of an inverted "U". Contact of the bars with the hose closes the tubes, and the open tubes between the contact points form pockets that contain the liquid. As the reel rotates, the liquid in the pockets is forced forward in each hose line. The rate of application is governed by the reel speed in relation to ground travel. As the machine slows or stops, the flow of liquid slows or stops automatically. There is no contact between the solution and the rotating mechanism. This pump can deliver liquid through 1 to 12 outlet hoses.

Any rate of application of the metering hose pump is uniform, regardless of throttle or gear

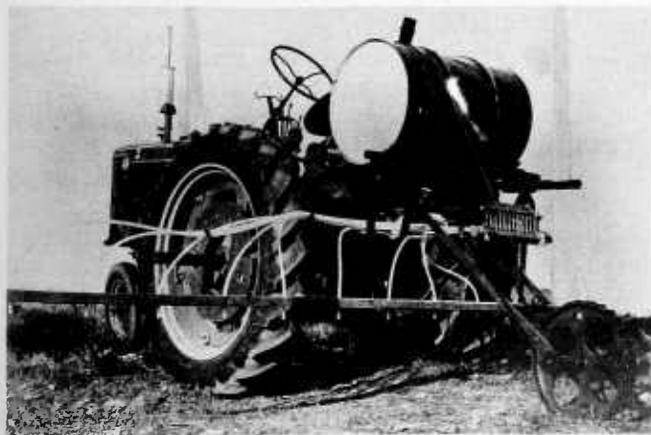
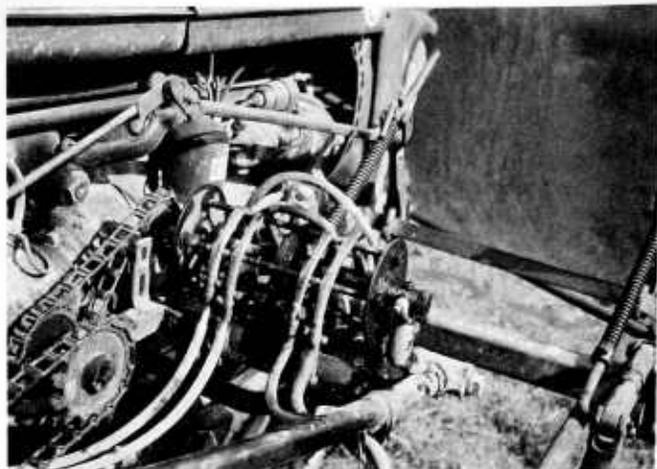


FIGURE 14.—Assembly, showing metering hose pump and wooden boom for broadcasting nonpressure solutions.



BN-12044

FIGURE 15.—Closeup of metering hose pump.

changes of the primary mover of the field equipment. The pump can also be used for subsurface applications.

Nitrogen Losses During Application

Nitrogen losses during application of liquid nitrogen fertilizers are due primarily to the ammonia vapor pressure of the liquids. The nitrogen salts in the solutions exert no vapor pressure and are not subject to loss. Ammonia losses can be minimized by the use of proper application equipment and good management practices. Dilution of the pressure solutions before application will aid in reducing nitrogen losses.

Ammonia gas may escape from the pressure liquids along the sides of the soil openers or from the furrows before they are closed. Additional losses may occur when the pressure liquids are applied to soils with low infiltration rates. Some evaporation of ammonia will occur from irrigation water to which pressure liquids are being added.

Losses of ammonia from irrigation water vary greatly. Rosenstein (161) stated that loss by evaporation is negligibly small at a concentration of 109 p.p.m. of ammonia in water. Chapman (59) calculated from experimental data that losses of ammonia from water containing 50 p.p.m. of ammonia-nitrogen would be less than 10 to 12 percent under most conditions. Losses may exceed 26 percent under conditions of high water temperature and very low soil permeability. Babcock (30) found that a solution containing 107 p.p.m. nitrogen, as ammonia, lost 80.2 percent of the nitrogen in traversing a distance of 540 feet in 30 minutes through an open concrete flume. A study by Sokoloff (179) indicated that losses of ammonia from irrigation water can be minimized by (1) irrigating on cool, humid, quiet days; (2) maintaining a concentration of not over 110 p.p.m. of ammonia; and (3) keeping the exposed surface of flowing water to a minimum by

reducing the turbulence of the water and by using narrow, deep ditches.

Rayburn (157) considered nitrogen losses negligible when water containing 30 to 40 p.p.m. of ammonia was applied to the soil through a sprinkler system. Henderson, Bianchi, and Doneen (97) determined the ammonia losses between the time aqua ammonia left a revolving sprinkler head and was caught in a receptacle. The losses from alkaline irrigation water solutions containing 50 and 100 p.p.m. of ammonia were 45 and 55 percent, respectively. Similar tests in alkaline irrigation water were made with solutions containing 25, 50, 100, and 300 p.p.m. of ammonia in the form of either ammonium nitrate, ammonium phosphate, or ammonium sulfate. Losses at the various concentrations were 10, 6, 4, and 0.5 percent, respectively, for ammonium nitrate and ammonium phosphate and 25, 12, 8, and 3 percent for ammonium sulfate. Ammonia losses decreased with decreasing alkalinity of the fertilizer-irrigation water solution and were negligible for neutral or acid solutions.

The work of Jackson, Alban, and Wolfe (103) also shows that appreciable amounts of nitrogen

are lost as aqua ammonia travels from the sprinkler head to the soil. Samples of solution were caught in basins set 10, 20, and 30 feet from the sprinkler head and the ammonia losses determined. The results, given in table 14, show that the greatest loss takes place near the sprinkler head and decreases with distance. Presumably, loss near the sprinkler head can be associated with droplet size, since a larger proportion of small drops fall near the sprinkler.

TABLE 14.—Ammonia losses during sprinkler application¹

Water source and concentration of ammonia (NH ₃) applied (pounds per acre-inch)	Ammonia loss at following distances from sprinkler head		
	10 feet	20 feet	30 feet
Ponded river water, 70° F.:			
9.0.....	Percent 33.3	Percent 25.7	Percent 20.0
11.0.....	41.9	40.6	34.9
19.5.....	48.4	47.4	43.4
25.5.....	60.2	57.5	45.9
Well water, 52° F.:			
11.5.....	26.4	24.0	21.7
18.5.....	36.9	30.6	25.1
25.5.....	50.4	44.7	35.4
38.5.....	47.4	44.4	36.0

¹ Data from Jackson, Alban, and Wolfe (103).

LIQUID NITROGEN FERTILIZERS IN THE SOIL

Many agronomic factors governing the use of solid nitrogen materials also apply to the use of the liquid forms. The effective use of the liquids depends on many things, including climatic conditions, type of soil, crop to be fertilized, and topography, size, and other physical characteristics of the farm or field. There is no single liquid nitrogen fertilizer that is best suited for all conditions.

Nitrogen Sorption

Retention of the ammonia in the pressure liquids is difficult in certain soils and the higher the ammonia concentration the more difficult it becomes. The sandier soils do not retain ammonia so effectively as the soils with high clay or organic matter content unless there are compensating factors, such as increased depth of application or increased soil moisture content. The finer textured soils are generally best adapted to the use of the high pressure solutions, although all agricultural soils will retain the greater portion of the nutritive value of the fertilizers. Nitrate-nitrogen, however, will leach badly under heavy rainfall when nonpressure solutions are applied to the surface of sandy soils.

The nitrogen in liquid nitrogen fertilizers is sorbed by the soil in either the ammonium (NH₄) or nitrate (NO₃) forms. The ammoniacal nitrogen in the solutions is present as ammonium hydroxide or as ammonium salts and is sorbed by the soil as the ammonium ion. Anhydrous ammonia applied directly to the soil, combines with

the soil moisture to form the hydroxide and then is sorbed as ammonium ion. Allison (17) reports limited experiments showing that anhydrous ammonia and ammonium salts produced the same quantities of fixed ammonium when added to soils of high ammonium-fixing capacity. The urea-nitrogen, according to Couturier and Perraud (65), is converted to ammonium-nitrogen rapidly and held by the soil in that form. Experimental results show that under ideal conditions of temperature and moisture only 10 or 20 percent of the ammonium fixed in the soil is available to plants during the first 6 months. Under different conditions and on different soils, about 90 percent was available within a period of 3 months (17). The nitrate-nitrogen in the solutions is sorbed in readily available form.

Liquid nitrogen fertilizers hasten the decomposition of plant residues in the soil. Part of the nitrogen is fixed by bacteria, fungi, and other organisms active in the decomposition process. This fixed nitrogen is only slowly available to crops.

The movement and retention of liquid nitrogen fertilizers in the soil is markedly affected by soil texture. The critical constituent of the liquids in this regard is ammonia, and considerable research work has been done on its behavior in the soil. McDowell and Smith (125) studied the movement of ammonia in three soils under laboratory conditions. The ammonia was applied at the rate of 100 pounds of nitrogen per acre in 40-inch spacing. The treated soils were stored for 2

months at 25° C., with the moisture levels being maintained at 70 percent of water-holding capacity. The ammonium- and nitrate-nitrogen levels were determined at the end of the storage period. The results are given in table 15. Comparable results were obtained by Stanley and Smith (181). Blue and Eno (44) made field applications of ammonia on Arrendondo loamy fine sand in rows 5 inches below the surface and 13.5 inches apart at rates of 58, 115, and 258 pounds of nitrogen per acre. The added nitrogen spread to a maximum distance of 8 inches from the point of injection, and the major portion was retained in an area 6 inches wide.

TABLE 15.—Distribution of ammonium- and nitrate-nitrogen at various distances from injection point of anhydrous ammonia¹

Distance from injection point (inches)	Concentration					
	Dexter fine sandy loam		Putnam silt loam		Houston black clay	
	Ammonium-N	Nitrate-N	Ammonium-N	Nitrate-N	Ammonium-N	Nitrate-N
0-1.....	<i>P. p. m.</i> 368	<i>P. p. m.</i> 669	<i>P. p. m.</i> 312	<i>P. p. m.</i> 913	<i>P. p. m.</i> 182	<i>P. p. m.</i> 1578
1-2.....	171	402	89	533	45	497
2-3.....	16	133	4	52	2	51
3-4.....	5	7	2	26	-----	-----
(2).....	3	5	4	29	4	29
Percent recovery of total nitrogen.....	93.9		80.2		72.6	

¹ Data from McDowell and Smith (125). The soils received nitrogen at the rate of 100 pounds per acre in 40-inch spacing and were stored for 2 months at 25° C. at a moisture level of 17 percent.

² No anhydrous ammonia added.

Sohn and Peech (178) determined the quantity of ammonia retained by representative New York State soils. Air-dry soil in a glass bottle was treated with gaseous ammonia until the soil was saturated. The saturated soil was stored overnight in an atmosphere of ammonia in the stoppered bottle. Part of the ammoniacal soil was allowed to aerate for 1 week, to remove physically absorbed ammonia. The amounts of ammonia taken up and fixed by the soils then were determined. Some of the results, given in table 16, show that the interaction between ammonia and soil matter is important in the sorption of ammonia by surface soils. The muck soils retained more ammonia than the mineral soils. Retention was also related to the soil pH. Acid soils containing large amounts of organic matter fixed the largest quantities of ammonia, with alkaline mineral soils sorbing and fixing much lesser quantities.

Allison and associates (18) have shown that the clay minerals, in addition to soil pH and organic matter content, have a marked effect on ammonia fixation in soil. Considerable moist fixation of ammonium-nitrogen may occur in soils high in illite or vermiculite, and the fixation is increased by drying and heating. Montmorillonitic clays fix little nitrogen unless heated. Surface

TABLE 16.—Sorption and fixation of ammonia by New York soils¹

Soil type	pH of original soil	Organic matter ²	Ammonia	
			Uptake ²	Fixed ²
		<i>Percent</i>	<i>Meg. per 100 g.</i>	<i>Meg. per 100 g.</i>
Dunkirk silt loam.....	7.15	2.54	4.89	0.94
Do.....	4.20	2.30	10.7	1.40
Honeoye silt loam.....	6.62	3.15	7.83	1.34
Do.....	4.25	3.04	13.9	2.17
Mardin silt loam.....	7.25	3.18	7.50	2.01
Do.....	5.68	3.15	12.8	2.06
Do.....	5.05	3.38	15.0	3.46
Do.....	4.70	4.15	17.7	3.62
Do.....	4.10	3.50	22.2	5.31
Sassafras fine sandy loam.....	6.52	2.37	8.02	1.16
Do.....	3.92	2.14	11.5	1.83
Anderson muck.....	4.90	90.7	115.6	21.9
Dryer muck.....	6.10	77.7	60.0	12.4
Woody muck.....	4.90	63.2	126.3	22.0

¹ Data from Sohn and Peech (178).

² Moisture-free basis.

soils fix less ammonium than the subsoils. This is probably caused by the interfering effect of organic matter and to the fact that the fixing capacity of the surface soil has already been satisfied by potassium and ammonium.

The importance of soil moisture in the fixation process appears to be related to the solubility of ammonia in the soil solution. McDowell and Smith (125) found the soil water to hold considerable ammonia and that movement of the water exposed the ammonia to a greater volume of soil. Laboratory studies by Blue and Eno (44, 45) showed that the quantity of ammonia held in sandy soils increased with increasing moisture content. The increased quantity was apparently in water solution, since, upon drying, the ammonia content was no greater than if the ammonia had been applied to the dry soil. Field applications showed no correlation between fixation and soil moisture content.

Effect of Soil Properties and Population

Although a temporary increase in the soil pH results from applications of anhydrous ammonia and solutions containing ammonia, the ultimate effect of the application of liquid nitrogen fertilizers is an increase in soil acidity. The magnitude of the potential acidity of the liquids is shown in table 5. Laboratory experiments by Burgess and Hawkins (53) showed that anhydrous ammonia might raise the soil pH initially as high as 9.5. Ayres and Humbert (29) found that the addition of 1,500 p.p.m. of nitrogen in the form of aqua ammonia increased the pH of Onomea and Waialua soils from 5.0 to 7.1 and 8.0, respectively, and a calcareous soil from approximately 8.0 to 10.5. As nitrification of the ammonia proceeded, the pH gradually dropped below the value exhibited originally.

From time to time, any excess acidity resulting from the use of liquid nitrogen fertilizers must be counteracted by liming, to maintain the soil pH

values at their most efficient level for crop production. This is a major problem in some localities where even the subsoils are becoming acid from deep injections of ammonia. Tiedjens and Robbins (187) and Blue and Eno (46) state that ammonium-nitrogen is absorbed by plants most rapidly in the pH range 7.0 to 8.0 and nitrate-nitrogen in the pH range 4.0 to 5.0. Very little ammonium-nitrogen is absorbed by plants at pH 4.0. In general, a soil pH of 6 to 8 would appear to be the most satisfactory for the use of liquid nitrogen fertilizers.

The ammonia in the liquid nitrogen fertilizers has a stimulating effect on nitrification, as shown by Eno and Blue (81). The results obtained by applying appropriate amounts of ammonium sulfate and ammonia to a Leon fine sand and incubating it at 82.4° F. are given in table 17. The original reaction of the soil was pH 5.1. Maximum nitrification occurred when the reaction after treatment was approximately 9.0 for both the limed and unlimed soil. Higher initial pH values, obtained by adding larger quantities of ammonia, inhibited the activity of the nitrifiers. The results in table 18 show that equivalent amounts of nitrogen applied to Leon fine sand in the form of urea or anhydrous ammonia affect nitrification in a like manner. Other workers (51, 76, 79, 80, 82, 87) report ammonia levels in the center of the application zone are high enough to

exert a toxic effect on the nitrifying bacteria. Nitrate production proceeds from the periphery of the concentrated area toward the center. As nitrification continues, the pH is reduced and the ammonia is converted completely to nitrate.

Ammonia also has a toxic effect on other members of the microbiological population of the soil. Eno and his coworkers (79, 82) studied the effect of anhydrous ammonia applications on fungi, bacteria, actinomycetes, and nematodes in sandy soils. Applications of 100 pounds of nitrogen per acre reduced the number of fungi, bacteria, and actinomycetes (table 19). The toxic effects were restricted to a 3-inch zone around the injection point. Reduction in the number of bacteria and actinomycetes persisted for less than 3 days, whereas the depressing effect on fungi lasted for at least 38 days.

The toxic effect of ammonia increases with concentration (table 20). Nematode and fungi populations were reduced by all concentrations of ammonia applied. Application of 608 p.p.m. of nitrogen as ammonia was toxic to all but 0.6 percent of the nematodes and 4.9 percent of the fungi. Concentrations of this magnitude are attained in anhydrous ammonia application zones.

The ammonia in the liquid nitrogen fertilizers also influences the availability of other soil nutrients. Stanley and Smith (181, 182) applied anhydrous ammonia to a silt loam at the rate of 100

TABLE 17.—Nitrification rates of anhydrous ammonia and ammonium sulfate in limed and unlimed Leon fine sand and changes in pH soil¹

Time after fertilizer added and quantity of ammonia-N	Ammonium sulfate						Anhydrous ammonia					
	No lime			2 tons of lime			No lime			2 tons of lime		
	Nitrate-N		pH	Nitrate-N		pH	Nitrate-N		pH	Nitrate-N		pH
	Quantity	Portion of added N		Quantity	Portion of added N		Quantity	Portion of added N		Quantity	Portion of added N	
P.p.m.	Percent		P.p.m.	Percent		P.p.m.	Percent		P.p.m.	Percent		
Initial day for—												
0 p.p.m.			5.1			7.6			5.1			7.6
92 p.p.m.			4.1			7.9			6.1			8.6
203 p.p.m.			3.9			7.9			7.8			9.1
380 p.p.m.			4.1			7.8			9.1			9.5
780 p.p.m.			4.0			7.8			9.6			9.8
At 14 days for—												
0 p.p.m.	0		5.3	0		6.9	0		5.3	0		6.9
92 p.p.m.	0	0	4.6	0	0	6.0	0	0	6.5	0	0	7.5
203 p.p.m.	0	0	4.5	0	0	5.9	0	0	7.0	0	0	7.8
380 p.p.m.	0	0	4.5	0	0	5.8	4	1.1	7.8	4	1.1	8.2
780 p.p.m.	0	0	4.3	0	0	5.7	2	0.3	8.7	0	0	8.8
At 28 days for—												
0 p.p.m.	0		5.3	16		5.8	0		5.3	16		5.8
92 p.p.m.	0	0	4.4	0	0	5.9	0	0	6.1	84	73.9	5.0
203 p.p.m.	0	0	4.4	0	0	5.8	27	13.3	6.5	106	44.3	5.2
380 p.p.m.	0	0	4.3	0	0	5.8	95	25.0	6.0	30	36.83	6.9
780 p.p.m.	0	0	4.2	0	0	5.9	0	0	8.6	3	0	8.1
At 42 days for—												
0 p.p.m.	4		4.8	37		5.3	4		4.8	37		5.3
92 p.p.m.	0	0	4.6	31	0	5.2	33	31.5	5.7	100	68.5	4.6
203 p.p.m.	0	0	4.4	25	0	5.1	58	26.6	5.1	130	45.8	4.7
380 p.p.m.	0	0	4.4	8	0	5.4	119	30.3	5.5	74	9.7	6.2
780 p.p.m.	0	0	4.2	9	0	5.5	19	1.9	7.8	18	0	7.5
At 63 days for—												
0 p.p.m.	21		4.2	50		5.2	21		4.2	50		5.2
92 p.p.m.	0	0	4.6	77	29.3	4.5	48	29.3	4.8	97	51.1	4.7
203 p.p.m.	0	0	4.5	68	8.9	4.5	81	29.6	5.0	124	36.5	4.6
380 p.p.m.	0	0	4.3	59	2.4	4.6	116	25.0	5.4	84	8.9	5.5
780 p.p.m.	0	0	4.3	2	0	5.5	100	10.1	6.8			6.4

¹ Data from Eno and Blue (81).

TABLE 18.—Nitrification rates of urea and anhydrous ammonia in limed and unlimed Leon fine sand and changes in pH of soil¹

Time after fertilizer added and quantity of ammonia-N	Urea						Anhydrous ammonia					
	No lime			2 tons of lime			No lime			2 tons of lime		
	Nitrate-N		pH	Nitrate-N		pH	Nitrate-N		pH	Nitrate-N		pH
	Quantity	Portion of added N		Quantity	Portion of added N		Quantity	Portion of added N		Quantity	Portion of added N	
P.p.m.	Percent	P.p.m.	Percent	P.p.m.	Percent	P.p.m.	Percent	P.p.m.	Percent			
Initial day for—												
0 p.p.m.-----			5.5						5.5			
129 p.p.m.-----			5.8						6.5			
335 p.p.m.-----			5.8						7.3			
600 p.p.m.-----			5.8						8.0			
887 p.p.m.-----			5.8						8.6			
At 14 days for—												
0 p.p.m.-----	12		5.7	29		6.9	12		5.7	29		6.9
129 p.p.m.-----	65	41.1	6.2	105	58.9	6.7	73	47.3	6.0	106	59.7	6.5
335 p.p.m.-----	106	28.1	6.8	95	19.7	7.3	141	38.5	6.1	69	11.9	7.0
600 p.p.m.-----	8	0	8.8	9	0	8.7	11	0	8.4	22	0	8.5
887 p.p.m.-----	7	0	8.9	7	0	9.0	8	0	8.9	8	0	8.9
At 28 days for—												
0 p.p.m.-----	22		5.4	42		7.1	22		5.4	42		7.1
129 p.p.m.-----	84	48.1	5.0	118	58.9	5.5	112	69.8	4.8	122	62.0	6.4
335 p.p.m.-----	123	30.1	5.4	155	33.7	6.3	163	42.1	5.1	88	13.7	6.6
600 p.p.m.-----	24	.3	7.8	35	0	8.0	17	0	7.6	42	0	7.7
887 p.p.m.-----	1	0	8.8	3	0	8.8	0	0	8.7	0	0	8.8

¹ Data from Eno and Blue (81).

TABLE 19.—Net effect of anhydrous ammonia on the numbers of fungi, bacteria, and actinomycetes in loamy fine sand¹

FUNGI					
Days after treatment	Soil moisture	Numbers per gram of oven-dry soil at 2—			
		Point of injection	1 inch from point of injection	2 inches from point of injection	3 inches from point of injection
	Percent	Thou-sands	Thou-sands	Thou-sands	Thou-sands
0-----	-15.00	-2.00	-0.88	-1.13	4.2
3-----	-9.87	-5.62	-1.87	+1.00	4.4
10-----	-5.75	-6.87	-4.12	-1.75	5.3
24-----	-13.00	-7.50	0	-2.50	1.8
31-----	-6.67	-4.17	+4.50	-2.17	4.8
38-----	-20.00	-12.17	-12.60	-6.67	1.6
BACTERIA					
		Millions	Millions	Millions	Millions
0-----	-1.987	+2.350	-1.075	-0.287	4.2
3-----	+4.989	+4.189	+739	+802	4.4
10-----	+6.112	+3.162	-738	-713	5.3
24-----	+2.850	-.166	+600	+500	1.8
31-----	+1.167	+300	+3.233	+1.084	4.8
38-----	-.025	-.175	-.358	+.225	1.6
ACTINOMYCETES					
0-----	-1.062	-0.775	-0.262	-0.125	4.2
3-----	+0.049	+274	+174	-076	4.4
10-----	+1.087	+612	+138	-102	5.3
24-----	+767	+184	+084	+250	1.8
31-----	+533	+316	+200	+133	4.8
38-----	+325	+308	+192	+125	1.6

¹ Data from Eno and Blue (79); ammonia applied at a rate of 100 pounds of nitrogen per acre.

² Numbers in ammonia-treated soil minus numbers in untreated soil.

pounds of nitrogen per acre and found after an interval of 8 weeks that the soil pH had been affected to a distance of about 4 inches from the point of injection. The added ammonia increased the availability of the soil phosphorus and potassium and reduced the readily available calcium.

TABLE 20.—The effect of anhydrous ammonia on the numbers of fungi and nematodes in Arredondo fine sand¹

NH ₃ -N added (p.p.m.)	pH	Nematodes ²	Fungi ³
0-----	6.7	367	61.0
136-----	8.4	241	58.0
292-----	9.0	116	55.2
365-----	9.2	60	49.2
608-----	9.4	2	3.0
741-----	9.5	1	1.2

¹ Data from Eno, Blue, and Good (82).

² Number per 150 milliliters of moist soil.

³ Number per gram of oven-dry soil.

Total exchangeable calcium, however, was not affected.

Nitrogen Losses After Application

Most of the studies of nitrogen losses that occur after liquid nitrogen fertilizers are applied to the soil have been made with anhydrous and aqua ammonia. The possible losses incurred by the other constituents of nitrogen solutions are usually based on studies of the behavior of the different materials when applied separately.

Jackson and Chang (102) investigated the possible nitrogen losses due to the volatilization of anhydrous ammonia injected at various depths in some Wisconsin soils. A beaker containing approximately a 5-inch layer of soil was placed in a desiccator, and anhydrous ammonia was injected at the desired depths. The desiccator was repeatedly exhausted through an acid trap to collect the escaping ammonia. A 2½-minute cycle of exhaustion followed by admission of air was continued for 30 minutes. The results in table 21 show that a large proportion of the ammonia applied at the surface of soils escaped into the air. The authors conclude that a soil of intermediate texture, mois-

TABLE 21.—Loss of anhydrous ammonia nitrogen injected into Wisconsin soils¹

Soil type, treatment, pH value, and soil moisture	Losses of the added nitrogen applied at 60 pounds per acre at depths of—				
	0 inch	0.5 inch	1.0 inch	2.0 inches	4.0 inches
Beach sand:					
Air-dry	93	-----	-----	90.5	81
Field moisture (7.7 percent)	81	-----	-----	29.3	8.4
Plainfield sand:					
From cultivated field (pH 6.0)—					
Air-dry	58	-----	16.5	5.7	0
Field moisture (9.1 percent)	49	-----	6.1	0	0
Excessively limed (pH 7.7)—					
Air-dry	74	-----	27.5	17.7	0
Field moisture (9.1 percent)	53	-----	11.6	0	0
Crosby silt loam:					
From cultivated field (pH 6.4)—					
Air-dry	45	29.4	12	0	0
Field moisture (15.3 percent)	39	-----	34	0	0
Excessively limed (pH 7.6)—					
Air-dry	64	37.1	24.2	5.6	0
Field moisture (15.9 percent)	63	-----	19.3	0	0
Na ₂ CO ₃ treated (pH 10.5)—					
Air-dry	84	-----	-----	-----	0
Field moisture (18.9 percent)	60	-----	-----	-----	0

¹ Data from Jackson and Chang (102).

ture content, and pH value should completely sorb the equivalent of 60 pounds of nitrogen per acre applied in the form of ammonia at a depth of 1 to 2 inches.

Stanley and Smith (181) state that ammonia applied at the rate of 100 pounds per acre in 40-inch rows 3 to 4 inches below the surface is more than many soils can sorb. The excess ammonia will be lost immediately or held as ammonium hydroxide in solution subject to later loss if the ammonium hydroxide evaporates from the surface of the soil. Such losses are generally eliminated by applying the ammonia at a depth of 6 inches. On the other hand, Baker and coworkers (31) state that losses are negligibly small when anhydrous ammonia is applied, even to a depth of only 4 inches, to soils with optimum moisture contents.

Martin and Chapman (137) found in the laboratory that nitrogen losses occur when ammonia is present at or near the surface of an alkaline soil. Nitrogenous fertilizers were mixed with or added in a solution to 2-inch layers of soil, and the volatilized ammonia was collected and measured. After the soil became dry, it was remoistened and ammonia collection repeated. This was continued until little or no ammonia was recovered. The addition of ammonium hydroxide or urea raised the soil pH; the extent and duration of the temporary alkalinity depended on the buffering capacity of the soil. Nitrogen losses, accounting for as much as 51 percent, are shown in table 22. The acid sandy loam, in this case, had a low buffering capacity.

Additional work by the same authors (138) shows that ammonia-nitrogen losses of 9 and 17 percent occur when ammonium hydroxide is ap-

TABLE 22.—Loss of nitrogen from California soil¹

Nitrogen source	Nitrogen added	Loss of nitrogen by volatilization from—		
		Clay loam (pH 8.0)	Sandy loam (pH 7.5)	Sandy loam (pH 6.7)
	Pounds per acre	Percent	Percent	Percent
Ammonium sulfate	150	23	26	5
	250	25	19	4
Ammonium hydroxide	150	27	36	51
	250	28	34	41
Urea	250	16	16	36
Ammonium nitrate	250	22	14	2

¹ Data from Martin and Chapman (137).

plied at the rate of 150 pounds of nitrogen per acre to soils with an initial pH of 4.5 and 4.6 respectively. The losses are caused by the temporary alkalinity of the soil resulting from the ammonium hydroxide and the losses increase with higher temperatures.

The application of low-pressure ammonia-ammonium nitrate-water solutions to the soil surface also incurs nitrogen losses. Trickey and Smith (190) showed that Solution LP-6 (see table 5) applied at a rate of 100 pounds of nitrogen per acre at a temperature of 73° to 75° F. lost 28.2 percent of the ammonia (14.9 percent of the nitrogen) in the first hour. Losses continued for some time and were greater at the lower soil moistures and higher atmospheric and soil temperatures.

The loss of volatile ammonia-nitrogen over a period of time from an experimental solution similar to Solution LP-4 has been demonstrated by Robertson and Hansen (160). The solution was dribbled on the surface of the soil at five locations and the ammonia-nitrogen losses determined. The results in table 23 show that the losses were pro-

TABLE 23.—Losses of ammonia from surface applications of a low-pressure nitrogen solution¹

Soil type	Application rate ²	Total volatile nitrogen lost at time intervals of—				
		25 minutes	50 minutes	100 minutes	200 minutes	400 minutes
	Pound N per acre	Pounds per acre	Pounds per acre	Pounds per acre	Pounds per acre	Pounds per acre
Conover loam ³	25	1.9	2.1	2.5	2.9	3.1
	50	3.7	4.2	4.9	5.5	6.0
	100	7.5	8.5	9.7	11.2	12.6
Hillsdale loam ⁴	25	2.2	2.5	2.8	4.2	4.4
	50	4.0	4.6	5.4	6.0	6.5
	100	7.9	9.0	10.1	11.4	12.7
Hillsdale loam ⁵	25	2.0	2.2	2.5	2.8	3.0
	50	3.9	4.5	5.2	5.8	6.2
	100	7.9	8.9	10.0	11.2	12.5
Hillsdale loam ⁶	25	2.0	2.3	2.5	2.7	2.9
	50	4.0	4.7	5.4	6.0	6.5
	100	8.1	9.2	10.2	11.3	12.4
Kalamazoo sandy loam ³	25	2.1	2.3	2.5	2.9	3.1
	50	4.3	4.8	5.4	6.3	6.8
	100	8.8	13.6	15.0	16.8	18.2

¹ Data from Robertson and Hansen (160).

² Solution application rates of 25, 50, and 100 pounds of N per acre supply 4.6, 9.1, and 18.3 pounds, respectively, of volatile ammonia-nitrogen per acre.

³ Cornfield with dry, crusted soil.

⁴ Wheatfield with dry, granular soil.

⁵ Cornfield with wet, crusted soil.

portional to the level of application and ranged from 63 to 100 percent of the ammonia-nitrogen applied.

Some nitrogen loss may also result from the leaching of the nitrates present in the solutions or formed by the nitrification of ammonium-nitrogen. Nitrate formation varies with temperature (20, 21, 86, 129, 163). It does not begin until the temperature rises above freezing, after which the rate of formation increases with temperature. Very little nitrification occurs under field conditions after soil temperatures drop below 40° to 50°F. Laboratory results obtained by Anderson and Purvis (21) on the temperature-nitrification relationship are given in table 24.

TABLE 24.—Influence of temperature on nitrification of ammonium hydroxide¹ in Nixon sandy loam, New Jersey²

Incubation period (days)	Nitrate content of samples derived from applied nitrogen at—			
	37° F.	42° F.	47° F.	52° F.
	Parts per million	Parts per million	Parts per million	Parts per million
7	0	0	0	0
14	0.8	0.8	2.4	4.0
21	0	1.6	6.1	15.2
28	2.0	5.6	18.4	22.4
35	3.2	6.4	22.4	37.6
42	4.8	17.6	36.0	48.0

¹ Applied at the rate of 100 p.p.m. N.
² Data from Anderson and Purvis (21).

Urea-nitrogen in solutions may be lost as such or after conversion to ammonia and nitrate forms. Fisher and Parks (84) report that urea hydrolysis is relatively slow at 50° F., so that losses below this temperature are probably due to the leaching of urea. Significant hydrolysis occurs above 50° F., and, once hydrolysis occurs, nitrogen losses will follow the pattern of ammonia-nitrogen losses. The rate of hydrolysis and subsequent nitrification increases with increasing temperature.

Volk (197) determined the gaseous losses of ammonia-nitrogen over a period of 7 days after surface applications of urea to a number of soils. The 7-day period was selected, as the loss by volatilization was about 95 percent completed in that time. A maximum nitrogen loss of 59 percent was obtained when pelleted urea was added to bare moist Lakeland fine sand II (cf. table 25) at the

TIME OF APPLICATION

The use of liquid nitrogen fertilizers, particularly ammonia and aqua ammonia, presents the possibility of fall application of nitrogen for use by the crops in the spring. The ammonia is fixed by the soil and its conversion to leachable forms is retarded by low soil temperatures and completely stopped at temperatures below freezing. McIntosh and Frederick (129) in Iowa found that ammonia-nitrogen applied in November just prior to freezing showed little nitrification before March. Rapid nitrification began in mid-April

TABLE 25.—Gaseous losses of nitrogen during 7 days following surface application of a urea-ammonium nitrate solution to bare moist soil in Florida at the rate of 100 pounds of nitrogen per acre¹

Soil	Soil pH	Nitrogen loss from solution NP-13 ²	
		Cation exchange capacity of the soil Meg. per 100 g.	Percent
Lakeland fine sand I	5.6	1.5	0.6
Lakeland fine sand II	6.3	1.6	29.4
Lakeland fine sand III	5.4	4.7	1.6
Lakeland fine sand IV	6.7	3.5	15.2
Lakeland fine sand V	6.3	1.9	4.4
Leon fine sand	4.4	2.8	3.2
Leon fine sand	5.9	5.8	7.5
Red Bay fine sandy loam	5.3	7.2	2.3
Arredondo fine sandy loam	5.8	11.5	.4
Fellowship fine sandy loam	5.9	23.4	.1
Ferrine marl	7.8	7.4	14.4

¹ Data from Volk (197).
² Contained 32 percent nitrogen—16.5 percent from urea and 15.5 percent from ammonium nitrate.

rate of 100 pounds of nitrogen per acre. Volatile nitrogen losses resulting from the application of a urea-ammonium nitrate solution to bare moist soil are given in table 25. The losses were smaller than those obtained with pelleted urea. However, if the loss on Lakeland fine sand II is attributed to the urea fraction, it amounts to over 57 percent of the urea-nitrogen. Nitrogen losses from bare soil were much smaller when the urea was applied to dry or cold soils. When applied to well-developed sods at the rate of 100 pounds of nitrogen per acre, the average volatile nitrogen losses from pelleted urea and the urea-ammonium nitrate solution were 20.6 and 11.5 percent, respectively.

More recent work by Kresge and Satchell (112) showed no appreciable ammonia volatilization losses when less than 100 pounds of nitrogen per acre were topdressed in the form of solid urea on a bare silt loam with a pH value of 6.3. A bermudagrass cover significantly reduced the losses occurring at higher rates of application on bare soils. Losses from a water solution of urea (23 percent N), surface-applied at a rate of 316 pounds of nitrogen per acre, amounted to 74.2 percent of the nitrogen on a sandy loam and 79.4 percent on a silt loam in a period of 11 days. Ammonium nitrate mixed with urea in concentrated solutions reduced the ammonia volatilization occurring with solutions of urea alone.

and approximately 8 weeks were required to complete nitrification of the ammonia. MacGregor (127) states that, generally, nitrogen applied in the late fall on the medium- to fine-textured soils in Minnesota was equally as effective as that applied during the spring. Overwinter losses of nitrogen were not evident.

Nitrogen losses during the winter are due primarily to erosion and to leaching. Care should be taken to select areas not subject to erosion for surface applications in the fall. Subsurface ap-

plications minimize erosion losses but are subject to leaching. Where percolation occurs, the nitrate-nitrogen is leached out of the root zone while the ammoniacal-nitrogen is held by the soil until converted to nitrate. Nelson and Uhland (146) classify various areas on the basis of practicability of fall application of nitrogen in figure 16. Area I is best suited for fall applica-

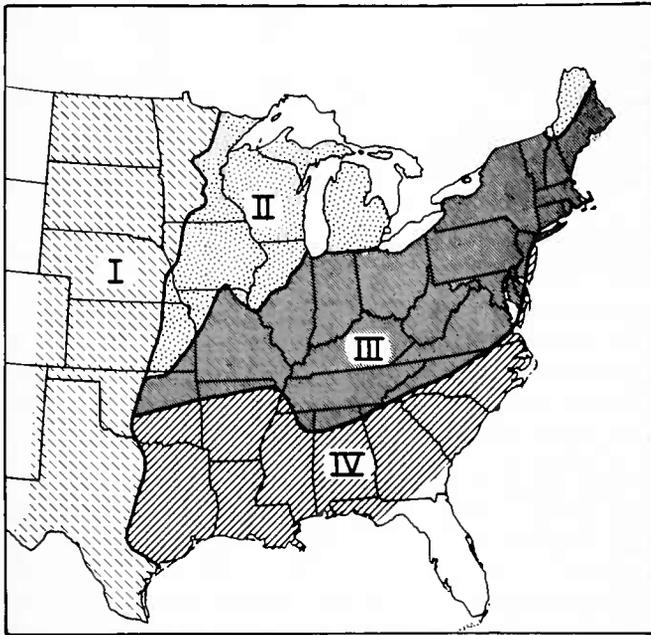


FIGURE 16.—Suitability of certain geographic areas for fall application of fertilizer ranging from the most suitable (area I) to least suitable (area IV). Nelson and Uhland (146).

tion, since leaching losses are unlikely because of the normally low rainfall. Area II includes sections either of relatively low percolation or low fall temperatures, or a combination of both. This area should be suitable for fall applications of ammoniacal-nitrogen, but nitrate applications should be limited to sections where percolation is relatively low. Fall application of liquid nitrogen fertilizers would appear to be questionable in area III and undesirable in area IV except for fall-planted crops that require nitrogen or for plants that grow during a good part of the winter. Fall plow-down applications of liquid nitrogen fertilizers are suitable for such crops in any area.

Split applications of fertilizer, particularly nitrogen carriers, are favored by many. The first application is made previous to planting. The second is made as the plant approaches its most rapid period of growth and greatest need for nitrogen. This practice lessens the danger of seed injury and provides the plant with adequate supplies of nitrogen when they are most needed.

Anhydrous and aqua ammonia are often used for preplant application on row crops. The ammonia is normally applied 10 days to 3 weeks before planting, after which the land is left undis-

turbed until the crop is planted. This prevents seed and seedling damage by allowing the ammonia to diffuse through the soil and to be fixed by the soil particles.

The solutions containing ammonium nitrate are most efficiently used if applied at the time plant requirements for nitrogen are high. This time varies with the crop. The liquid is applied previous to the major vegetative growth and is of little value if added too late. For example, sidedressing corn at the last cultivation is beneficial, since leafy crops need nitrogen late in the growing season.

Application on Small Grains

The effect of time of application on winter wheat yields was studied by Lowrey and his co-workers (124) in Nebraska. The results are given in table 26. Phosphate applications were made with the seed, ammonium nitrate was applied as a topdressing, and anhydrous ammonia was injected 6 inches deep. Little difference in wheat yields was found between fall and spring applications of ammonium nitrate or between ammonium nitrate and fall applications of anhydrous ammonia. The lower yields from spring applications of anhydrous ammonia were probably due to unfavorable soil conditions at the time of application. Part of the decrease in yield may be due to mechanical injury to the stand, which Eck and his coworkers (77) found might occur from spring application of anhydrous ammonia to wheat.

Olson and Rhoades (151), however, found anhydrous ammonia applied 4 to 5 inches deep prior to planting in the fall or early spring was as effective in promoting the growth of winter wheat as ammonium nitrate broadcast either in the fall or in the spring. The response to ammonium nitrate substantially was independent of time of application, whereas spring application of anhydrous ammonia was somewhat less effective. Their experiments were carried out in eastern Nebraska on Sharpsburg silt loam in 1948, 1949, and 1950 and on Crete silty clay loam in 1952. A basal applica-

TABLE 26.—Response of winter wheat to anhydrous ammonia and ammonium nitrate in Nebraska¹

Source of nitrogen	Treatment ²			Yield	
	N	P ₂ O ₅	K ₂ O	Saline County	Seward County
	Pounds per acre	Pounds per acre	Pounds per acre	Bushels per acre	Bushels per acre
None.....	0	30	0	36	9
Anhydrous ammonia..	40(F)	30	0	45	24
Do.....	40(S)	30	0	38	11
Ammonium nitrate....	40(F)	30	0	48	21
Do.....	40(S)	30	0	46	20
Least significant difference at 5-percent level.....				4	4

¹ Data from Lowrey, Olson, Dreier, and Ehlers (124).

² (F)=fall application, (S)=spring application.

tion equivalent to 45 pounds of phosphoric oxide was made with the seed at planting time; potash was assumed to be adequate. The results of these experiments are given in table 27.

Under the climatic conditions prevailing in Mississippi, anhydrous ammonia applied in the fall was superior to fall-applied ammonium nitrate as a source of nitrogen for fall-sown oats (27). Table 28 further shows that fall-applied ammonia was more effective than spring-applied ammonium nitrate on the more acid soils but less effective on the soils with pH values above 5.1. The ineffectiveness of the fall-applied anhydrous ammonia on these latter soils was attributed to the more rapid conversion of ammonia to nitrates and subsequent leaching losses.

TABLE 27.—Response of winter wheat to anhydrous ammonia and ammonium nitrate in Nebraska¹

Year and source of nitrogen	Time of application	Mean yield
		<i>Bushels per acre</i>
1948 ²		
Anhydrous ammonia.....	September.....	50.7
Ammonium nitrate.....	.....do.....	48.6
Check.....	.....	35.8
1943 ³		
Anhydrous ammonia.....	September.....	33.8
Ammonium nitrate.....	.....do.....	33.1
Anhydrous ammonia.....	April.....	27.3
Ammonium nitrate.....	.....do.....	32.8
Check.....	.....	30.8
1950 ³		
Anhydrous ammonia.....	September.....	40.2
Ammonium nitrate.....	.....do.....	35.7
Check.....	.....	31.4
1952 ⁴		
Anhydrous ammonia.....	April.....	32.5
Ammonium nitrate.....	.....do.....	35.5
Check.....	.....	22.0

¹ Data from Olson and Rhoades (151).
² Mean yields obtained with 30 to 60 pounds of nitrogen per acre.
³ Mean yields obtained with 20, 40, and 60 pounds of nitrogen per acre.
⁴ 50 pounds of nitrogen per acre.

TABLE 28.—The response of oats in Mississippi to fall-applied anhydrous ammonia and to fall- and spring-applied ammonium nitrate—32 pounds of nitrogen per acre¹

Soil Nos. and pH	Increase in yield due to—		
	Anhydrous ammonia applied in fall	Ammonium nitrate applied in—	
		Fall	Spring
Soils with pH 5.1 or below:	<i>Bushels per acre</i>	<i>Bushels per acre</i>	<i>Bushels per acre</i>
1.....	30	16	21
2.....	32	15	25
3.....	30	16	25
4 ²	29	20	27
5 ³	19	10	19
Soils above pH 5.1:			
6.....	25	15	30
7.....	12	8	19
8.....	15	8	22
9.....	14	10	24
10 ⁴	4	5	24

¹ Data from Andrews, Neely, and Edwards (27).
² pH 4.95.
³ pH 5.1.
⁴ pH 7.8.

Application to Crops for Grazing

The time for applying nitrogen fertilizers to crops for grazing depends to a large extent on the time of seeding and the ultimate use of the crop. Thompson (186) points out that there are three planting periods for winter grazing in Mississippi. Cereals, fescue, and ryegrass can be planted in early and late September and October so that at least part of the required nitrogen should be applied at the time of seeding. March and early April applications supply early and luxuriant extra pasturage, whereas applications made in the late summer are effective when fall pasturage is desired. Early spring applications are also recommended when a hay crop is to be harvested.

SELECTION OF LIQUID NITROGEN FERTILIZER

The selection of a liquid nitrogen fertilizer is governed to a limited extent by the type of crop to be fertilized, but no hard and fast rule can be given. The pressure liquids, which should be injected in the soil, find their greatest use in side dressing row crops, but care must be taken not to place these liquids too close to young seedlings at time of planting or transplanting. Lorenz, Bishop, and Wright (121) observed toxic injury to onion and potato seedlings in light-textured soils by this practice, whereas similar placement of ammonium sulfate caused no injury. The toxic condition remained for some time and was related to the greater upward movement in the soil of the ammonia from the pressure liquids. Subsurface application to growing row crops prevents burning and can be carried out without excessive damage to the root system. Root-system damage has been a deterrent to the use of pressure liquids on pastures and for cereals, but current research may solve some of these difficulties. The nonpressure liquids do not require soil injection, but they may

cause slight burning upon contact with the foliage. This is soon offset by the stimulated growth that follows. Greater use has been made of the non-pressure liquids than of the pressure liquids for pastures, hayland, and cereal crops and for application during seeding.

TABLE 29.—Percentage of applied nitrogen recovered in forage crops

Source and quantity of nitrogen applied per acre		Applied nitrogen recovered in—			
Sodium nitrate ¹	Ammonium nitrate ²	Bermuda-grass	Orchard-grass	Tall fescue	Brome-grass
<i>Pounds N</i>	<i>Pounds N</i>	<i>Percent</i>	<i>Percent</i>	<i>Percent</i>	<i>Percent</i>
50.....	80.....	42.3	83	78	30
100.....	160.....	60.2	84	76	26
200.....	240.....	65.7	69		
400.....		64.4			

¹ Data from Burton and DeVane (54); Tifton sandy loam in Georgia.
² Data from Wagner (199); Codorus silt loam limed to pH 6.5, Maryland.

Crop utilization of applied nitrogen fertilizers is of major importance, but little if any work has been done on the uptake of nitrogen from liquid sources. Most of the studies on nitrogen utilization have been made with solid forms of nitrogen, but liquid forms may be expected to give comparable results. The percentage of nitrogen ap-

plied in solid form and recovered in forage crops the first season has been determined by Wagner (199) at Beltsville, Md., and Burton and DeVane (54) at Tifton, Ga., with results as shown in table 29. It is assumed that a part of the unused applied nitrogen will be held in a slowly available form and utilized in part in subsequent years.

CROP RESPONSE

The advent of liquid sources of nitrogen for use as fertilizer has raised many questions and presented many problems that are being investigated in a number of institutions. The relative value of this form of nitrogen in comparison with the customary solid nitrogen carriers is of primary importance. Considerable research work has been conducted on this subject. The comparisons, in general, have been between anhydrous ammonia and solid ammonium nitrate. Some comparisons have been made between liquid nitrogen fertilizers and solid ammonium nitrate. Solid ammonium nitrate has been chosen as a standard because it introduces no accompanying ion or other constituents that might produce beneficial or detrimental side-effects upon plant growth. A summary of some of the experimental results is given here. The response data indicate that the total nutritive value of nitrogen, when properly applied, is the same, irrespective of the form in which it is used. Any preference among liquids must be based on the ratio of nitrate-, urea-, and ammoniacal-nitrogen content.

Corn

Studies of the use of liquid forms of nitrogen for fertilizing corn have been rather extensive, owing to the widespread cultivation of the crop, its high nitrogen requirement, and the responses obtained from the use of nitrogen.

Work by Lowrey and Ehlers (123) in Nebraska shows there is no appreciable difference between corn yields obtained with anhydrous ammonia or ammonium nitrate. Yields were similar for both materials applied prior to planting or sidedressed when the corn was 10 to 18 inches tall. However, results, although not conclusive, indicate that sidedressings of anhydrous ammonia may be superior to earlier applications. MacGregor (126) found anhydrous ammonia sidedressing substantially increased yields of both corn and protein per acre in Minnesota, provided there was an adequate supply of available phosphorus and potassium in the soil.

Chandler (57) compared the use of anhydrous ammonia, solution NP-13, ammonium nitrate, and other solid nitrogen materials as sources of nitrogen for corn in North Carolina. Anhydrous ammonia and solution NP-13 were fully as effective as the solid forms of nitrogen in promoting the growth of corn.

These observations with respect to anhydrous ammonia have been confirmed by the work of Andrews and his coworkers (27) in Mississippi, the results of which are given in table 30. In general, anhydrous ammonia was fully as effective as ammonium nitrate in promoting the growth of corn. The average yield increase obtained with sidedressed applications of anhydrous ammonia was greater than that obtained with preplanted applications.

TABLE 30.—Average response of corn to anhydrous ammonia and ammonium nitrate applied at various locations in Mississippi¹

Location	Anhydrous ammonia		Ammonium nitrate			Check
	Pre-plant, 4 inches deep	Sidedress, 4 inches deep	Pre-plant, 4 inches deep	Sidedress, 4 inches deep	Sidedress, on the surface	No nitrogen applied
	<i>Bushels per acre</i>	Bushels per acre	Bushels per acre	Bushels per acre	Bushels per acre	<i>Bushels per acre</i>
Columbus.....	28.3	27.4	24.2	27.8	28.5	12.1
Starkville.....	26.0	34.6	21.8	28.7	26.2	12.4
Tommolon.....	56.1	57.8	55.3	55.3	54.6	42.8
Holly Springs.....	84.6	79.1	82.8	79.5	80.6	69.9
Do.....	60.5	69.5	66.3	62.3	63.7	56.0
Average.....	51.1	53.7	50.1	50.7	50.7	38.6
Average increase.....	12.5	15.1	11.5	12.1	12.1	

¹ Data from Andrews and coworkers (27); nitrogen applied at the rate of 32 pounds per acre.

Cotton

Some of the earliest field experiments using anhydrous ammonia as a source of nitrogen in cotton culture were carried out in Mississippi. Andrews and his coworkers (27) compared the relative efficiencies of anhydrous ammonia and ammonium nitrate and found nitrogen in either form was about equally available to the cotton plant. Greater variations in yield occur as a result of fertilizer placement and time of application rather than from different sources of nitrogen.

Oakes (150) reports that the production of seed cotton fertilized with ammonia was comparable in practically all cases to the yields obtained with ammonium nitrate, ammonium sulfate, or sodium nitrate. No significant differences were observed in the yields obtained either from preplanting or from sidedressing applications. Table 31 gives the results obtained with applications of 40 pounds of nitrogen per acre in the Red River Valley of Louisiana.

An evaluation of nitrogen carriers under irrigation conditions was made by Mikkelsen and Smith

TABLE 31.—Seed cotton yields obtained in Louisiana with 40 pounds of nitrogen per acre, 1950-53¹

Source of nitrogen and time of application	Seed cotton yields per acre			
	1950	1951	1952	1953
Applied 10 days before planting:				
Ammonia, anhydrous.....	Pounds 2, 185	Pounds 1, 579	Pounds 2, 791	Pounds 2, 923
Ammonium nitrate.....	2, 213	1, 324	2, 956	2, 919
Ammonium sulfate.....	2, 038	1, 465	2, 806	2, 959
Sodium nitrate.....	2, 129	1, 375	2, 969	2, 865
Sidedressed:				
Ammonia, anhydrous.....	2, 355	1, 259	2, 937	2, 872
Ammonium nitrate.....	2, 212	1, 025	2, 779	2, 978
Ammonium sulfate.....	2, 318	1, 118	2, 557	2, 904
Sodium nitrate.....	2, 164	1, 490	2, 832	2, 926

¹ Data from Oakes (150).

(141) in California. The results are given in table 32. The comparisons were made on soils under continuous cotton production. Aqua ammonia and the dry materials were applied in 2 bands 6 inches each side and 3 to 5 inches below the seed. Anhydrous ammonia was applied in the middle of each row to a depth of 6 inches. The test plots received a basal application of 100 pounds of available phosphoric oxide per acre; potash was assumed to be adequate. Marked increases in seed cotton yields were obtained from the use of nitrogen on both soils, but no significant differences were noted in the cotton-producing efficiencies of anhydrous ammonia, aqua ammonia, ammonium nitrate, and ammonium sulfate. Yields obtained in 1952 with calcium nitrate and urea were significantly lower than those obtained with aqua ammonia.

Bhat, Ingreji, and Patel (40) studied the relative cotton-producing efficiency of ammonia liquor in India in 1953-54. Aqua ammonia and ammonium sulfate were drilled into the soil midway between the cotton rows. Nitrogen fertilization increased both the seed cotton yield and plant weight significantly, with both sources of nitrogen giving almost identical results.

TABLE 32.—Relative efficiency of nitrogen sources on seed cotton production in California¹

Nitrogen source	Seed cotton yields per acre on—		
	Hesperia sandy loam ²		Panoche loam ³
	1951	1952	1952
	Pounds	Pounds	Pounds
Ammonia, anhydrous.....	2, 705	3, 053	3, 767
Ammonia, aqua.....	2, 727	2, 858	3, 999
Ammonium nitrate.....	3, 051	2, 966	3, 798
Ammonium sulfate.....	2, 489	2, 620	3, 938
Calcium nitrate.....	2, 748	2, 728	3, 858
Urea.....	2, 142	1, 537	3, 752
Check.....			2, 032
L.S.D. at the 5-percent level.....	366	279	353

¹ Data from Mikkelsen and Smith (141).² Received 80 pounds of nitrogen and 100 pounds P₂O₅ per acre.³ Received 100 pounds of nitrogen and 100 pounds P₂O₅ per acre.

Hay and Pasture

The relative efficiency of anhydrous ammonia as compared with ammonium nitrate for the production of oats for fall and winter forage was determined by Hammons (94) on three sandy loams in Mississippi. Anhydrous ammonia was applied 6 inches deep the day before planting and the ammonium nitrate was applied 2 weeks later as a top-dressing. Each plot received a basal application of phosphorus and potassium. Grazing was simulated by clipping on December 4 and February 14. The forage yields are given in table 33. Anhydrous ammonia was more effective than ammonium nitrate for the production of forage on Savannah soil, and the two nitrogen carriers were equally effective on Ora soil. A spot clipping on January 24 indicated that 75 percent of the nitrogen applied to the Ora soil had been assimilated. The fall-applied nitrogen had little influence on the grain yields from Savannah soil and no influence on the yields from Ora soil.

TABLE 33.—Response of fall-planted oats to anhydrous ammonia and ammonium nitrate on two Mississippi soils¹

Source of nitrogen	Quantity of nitrogen added per acre		Yield per acre of oven-dry forage from—			
	Fall	Spring	Ora very fine sandy loam ²		Savannah fine sandy loam ³	
			Dec. 4	Feb. 14	Dec. 4	Feb. 14
	Pounds	Pounds	Pounds	Pounds	Pounds	Pounds
Ammonia.....	32	0	737	185	481	138
Ammonium nitrate.....	32	0	598	161	281	100
Do.....	64	0	1, 394	233	494	209
Ammonia.....	64	0	1, 343	239	863	213
Do.....	32	32	721	223	476	129
Ammonium nitrate.....	32	32	639	181	218	87

¹ Data from Hammons (94).² No-nitrogen plots produced an average of 57 pounds of oven-dry forage per acre.³ No-nitrogen plots produced an average of 13.5 pounds of oven-dry forage per acre.

Additional experiments in Mississippi by Jones and coworkers (108) showed that summer grasses responded about 2 weeks earlier to ammonium nitrate than to anhydrous ammonia. The overall total response to both sources of nitrogen, however, was the same. In these experiments, the nitrogen was applied to permanent pasture sods by broadcasting ammonium nitrate and by injecting ammonia 5 inches deep.

Ammonia, even in dilute water solutions, is unsuitable for topdressing grassland. Pratt and O'Brien (155) found that surface applications of a 1-to-9 dilution of ammonia liquor supplying 50 to 150 pounds of nitrogen per acre yellowed the grass and retarded early spring growth of permanent pastures. Similar results were observed by Bear (34) when solutions containing 100, 200, 300, and 400 pounds of aqua ammonia (20.7 percent) in 200 gallons of water were applied per acre to the surface of grassland.

More recently, Jameson (105) has conducted field studies on the effects of a number of liquid fertilizers on grassland in England. The dry-matter yields obtained with anhydrous ammonia, ammonia liquor (24.6 percent N), solution "32" (comparable to NP-13, table 5), solution "S" (26.0 percent ammonia and 26.0 percent urea = 33.5 percent N) were compared with those obtained with ammonium sulfate (20.6 percent N) and nitro-chalk (15.5 percent N). The liquids were injected 2 to 4 inches deep and the solid fertilizers were broadcast. Little significant difference was observed among the yields with the liquid fertilizers. These yields, however, were generally lower than those obtained with the conventional solid fertilizers.

Rice

Wyche, Cheaney, and Moncrief (202) studied the rice responses obtained in Texas from anhydrous ammonia and ammonium sulfate applied at different times. Basal applications of 40 pounds of phosphoric oxide per acre were made on each plot, and the nitrogen carriers were applied at the rate of 80 pounds of nitrogen per acre. The results are given in table 34. Anhydrous ammonia was fully as satisfactory as ammonium sulfate when used as a preplant application, except when added in flooding water prior to muddying up for planting. Ammonium sulfate gave better yields than anhydrous ammonia when the nitrogen was applied after planting.

In California, Mikkelsen (140) found that 30 pounds of nitrogen per acre drilled into Stockton clay in the form of anhydrous ammonia gave significantly larger yields of rice than the same quantity of nitrogen broadcast in the form of am-

TABLE 34.—Effect of method and time of application of anhydrous ammonia and ammonium sulfate on rice production in Texas¹

Method and time of application	Yield of rice per acre ²	
	Anhydrous ammonia ³	Ammonium sulfate ³
Fertilizers applied to drill-planted rice in dry soil:	<i>Barrels</i>	<i>Barrels</i>
In the soil just prior to planting.....	29.56	28.27
Ammonium sulfate on top of soil just before flush and ammonia in flushing water.....	23.84	26.02
On shallow-flooded field—		
4 weeks after planting.....	21.57	23.49
8 weeks after planting.....	20.69	24.12
On field with full flood—		
4 weeks after planting.....	22.04	24.60
8 weeks after planting.....	20.79	23.53
Fertilizers applied to water-planted rice, using soaked seed:		
In soil prior to flooding for water planting.....	25.84	22.78
In flooding water prior to muddying-up for planting.....	17.85	24.07
In soil during muddying-up operations.....	26.14	-----
Injected on crop 4 weeks after planting.....	26.76	-----

¹ Data from Wyche, Cheaney, and Moncrief (202).

² Yields without nitrogen were 16.16 barrels per acre for rice drill-planted in dry soil and 17.60 for the water-planted rice.

³ Applied at the rate of 80 pounds of nitrogen per acre.

monium sulfate, cyanamide, or urea. Rice yields obtained with anhydrous ammonia were the same for application rates of both 30 and 60 pounds of nitrogen per acre and were smaller for rates of 90 pounds. Yield reduction at the highest rate of application was caused by delayed crop maturity. The other nitrogen carriers produced increased yields with each additional increment of nitrogen. The work of Beacher (33) in Arkansas showed that rice yields were greater from 60 pounds of ammonia injected into the soil than yields from an equivalent amount of nitrogen as solid ammonia nitrate used as a topdressing.

Oats and Barley

Andrews and coworkers (27) have shown that the relative efficiencies of anhydrous ammonia and solid ammonium nitrate for the production of oats for grain in Mississippi is dependent on both the time of application and the character of the soil. Fall-applied ammonium nitrate was a poor source of nitrogen in comparison to fall-applied anhydrous ammonia or to spring-applied ammonium nitrate. On the more acid soils, ammonia applied in the fall was superior to spring-applied ammonium nitrate. The reverse was true when the soil pH was more than 5.5. Little difference in the forage yields was obtained with split applications of anhydrous ammonia or ammonium nitrate. A single application of either nitrogen carrier in September was as effective as the split application made in September and December. A March application of nitrogen was necessary to produce grain after grazing the oats.

Additional experiments in Mississippi (28) show that water solutions of ammonium nitrate sprayed on oats produced larger grain yields than surface applications of solid ammonium nitrate. Poor responses were obtained when either form of ammonium nitrate was applied late in the growing season. Some results of these tests are given in table 35.

Jones and Caldwell (107) found anhydrous ammonia and solid ammonium nitrate were effective sources of nitrogen for oats and barley grown under Minnesota conditions. The two nitrogen carriers were applied several days before planting

TABLE 35.—Oat responses to applications of solution and solid forms of ammonium nitrate¹

Location and time of application	Check	Form of ammonium nitrate ²	
		Solution	Solid
	<i>Bushels per acre</i>	<i>Bushels per acre</i>	<i>Bushels per acre</i>
State College, Miss.:			
March 8 and 9.....	27.9	48.3	41.6
March 31.....	34.0	60.1	55.4
April 12.....	27.1	37.9	30.0
New Hope, Miss.:			
March 16.....	17.2	42.9	41.6

¹ Data from Andrews, Welch, and Beckett (28).

² Application rate: 40 pounds of nitrogen per acre.

at a rate of 40 pounds of nitrogen per acre. The fields had received blanket applications of phosphorus and potassium. Average yields of 81.5 bushels per acre were produced by anhydrous ammonia injected 4 to 5 inches below the surface of the soil. A broadcast application of ammonium nitrate produced average yields of 83.1 bushels per acre. Yields on the check plots averaged 67.8 bushels. An experiment with barley gave corresponding yields of 48.5, 44.2, and 31.8 bushels per acre.

In Russia Byczkowski and coworkers (55, 56) observed that the yields of oats and barley produced by applications of anhydrous ammonia, aqua ammonia, ammonium nitrate, sodium nitrate, and an ammoniating solution containing 16.3 percent ammonium nitrate-nitrogen and 13.8 percent ammonia-nitrogen in water were generally similar.

Wheat

As pointed out previously (table 25), anhydrous ammonia and ammonium nitrate were equally effective in promoting the growth of winter wheat in Nebraska, particularly when applied in the fall. Comparable results were observed in Kansas where Smith (175) obtained almost identical increases in wheat yields from the use of anhydrous ammonia, an ammoniating solution (LP-2), and ammonium nitrate applied at a rate of 60 pounds of nitrogen per acre. The two liquid nitrogen carriers were injected into the soil, and the solid ammonium nitrate was applied by means of a fertilizer attachment on a grain drill.

One of the few experiments using an ammoniating solution as a source of nitrogen was conducted by Hanway and coworkers (95) on two silty clay loams in Nebraska. A comparison was made of the effects of anhydrous ammonia, an ammoniating solution (LP-6), ammonium nitrate, and ammonium sulfate on wheat production. The two liquids were applied 3 to 4 inches beneath the surface of the soil, and the solids were applied with a combination fertilizer-grain drill. Results (table 36) show that a fall application of 30 pounds of nitrogen per acre in the form of anhydrous ammonia gave larger yields than equivalent amounts of ammonium nitrate or ammoniating solution. No significant differences in yields were obtained with any of the nitrogen carriers applied at 60 pounds of nitrogen per acre. Early spring application of the ammoniating solution was not so effective as the solid nitrogen carriers on the Waukesha soil; there was no significant differences on the Sharpsburg soil. Protein content of the grain varied with both the rate and time of application of nitrogen.

Sugarcane

The efficiency of different nitrogen carriers in sugarcane and sugar production has been investigated by Davidson (68). Some of the results are

TABLE 36.—Influence of rate and time of application of various nitrogen carriers on wheat production in Nebraska¹

Source of nitrogen and time of application	Quantity of nitrogen applied per acre	Soil type			
		Waukesha silty clay loam		Sharpsburg silty clay loam	
		Yield per acre	Protein content	Yield per acre	Protein content
Check.....	Pounds 0	Bushels 37.2	Percent 9.6	Bushels 34.3	Percent 10.5
Planting time:					
Ammonium nitrate.....	30	47.4	10.7	43.8	10.4
Ammoniating solution ²	30	49.3	10.9	43.7	10.7
Anhydrous ammonia.....	30	52.8	10.8	45.5	10.8
Ammonium nitrate.....	60	51.6	11.1	51.7	12.0
Ammoniating solution ²	60	51.5	12.2	49.9	12.5
Anhydrous ammonia.....	60	52.6	12.2	51.9	14.3
Early December:					
Ammonium nitrate.....	30	47.2	10.5	43.8	10.8
Do.....	60	50.0	11.2	44.7	10.7
Early spring:					
Ammonium nitrate.....	30	53.2	11.9	45.1	12.2
Ammoniating solution ²	30	40.0	11.1	45.5	11.6
Ammonium sulfate.....	30	50.2	12.4	41.5	10.8
Ammonium nitrate.....	60	52.7	14.0	46.9	12.8
Ammoniating solution ²	60	47.8	12.2	49.0	12.5
Ammonium sulfate.....	60	52.9	13.1	44.2	11.1

¹ Data from Hanway, Luehs, and Rhoades (95); superphosphate was applied to all plots at the rate of 40 pounds of P₂O₅ per acre.
² Solution LP-6, table 5.

given in table 37. Sources of phosphorus and potassium were not used in these experiments, as these nutrients have a negligible influence on cane production in the alluvial soils of Louisiana. The nitrogen was applied during March and April and the crop was harvested from late October through November. Nitrogen applications increased the yields of cane and sugar, but the differences due to the various sources of nitrogen were not significant. Subsequent experiments (69) confirmed the earlier results.

Further information on the comparative value of a number of nitrogen carriers is supplied by De Ment and Sturgis (73). Solid nitrogen carriers were mixed with superphosphate and potassium chloride and applied in the off-bar furrow of stubble cane and covered immediately by the

TABLE 37.—Comparisons of sources of nitrogen for first-stubble sugarcane on two soil types in Louisiana¹

Source of material	Quantity of nitrogen applied per acre	Mahoon silt loam to very fine sandy loam		Baldwin silt loam	
		Cane yield	Indicated available 96° sugar at harvest	Cane yield	Indicated available 96° sugar at harvest
	Pounds	Tons per acre	Pounds per acre	Tons per acre	Pounds per acre
Androus ammonia..	72	20.67	5,173	33.62	7,538
Aqua ammonia.....	35	22.61	5,733	31.45	7,215
	64	25.60	6,514	31.29	7,074
	72	19.41	4,865	21.11	4,638
Ammonium nitrate..	35	23.68	5,922	21.11	4,638
	64	25.09	6,364	21.11	4,638
	72	15.34	3,737	21.11	4,638
Check.....	100	15.34	3,737	21.11	4,638

¹ Data from Davidson (68).

first dirting. Anhydrous ammonia was injected below the superphosphate and potassium chloride. Fertilizer grade urea and ammonium sulfate gave significantly larger yields of sugarcane and sugar on a neutral clay loam than calcium cyanamide, but they were no better than ammonium nitrate, sodium nitrate, or anhydrous ammonia. All sources of nitrogen tested were equally effective on a silt loam with a pH of 6.2.

Li (119, 120) found no significant differences in the sugar yields obtained with different sources of nitrogen applied to various soil types under

Taiwan conditions. Nitrogen sources included anhydrous ammonia, aqua ammonia, and solution LP-2 applied below the surface of the soil and ammonium sulfate, calcium cyanamide, and calcium ammonium nitrate applied in the customary manner. On the other hand, sugarcane yields in Jamaica (100) showed that aqua ammonia injected at depths of approximately 6 inches in the soil is only about 70 percent as effective as ammonium sulfate broadcast. The difference was attributed to ineffective sealing of the ammonia in the soil.

ECONOMIC CONSIDERATIONS

The cost of producing anhydrous ammonia is less than that of any other synthetic nitrogen fertilizer, as it is one of the raw materials required in nitrogen fertilizer manufacture. More processing is required for the preparation and packaging of solid forms of nitrogen from anhydrous ammonia than for the preparation in marketable form of other liquids therefrom. These differences in processing, transportation, and handling requirements are reflected by market quotations that are appreciably lower on the basis of nitrogen content for liquid nitrogen materials than for the solid products, as shown by the data in table 38 (9).

The cost of the nitrogen applied to the soil rather than its f.o.b. price is of prime importance to the farmer. This cost includes f.o.b. price, freight and handling charges, cost of storage, a reasonable dealer markup, and cost of application. Location and type of farming area will have a bearing on the relative costs to the farmer of the liquid and solid forms of nitrogen.

Bowen, Ferguson, and Pierce (48) developed the data shown in figure 17 on North Carolina costs of top- or side-dressing liquid and solid forms of nitrogen at a rate of 60 pounds of nitrogen per acre. A custom application charge of 15 cents per pound of liquid nitrogen fertilizer was used and basic costs of 11 and 15 cents per pound of nitrogen were assumed for the liquid and solid forms, respectively.

TABLE 38.—F.o.b. prices of chemical nitrogen fertilizers, May 30, 1960¹

Material	Price per ton	Price per pound N
	Dollars	Cents
Ammonia, anhydrous, fertilizer, tanks, works, freight equalized, east of Rockies	88.00	5.3
Ammonia, aqueous, 29.4 percent, tanks, works, anhydrous basis, east of Rockies	91.00	5.4
Ammonium nitrate, domestic, fertilizer grade, 33.5 percent N, bags, f.o.b. works	68.00	10.1
Ammonium sulfate, standard granular, bulk, f.o.b. works, base price	32.00	7.6
Nitrogen solutions, tanks, freight equalized, N unit	² 1.28	6.4
Sodium nitrate, domestic, crude, bulk, carlots, works	48.00	14.8
Urea, 45 percent N, agricultural, bags, carlots, (30 tons) delivered, East	103.00	11.4

¹ Data from Oil, Paint, and Drug Reporter (9).

² Price per unit of 20 pounds of nitrogen.

Figure 17 shows that under these conditions custom-applied liquid nitrogen fertilizer is more economical than solid nitrogen fertilizer applied by the farmer. Twelve acres is the break-even point for the costs of liquid nitrogen fertilizer applied by the farmer with equipment costing \$100 versus the costs of farmer-applied solid nitrogen fertilizer; 23 acres if the equipment costs \$200. The break-even acreages for liquid nitrogen fertilizer custom-applied versus farmer-applied with \$100 and \$200 equipment are 17 and 31 acres, respectively.

Data developed by Gaines and Crowe (89), given in table 39, show that 56 pounds of nitrogen per acre, derived either from anhydrous ammonia or ammonium nitrate, can be applied to 50 acres of cropland for 13.6 cents per pound. Anhydrous ammonia would have an economic advantage with the fertilization of larger acreages, the use of higher rates of application, or a combination of the two conditions. Under 1949 price relationships, 56 pounds of nitrogen per acre in the form of anhydrous ammonia could be applied to 850 acres for 10.2 cents per pound of nitrogen. The corresponding cost of nitrogen in the form of ammonium nitrate would be 12.9 cents. The purchase prices of the ammonia and the ammonium nitrate constituted 86 and 90 percent, respectively,

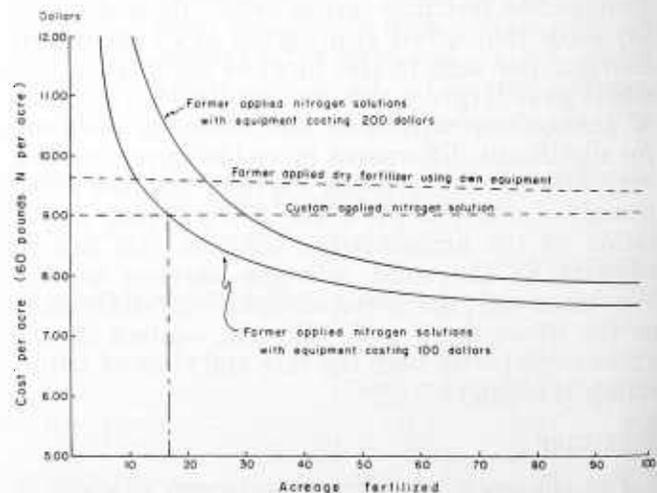


FIGURE 17.—Cost of applied nitrogen per fertilized acre in North Carolina, Bowen and coworkers (48).

of the total applied cost. The total cost for custom application of anhydrous ammonia at the rate of 100 pounds of nitrogen per acre was estimated as only slightly more (\$0.30) than the purchase price of the equivalent ammonium nitrate.

TABLE 39.—Cost of using anhydrous ammonia and ammonium nitrate at an average rate of 56 pounds of nitrogen per acre on 50 acres of Mississippi cropland at 1949 prices¹

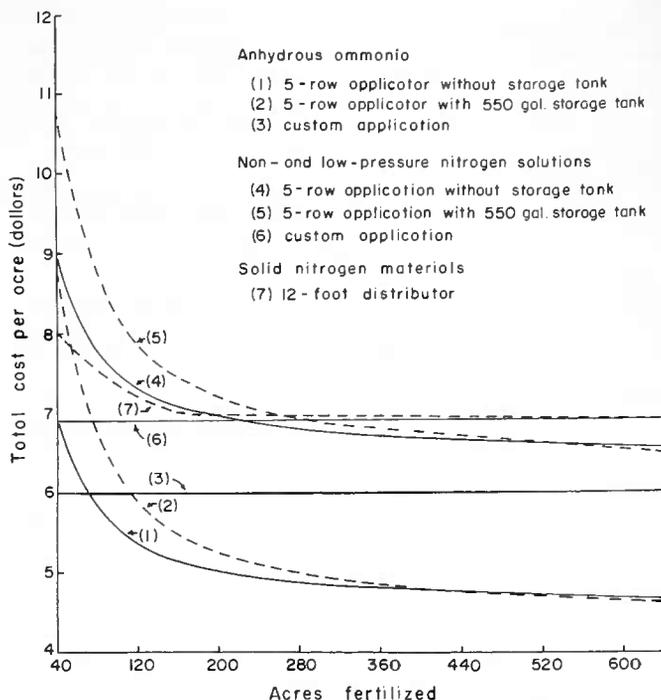
Items of cost	Anhydrous ammonia	Ammonium nitrate
Storage and handling.....	\$62.49	\$9.33
Application.....	71.27	44.08
Material.....	246.50	327.25
Total costs.....	380.26	380.66
Cost per acre.....	7.60	7.61
Cost per pound of N.....	.136	

¹ Data from Gaines and Crowe (39).

Heady and Baum (96) compared the cost of farmer-applied solid and liquid forms of nitrogen fertilizer in northern Iowa on the basis of 1956 prices. The study was based on fixed costs associated with the application equipment and storage facilities and such variable costs as the acreage fertilized, rate of fertilization, cost of fertilizer, labor, and tractor power.

Figure 18 shows the total cost per acre of applying liquid and solid nitrogen fertilizers at a rate of 50 pounds of nitrogen per acre. A farmer with a 5-row applicator and a 550-gallon storage tank applied 61 pounds of ammonia (50 pounds N) per acre on approximately 56 acres as economically as the same amount of a solid source of nitrogen was applied with a 12-foot distributor. The cost of applied ammonia per acre was less than the cost of solid fertilizer when applied on more than 56 acres or at higher rates of application. It was more when applied on less than 56 acres or at lower rates than 50 pounds nitrogen per acre. The break-even acreage for a farmer without a storage tank was about 30 acres. Break-even acreages for the farmer using nonpressure and low-pressure solutions were approximately 185 acres if he had no storage tank, and 260 acres if he had a 550-gallon storage tank.

At a nitrogen application rate of 100 pounds



DN-1951

FIGURE 18.—Total cost per acre of applying 50 pounds of nitrogen in liquid and solid forms.

per acre, anhydrous ammonia was applied for less per acre than solid nitrogen materials even on small acreages. This high application rate lowers the break-even acreages for nonpressure and low-pressure solutions to 50 acres if the farmer has no tank and to 80 acres if a 550-gallon storage tank has been purchased.

Custom application for anhydrous ammonia was 90 cents per acre less than for nitrogen solution. Nitrogen solutions can be custom-applied on a small acreage at rates of 50 pounds of nitrogen per acre at a lower cost than the solid form can be applied with farmer-owned equipment. Custom application of liquids was much less expensive than farmer application of solid materials when 100 pounds of nitrogen were applied per acre. At this rate of application, average custom costs per acre for anhydrous ammonia were less than the cost of farmer application up to about 120 acres. A comparable figure for the nonpressure and low-pressure solutions was about 320 acres.

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APPENDIX

State agencies having jurisdiction over the storage and handling of liquid nitrogen fertilizers

State	Agency and location	State	Agency and location
Alabama.....	Division of Agricultural Chemistry, Department of Agriculture and Industries, State Office Bldg., P.O. Box 220, Montgomery.	Mississippi.....	Motor Vehicle Comptroller, Jackson.
Alaska.....	Commissioner, Department of Commerce, P.O. Box 2259, Juneau.	Missouri.....	Industrial Inspection, Labor and Industrial Relations Department, 221 West High St., Jefferson City.
Arizona.....	Corporation Commission, Capitol Annex, Phoenix.	Montana.....	.....
Arkansas.....	Boiler Inspection Division, State Labor Department, A. E. A. Building, Capitol Grounds, Little Rock.	Nebraska.....	.....
California.....	Division of Industrial Safety, Department of Industrial Relations, 965 Mission St., San Francisco 3.	Nevada.....	.....
Colorado.....	.....	New Hampshire.....	.....
Connecticut.....	Department of State Police, 100 Washington St., Hartford 1.	New Jersey.....	Bureau of Engineering and Safety, Department of Labor and Industry, 29 East Front St., Trenton.
Delaware.....	.....	New Mexico.....	Border Inspector, New Mexico Cooperation Commission, Santa Fe.
Florida.....	Fire Marshal (storage and handling); Florida Railroad and Public Utilities Commission (transportation), Tallahassee.	New York.....	.....
Georgia.....	Safety Fire Commissioner, Atlanta 3.	North Carolina.....	Weights and Measures Division, North Carolina Department of Agriculture, Raleigh.
Hawaii.....	Bureau of Industrial Hygiene, Department of Health, Honolulu.	North Dakota.....	.....
Idaho.....	Division of Commercial Feed and Fertilizer, Department of Agriculture, 206 State House, Boise.	Ohio.....	Industrial Relations Department, State Office Bldg., Columbus.
Illinois.....	Division of Foods, Dairies and Standards, Department of Agriculture, 160 North LaSalle St., Chicago 1.	Oklahoma.....	Seed, Feed and Fertilizer Division, Oklahoma State Board of Agriculture, 122 Capitol Bldg., Oklahoma City.
Indiana.....	Fire Marshal, State House, Indianapolis.	Oregon.....	Bureau of Labor, 325 State Office Bldg., Salem.
Iowa.....	Department of Public Safety, Des Moines 19.	Pennsylvania.....	Bureau of Inspection, Pennsylvania Department of Labor and Industry, Harrisburg.
Kansas.....	State Board of Agriculture, State Office Building, Topeka.	Rhode Island.....	Industrial Inspection Division, Rhode Island Department of Labor, 83 Park St., Providence.
Kentucky.....	Department of Agriculture, Labor and Statistics, Capitol Annex, Frankfort.	South Carolina.....	Department of Fertilizer Inspection and Analysis, Clemson.
Louisiana.....	Anhydrous Ammonia Commission of Louisiana, Box 4261, Capitol Station, Baton Rouge 4.	South Dakota.....	.....
Maine.....	Department of Agriculture, Augusta.	Tennessee.....	Division of Feeds, Seeds, and Fertilizers, 411 State Office Bldg., Nashville.
Maryland.....	.....	Texas.....	.....
Massachusetts.....	.....	Utah.....	.....
Michigan.....	Chemical Laboratories Division, Michigan Department of Agriculture, 1615 South Harrison Rd., East Lansing.	Vermont.....	Vermont Agricultural Experiment Station, Burlington.
Minnesota.....	Safety and Accident Division, Labor and Industry Department, 137 State Office Bldg., St. Paul 1.	Virginia.....	Transportation Division, State corporation Commission, Blanton Bldg., Richmond.
.....	.....	Washington.....	.....
.....	.....	West Virginia.....	Department of Agriculture, Charleston 5.
.....	.....	Wisconsin.....	Industrial Safety and Buildings Division, Industrial Commission, Room 234, State Office Bldg., Madison.
.....	Wyoming.....	State Chemist and Director, Chemical and Bacteriological Laboratory, Box 656, Laramie.



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