ECUT Energy Data Reference Series: Ammonia Synthesis Energy-Use and Capital Stock Information

**J. K. Young
D. R. Johnson**

July 1984

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AND CAPITAL STOCK INFORMATION

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Prepared for
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Technologies Division
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Richland, Washington 99352

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D. L. Brenchley
Project Manager

PREFACE

This study was completed for the Division of Energy Conversion and Utilization Technologies (ECUT) in the Department of Energy. The division's mission has three parts:

1. to monitor advances in basic scientific research and evaluate them for their applicability to energy conservation
2. to perform exploratory development on novel or innovative conservation concepts
3. to expand the technology base for advanced conservation technologies.

To aid in achieving this mission the ECUT staff established a planning and systems analysis function to identify and assess the array of opportunities for energy conservation R&D.

This on-going activity provides ECUT Staff with the information necessary to decide where to invest limited research dollars to derive the maximum benefit to the public. As part of its systems analysis role for ECUT, PNL published a general energy use data book covering all major end-use sectors (Imhoff, Liberman, and Ashton 1982). In contrast, the current ECUT Energy Data Reference Series is more narrowly targeted; each volume contains detailed capital stock and energy-use data for selected end-use sectors that are likely to be most impacted by existing or proposed ECUT R&D activities.

This volume relates to the ECUT R&D activity on engine combustion systems technology. The objective of this R&D is to develop and accelerate the application of new combustion technologies that can be used by engine designers to improve fuel efficiency, to maintain environmental acceptability, and to ease the transition to alternative fuels. This volume explores the potential for the results of this research to be applied to transportation modes that use Otto cycle engines.

Other volumes in the ECUT Energy Data Reference Series include:

Abarcar, R. B., G. J. Hane and D. R. Johnson. 1984. ECUT Energy Data Reference Series: Lightweight Materials for Ground Transportation. PNL-5192, Pacific Northwest Laboratory, Richland, Washington.

Abarcar, R. B., G. J. Hane and D. R. Johnson. ECUT Energy Data Reference Series: High-Temperature Materials for Advanced Heat Engines. PNL-5193, Pacific Northwest Laboratory, Richland, Washington.

Hane, G. J. and D. R. Johnson. 1984. ECUT Energy Data Reference Series: Otto Cycle Engines in Transportation. PNL-5191, Pacific Northwest Laboratory, Richland, Washington.

Chockie, A. D. and D. R. Johnson. 1984. ECUT Energy Data Reference Series: Boilers. PNL-5195, Pacific Northwest Laboratory, Richland, Washington.

The bulk of the research for this series was conducted in calendar year 1982. While the data portrayed in these publications have not changed dramatically, certain trends, particularly those that were forecast, may have shifted in the interim between research and publication.

The ECUT Data Reference Series is part of a series of studies in support of the ECUT research planning effort. Other ECUT publications are:

Bomelburg, H. J. 1983. Efficiency Evaluation of Oxygen Enrichment in Energy Conversion Processes. PNL-4917, Pacific Northwest Laboratory, Richland, Washington.

Chockie, A., et al. 1983. "An Overview of Research Requirements for Stationary Combustion Systems." In Proceedings of the 18th Intersociety Energy Conversion Engineering Conference, pp. 2092-2098. American Institute of Chemical Engineers, 345 E. 47 St., New York, New York.

Hane, G. 1983. Efficiency Evaluation of the DISC, DHC, and DI Diesel Engines. PNL-4568, Pacific Northwest Laboratory, Richland, Washington.

Hane, G., et al. 1983. A Preliminary Overview of Innovative Industrial Materials Processes. PNL-4505, Pacific Northwest Laboratory, Richland, Washington.

Hane, G., et al. 1984. A Review of Studies of Research Opportunities in Energy Conservation. PNL-4571, Pacific Northwest Laboratory, Richland, Washington.

Hopp, W., et al. 1981. An Overview of Energy Conservation Research Opportunities--Executive Summary. PNL-3944 Ex. Sum., Pacific Northwest Laboratory, Richland, Washington.

Hopp, W., et al. 1981. An Overview of Energy Conservation Research Opportunities. PNL-3944, Pacific Northwest Laboratory, Richland, Washington.

Hopp, W., et al. 1982. Identification of Energy Conservation Research Opportunities: A Review and Synthesis of the Literature. PNL-3966, Pacific Northwest Laboratory, Richland, Washington.

- U.S. Department of Energy. 1981. The 1981 ECUT Work Element Appraisal. DOE/CE-0024, U.S. Department of Energy, Washington, D.C.
- U.S. Department of Energy. 1983. Energy Conversion and Utilization Technologies Program Report, 1981-1982. U.S. Department of Energy, Washington, D.C.
- Vallario, R. W. and D. E. DeBellis. 1984. State of Technology of Direct Contact Heat Exchanging. PNL-5008, Pacific Northwest Laboratory, Richland, Washington.
- Vitullo, M., C. Winter and D. R. Johnson. 1984. The Executive Information System. PNL-5190, Pacific Northwest Laboratory, Richland, Washington.

BACKGROUND ON ECUT ENERGY DATA REFERENCE SERIES

The ECUT Energy Data Reference Series defines and assesses in quantitative terms the potential markets for expected ECUT R&D results. Each volume in the series provides data on a particular class of hardware systems that use and convert fuel. The data for each system include inventories of energy capital stocks, specific fuels consumption and product or service activity levels for the years 1980 and 2000, and average thermal efficiencies. Each data set characterizes the capital stock in a sector or subsector of the U.S. economy to which expected results from ECUT R&D projects can be applied. Each reference volume is consistent with the others in the series in format and approach, thus forming a framework for comparing certain aspects of ECUT R&D activities.

The ECUT Energy Data Reference Series serves as a benchmark for energy consumption and for conservation data for technologies addressed by the ECUT Program. The series incorporates the most accurate and up-to-date projections available in the open literature on energy capital stocks and their consumption levels. The series is specifically intended to be one of the many planning tools ECUT management can use to assess what potential impact its research projects will have. The series can also be used to demonstrate the potential impact of research on various stakeholders and constituencies, including industrial interest groups, budget decision makers, and the general public.

METHODOLOGY

The ECUT Energy Data Reference Series synthesizes data from the open literature, including technical reports, results of techno-economic models, industry surveys, and trade journal publications. A specific format was developed around the data items of interest and the intended purpose of the series. Each volume deals with a unique R&D application. Two scenarios are described--a baseline for 1980 and a projection for 2000.

The first line of effort is to extract the most recent data that are already in usable form in the open literature. In the case of competing data from disparate sources, the most reliable data are selected on the basis of the

completeness and extensiveness of the research. Where data sources appear to be equally reliable, an averaging method is employed to derive a single data point.

The second line of effort is to derive or extrapolate the needed data from the literature. For instance, if no energy consumption data are reported, production data can be multiplied by energy intensity data to derive consumption data.

Certain assumptions are used in projecting data points to the year 2000. The general rule is that the status quo is maintained throughout the projected future unless otherwise specified in the text. The energy capital stock is assumed to remain at its 1980 state of technology, and no competing technologies are considered to capture market share. This is in keeping with the objective of defining the potential impact of R&D results. In characterizing systems or processes with multiple fuel inputs, the mix of conventional fuels (those commonly used today) is allowed to change as each fuel is impacted by obvious and compelling factors, but no alternative, non-conventional fuels are projected as part of the fuel mix.

For simplicity, electricity is considered to be a fuel. This allows for a discussion of capital stocks that use electricity as an input without going through the machinations of breaking out power generation inputs, transmission losses, etc. These factors are considered to be constant at the national average, and are readily available in the literature.

SCOPE

The scope is defined along two directions: the data items of interest, and the end-use sector applications for ECUT R&D activities. The data items of interest, described below, are essential to a basic perspective on the potential impact of expected ECUT R&D results. Data items that change with time are defined for the year 1980 and projected for the year 2000.

DATA ITEMS

The data items considered in this series of reports are unit process hardware systems, efficiency estimates, capital stock information, fuel consumption demand, and product or service activity level.

Unit Process Hardware System

A unit process hardware system (UPHS) is generally defined as the least extensive configuration of components in a conversion or utilization system to which R&D results can be applied, and for which efficiency and fuel consumption estimates can be made. A UPHS is uniquely defined for each sector potentially impacted by ECUT R&D activity.

Efficiency Estimates

A specific definition of efficiency is developed for each application of each R&D activity. In general, the definition is based on the first law of thermodynamics, and is applied to the UPHS of interest. A broad discussion of major efficiency-loss mechanisms is included in each section on efficiency.

Capital Stock Information

Data derived for 1980 and projected for 2000 are based on the number of UPHSs in the economy that would be potential recipients of ECUT R&D results. UPHSs are disaggregated according to the type of fuel they use or convert. Other factors that help characterize the capital stock as a market for ECUT research are included as necessary and/or available.

Fuel Consumption Demand

Fuel consumption demand is developed for 1980 and projected for 2000. The thermal energy value (measured in Btu) of each fuel type consumed or converted by the capital stock of interest is developed for each application of each R&D activity. Electricity is considered to be a fuel. The extent to which use of alternative (non-conventional) fuels will penetrate the end-use sectors of interest by the year 2000 is not predicted. The relative contribution of conventional fuels in use today is, however, allowed to change with the turnover of capital stocks and with trends in consumer preferences. No attempt is made to project the availability of conventional fuels in 2000.

Product or Service Activity Level

Data on the demand for each product or service resulting from the use or conversion of energy by the capital stock of UPHSs are developed for 1980 and projected for 2000.

SUMMARY

Energy requirements for ammonia synthesis totaled 0.55 quadrillion Btu of natural gas in 1980 and 28,500 MMBtu (8.3×10^6 kWh) of electricity (Table S.1). Efficiencies ranged from 0.72 to 0.8 for natural gas and 0.65 for electricity. Ammonia production in 1980 is estimated at 21 million tons. In the year 2000, U.S. ammonia production is estimated to be between 27 to 34 million tons with 19 to 31 million tons being produced using natural gas. A most likely value of 25 million tons of ammonia from natural gas feedstock is projected. As much as 20% of the energy from natural gas fuel could be saved if a more active catalyst could be developed that would reduce the operating pressure of ammonia synthesis to 1 atm.

TABLE S.1. R&D Application Summary

Fuel Type	UPHS Average Efficiency	# Unit Process Hardware Systems		Fuel Consumption Demand (BTU)		Product or Service Activity Level (tons NH ₃)	
	1980	1980	2000	1980	2000	1980	2000
Natural Gas (fuel)	0.72	175	186	1.2×10^{14}	1.6×10^{14}	19×10^6	25×10^6
Natural Gas (feedstock)	0.8	--	--	4.3×10^{14}	5.7×10^{14}	--	--
Electricity (fuel)	0.65	--	--	8.8×10^{11}	9.4×10^{11}	--	--
Coal	--	0	19	--	--	--	--

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1.0 INTRODUCTION

Direct synthesis of ammonia from atmospheric nitrogen and hydrogen is one of the classic heterogenous catalytic reactions. The current ammonia process is a mature one, but successful research by ECUT on improved catalysts could produce benefits in terms of both feedstock and process energy savings. The purpose of this study is to characterize the ammonia production industry, one segment of the potential market for expected ECUT R&D results. The ammonia production process will be characterized in terms of its present day efficiency, the capital stock of facilities in the U.S. to produce ammonia, and the energy content of fuels and feedstocks used in the process.

The process of synthesizing ammonia has undergone nearly continuous evolution since the development of the Haber process during World War I. Virtually all ammonia in the world is currently manufactured by the catalytic reaction of hydrogen with nitrogen. Generally, the hydrogen is produced by steam reforming of hydrocarbons. In the U.S., the hydrocarbon most frequently used is natural gas (Burch et al. 1979). Therefore, natural gas was chosen as the feedstock for our study.

The manufacture of synthetic anhydrous ammonia consists of three basic steps: preparation of synthesis gas, purification, and ammonia synthesis. The first two involve the generation of hydrogen, the introduction of nitrogen in the stoichiometric synthesis proportion, and the removal of catalyst poisons such as carbon dioxide, carbon monoxide, and water (Le Blanc et al. 1978). These procedures are included in the material balance, but this study will focus only on the ammonia synthesis step.

Ammonia synthesis is accomplished at elevated temperatures and pressures that result in high process energy requirements. Conditions vary greatly, but basically a relatively pure gas stream consisting of approximately three parts hydrogen and one part nitrogen is fed as make-up gas to a synthesis loop. Ammonia is produced by passing the make-up gas and synthesis gas over a catalyst. Ammonia is removed from the exit gas by condensation. The limiting factors that affect catalyst performance and conversion of feed gases to ammonia are described as follows (Le Blanc et al. 1978):

1. Synthesis Pressure: Increases in pressure increase the equilibrium percentage of ammonia and also the reaction rate. Operating pressures range from 2,000 to 11,000 psig. Higher pressures favor equilibrium but lower pressures favor economics. A pressure of 3,000 psig was used in this study.
2. Synthesis Temperature: Higher temperatures increase reaction rates, but lower equilibrium amounts of ammonia. Temperatures range from 700°F to 1050°F. A temperature of 700°F was used in this study.
3. Space Velocity: Space velocity is the ratio of the volumetric rate of gas at standard conditions to the volume of the catalyst. As space velocity is increased through increased recycle rate, ammonia production increases although conversion per pass decreases. A space velocity of approximately $15,000 \text{ hr}^{-1}$ was assumed for this study.
4. Hydrogen/Nitrogen Ratio: The maximum conversion occurs at ratios of 2.5:1 to 3:1. A ratio of 3:1 was chosen for this study.
5. Inlet Ammonia Concentration: As the amount of ammonia in the inlet stream increases, ammonia conversion decreases. Condensation does not remove all the ammonia so that 1.5% to 5% will be recycled. We assumed 2 mol% is recycled.
6. Inerts: Methane and argon are the components in the synthesis gas referred to as inerts. They negatively influence both reaction rate and equilibrium. The inerts are removed by a purge, but synthesis gas is lost, which also limits the usefulness of the purge. Our study assumes that 4 mol% argon and 5 mol% methane are contained in the synthesis gas.

The parameters chosen in this study are those used by the Battelle Columbus study (Burch et al. 1979). The ammonia process described in the following section does not represent any particular process, but it is representative of current industrial practices.

1.1 PROCESS DESCRIPTION

A schematic of the ammonia process is shown in Figure 1.1. The encircled numbers refer to the various gas streams. The compositions are shown in Table 1.1. The process shown is intended to approximate average conditions for a plant built within the last 12 years (Burch et al. 1979). A capacity of 1300 tons per day was assumed for pressure drop calculations (Strelzoff 1981, p. 31).

1.1.1 Preparation of Synthesis Gas

The feedstock to the ammonia synthesis step is nitrogen and hydrogen. The hydrogen is made from natural gas that has been desulfurized, mixed with steam, and converted to hydrogen in the primary reformer. From the primary reformer, the feedgas is introduced into the secondary reformer along with sufficient air to provide the necessary amount of nitrogen to react with the hydrogen. The gas exiting the secondary reformer also contains carbon monoxide and carbon dioxide. The carbon monoxide is converted to carbon dioxide in a two-stage "shift" reactor. The carbon dioxide is removed in a methanation step. The feedgas is now ready for the ammonia synthesis reactor (Burch et al. 1979).

1.1.2 Ammonia Synthesis

The ammonia synthesis step is detailed in Figure 1.2. Modern loops all recycle the unreacted gases because of equilibrium limitations. The synthesis loops are of two types. One type recovers ammonia after recycle compression (to be analyzed in our study), the other type recovers ammonia product before recycle compression (Le Blanc et al. 1978).

The synthesis gas is compressed to 3000 psig and combined with recycle gas. Almost without exception all modern large-scale ammonia plants employ centrifugal compressors for synthesis service (Le Blanc et al. 1978). There is a tendency for inert material, such as methane and argon, to concentrate within the synthesis loop. Therefore, there is a purge stream after the compressor to remove inerts from the ammonia synthesis loop (A. Little 1976).

After the final compressor stage, the gas mixture is cooled to -10°F to liquefy ammonia. This is accomplished by refrigeration using ammonia as the refrigerant. About 80% of the ammonia content of the gas is liquefied and thus

FIGURE 1.1. Process for Producing Ammonia and Carbon Dioxide

TABLE 1.1. Compositions of Process Streams Shown in Figure 1.1

Stream Number	Description	Pounds per Short Ton of Ammonia Produced								
		Methane	Nitrogen	Hydrogen	Ammonia	Argon	Carbon Dioxide	Carbon Monoxide	Water	Oxygen
1	Desulfurized natural gas (feedstock)	882	--	--	--	--	--	--	--	--
2	Natural gas (fuel)	767	--	--	--	--	--	--	--	--
3	Process air	--	1778	--	--	21	1	--	--	477
4	Reformed gas	17	1778	314	--	21	725	1080	2050	--
5	Shifted gas	17	1778	390	--	21	2415	12	1363	--
6	Gas to methanator	17	1778	390	--	21	15	12	--	--
7	Make-up synthesis gas	29	1778	385	--	21	--	--	20	--
8	Converter outlet gas	1249	7458	1626	2567	2069	--	--	--	--
9	Recycle gas containing ammonia product	1220	7333	1598	2558	2048	--	--	--	--
10	Compressed gas	1249	9112	1980	2558	2069	--	--	20	--
11	Ammonia product	tr	tr	tr	1974	tr	--	--	20	--
12	Converter inlet gas	1249	9112	1980	584	2069	--	--	--	--
13	Purge gas (used for fuel)	29	125	28	9	21	--	--	--	--
14	Ammonia recovered from purge and let-down	--	--	--	26	--	--	--	--	--
15	Recovered carbon dioxide	--	--	--	--	--	2415	--	--	--

FIGURE 1.2. Ammonia Synthesis Materials and Energy Balance

removed. The ammonia product is transferred to storage via a pressure let-down system. An additional 1.3% of total ammonia product recovered from the purge stream also enters storage at this point (Burch et al. 1979).

After most of the ammonia has been removed from the gas stream, the gas is reheated to about 360°F in a heat exchanger by exit gases from the converter. The gas stream enters the catalytic converter and is channeled through intricate piping that uses heat from exiting gases to obtain an initiation temperature for the synthesis gas. The gas stream exits the converter at 700°F and passes through a waste heat boiler. It is cooled further by incoming gases in a heat exchanger. The gas is then recompressed and reenters the synthesis loop.

The heat generated by the exothermic synthesis reaction is transferred to superheated steam used to power turbines for the compressors and refrigeration units (Burch et al. 1979).

1.2 EFFICIENCY ESTIMATES

Three efficiencies were shown in Table S.1. Each is based on the first law of thermodynamics, and is defined as

$$\text{efficiency} = \frac{\text{total thermal energy available} - \text{losses}}{\text{total thermal energy available}}$$

Each efficiency estimate relates to an energy feedstock or fuel type and its ultimate use in the process. Taken together, these estimates provide a measure of efficiency for the entire ammonia reduction process. Disaggregated, each helps to pinpoint where expected ECUT R&D results can lead to energy savings and fuel switching. In one case, the fuel (natural gas) is a feedstock for the process.

The efficiency is a measure of the amount of feedstock in Btu that is actually used as hydrogen in the ammonia synthesis step. The losses assuming 882 lb CH₄ (from natural gas) per ton NH₃ produced (Burch et al. 1979) are summarized as follows:

17 lb CH₄ (unreacted)
 120 lb CH₄ (side reactions)
112 lb CH₄ (purge gas as hydrogen)
 249 lb CH₄

$$\text{efficiency} = \frac{(882 \text{ lb} - 249 \text{ lb}) \times 100}{882 \text{ lb}} = 72\%$$

In the second case, natural gas is utilized as a fuel. For every ton of ammonia produced, the boiler superheats 41,000 lb of 300°F (400 psia) steam using 5.22 MMBtu of natural gas as a fuel. This value does not include the average efficiency of a gas-fired, water-tube boiler, which is 0.8 (KVB Inc. 1977).

In addition, electricity is needed to pump 69,000 lbs of cooling water per lb NH₃ produced to the ammonia separations step. The efficiency of 0.65 is assumed for the centrifugal pump and motor (Peters and Timmerhaus 1980).

An overall efficiency of 0.74 for ammonia synthesis can be defined by combining these three subprocess efficiencies according to their proportion of energy throughput:

	Btu/lb	Percent of Total Energy/lb
Natural Gas Feedstock	11,500	78
Natural Gas Fuel	3,250	22
Electric Fuel	1	--

$$\text{process efficiency} = \begin{aligned} &(\text{nat. gas feedstock eff.})(\% \text{ of total Btu/lb}) + \\ &(\text{nat. gas fuel eff.})(\% \text{ of total Btu/lb}) + \\ &(\text{elec. fuel eff.})(\% \text{ of total Btu/lb}) \end{aligned}$$

While this is a handy reference number, it is of limited value in projecting the potential impact of expected biocatalysis R&D results. The only efficiency to be impacted by this R&D is the natural gas feedstock conversion efficiency. Biocatalytic processes may convert a smaller percentage of feedstock than the

conventional process. The boiler efficiency and the pumping efficiency are not addressed by this research activity.

The real impact of the R&D would be to eliminate the absolute demand for the services provided by the boiler. If the result of the research is the successful design of a catalyst that would operate near ambient temperature and pressure, then the work performed by the boiler is no longer needed. The subprocess efficiency estimates find their real importance in the calculation of the total amount of fuels consumed in ammonia production.

1.3 CAPITAL STOCK INFORMATION

1.3.1 Capital Stock Information, 1980

Table 1.2 shows U.S. plant capacities for producing ammonia. In 1980, calculated U.S. ammonia production capacity was about 23,500,000 short tons/yr. However, actual production for 1980 was estimated at 19 million tons ("Ammonia," 1982). The total number of plants in 1980 was 175.

1.3.2 Capital Stock Information, 2000

The world population is expected to double in the next 35 years, and more than 75% of this increase will occur in less developed countries. Since underdeveloped countries have a low per capita fertilizer consumption, the world production of fertilizer must more than double in the same period to raise per capita consumption to acceptable levels (U.S. Dept. of Commerce 1982).

Since 80% of ammonia produced is used to manufacture nitrogenous fertilizers (A. Little 1976), fertilizer production can be an indicator of future ammonia production. World consumption of nitrogenous fertilizer is expected to increase at 6% per year overall in the 1980 to 1985 period. U.S. consumption is expected to increase at 4% for the same period (U.S. Dept. of Commerce 1982).

Despite increasing demand, shortages and high prices for natural gas in the U.S. have stagnated U.S. ammonia plant production. U.S. consumers are forced to look for foreign services to satisfy growth of consumption ("Fertilizer...", 1982). Ammonia plants will not be built in the U.S. unless:

- 1) there is a government resolution regarding imports of ammonia from gas-rich

TABLE 1.2. 1982 Production Capacity for Ammonia and Carbon Dioxide

State/City	Company	Production Capacity (in thousands of short tons/yr)
<u>Alabama</u>		
Cherokee	U.S. Steel Corp., USS Agri-Chemicals Division	175
Muscle Shoals	Tennessee Valley Authority	68
<u>Alaska</u>		
Kenai	Union Oil Co. of California, Union Chems. Div.	1,039
<u>Arizona</u>		
Benson	Apache Powder Co.	14
Benson	Dye Carbonic, Inc.	--
Chandler	Dye Carbonic, Inc.	--
Chandler	Valley Nitrogen Producers, Inc., Arizona Agro-chemical Co., subsid.	40
<u>Arkansas</u>		
Blytheville	The Williams Companies, Agro Chem. Co., subsid.	340 ^(a)
Helena	Allied Chemical Corp., Agricultural Div.	187
Helena	Houston Natural Gas Corp., Liquid Carbonic Corp., subsid., I/M Div.	--
<u>California</u>		
Brea	Union Oil Co. of California, Union Chems. Div.	280
Carson	Atlantic Richfield Co., ARCO Chem. Co., Div.	--
El Centro	Valley Nitrogen Producers, Inc.	180
El Segundo	Standard Oil Co. of Calif. Chevron U.S.A., Inc., subsid.	6
Hanford	Carbonic Engineering Co.	--
Hanford	Occidental Petroleum Corp., Hooker Chem. Corp., subsid., Occidental Chem. Co., subsid., Western Div.	40 ^(b)
Helm	Valley Nitrogen Producers, Inc.	150
Hercules	Valley Nitrogen Producers, Inc.	69 ^(b)
Lathrop	Carbonic Engineering Co.	--
Lathrop	Occidental Petroleum Corp., Hooker Chem., Corp., subsid., Occidental Chem. Co., subsid., Western Div.	99 ^(c)
Ontario	Union Carbide Corp., Linde Div.	--
Richmond	Standard Oil Co. of California, Chevron Chem. Co., subsid. Petroleum Div., Indust. Chems.	--
Richmond	Standard Oil Co. of California, Chevron U.S.A. Inc., subsid.	120
Taft	Houston Natural Gas Corp., Liquid Carbonic Corp., subsid., I/M Div.	--
Torrance	Mobil Corp., Mobil Oil Corp., United States Div.	--
Ventura	U.S.A. Petrochem Corp.	147
Wilmington	Union Oil Co. of California, Union Chems., Div.	--
Tehama Co.	Valley Nitrogen Producers, Inc.	34

TABLE 1.2. (contd)

State/City	Company	Production Capacity (in thousands of short tons/yr)
<u>Colorado</u>		
Cortez	Dye Carbonic, Inc.	--
<u>Delaware</u>		
Delaware City	Allegheny Ludlum Indust., Inc., Chemetron Corp., subsid., Carbon Dioxide Div.	--
Delaware City	Getty Oil Co., Getty Refining & Marketing Co., subsid.	--
<u>Florida</u>		
Pensacola	Air Products and Chems., Inc.	75
Sunterville	Rosario Resources Corp., Dixie Lime and Stone Co., subsid.	--
Tampa	Houston Natural Gas Corp., Liquid Carbonic Corp., subsid., I/M Div.	--
Tampa	The Gardinier Companies, Gardinier Inc., U.S. Phosphoric Products	133
<u>Georgia</u>		
Augusta	Columbia Nitrogen Corp.	635
Augusta	Houston Natural Gas Corp., Liquid Carbonic Corp., subsid., I/M Div.	--
Savannah	Kaiser Aluminum & Chem. Corp., Kaiser Agri- culture Chems. Div.	150
Gordon	Georgia Nitrogen, Inc.	35
<u>Hawaii</u>		
Barber's Point	Gaspro, Inc.	--
<u>Idaho</u>		
Conda	Baker Indust. Corp.	95
Pocatello	Simplot Co., Minerals and Chem. Div.	94
<u>Illinois</u>		
East Dubuque	N-Ren Corp., St. Paul Ammonia Products Div.	225
Morris	Airco, Inc., Airco Indust. Gases Div.	--
Morris	Allegheny Ludlum Indust., Inc., Chemetron Corp., subsid., Carbon Dioxide Div.	--
<u>Indiana</u>		
Jeffersonville	Allegheny Ludlum Indust., Inc., Chemetron Corp., subsid., Carbon Dioxide Div.	--
Terre Haute	CF Indust., Inc., Terre Haute Nitrogen Complex	146
Terre Haute	Houston Natural Gas Corp., Liquid Carbonic Corp., subsid., I/M Div.	--
<u>Iowa</u>		
Clinton	Getty Oil Co., Hawkeye Chem. Co., subsid.	136
Creston	Green Valley Chem. Corp.	35
Fort Dodge	Famland Indust., Inc.	215

TABLE 1.2. (contd)

State/City	Company	Production Capacity (in thousands of short tons/yr)
<u>Iowa (contd)</u>		
Fort Dodge	Houston Natural Gas Corp., Liquid Carbonic Corp., subsid., I/M Div.	--
Fort Madison	First Mississippi Corp., FIRSTMISS INC., subsid.	320
Fort Madison	Standard Oil Co. of California, Chevron Chem. Co., subsid., Ortho Div.	95
Muscataine	Publicker Indust. Inc.	--
Port Neal	Terra Chems. Internat'l, Inc.	204
<u>Kansas</u>		
Atchison	Midwest Solvents Co., Inc.	--
Dodge City	Famland Indust., Inc.	230
Dodge City	Houston Natural Gas Corp., Liquid Carbonic Corp., subsid., I/M Div.	--
Lawrence	Airco, Inc., Airco Indust. Gases Div.	--
Lawrence	Cooperative Farm Chems. Association	380(d)
Lawrence	FMC Corp., Indust. Chem. Group	--
Wichita	Vulcan Materials Co., Chems. Div	35
<u>Kentucky</u>		
Brandenburg	Olin Corp., Olin Chems. Group	--
<u>Louisiana</u>		
Donaldsonville	Ampro	410(e)
Donaldsonville	CF Indust., Inc., Donaldsonville Nitrogen Complex	1,499
Donaldsonville	The Williams Companies, Agrico Chem. Co.	410(f)
Donaldsonville	Triad Chem.	350
Geismar	Allied Chem. Corp., Agricultural Div.	340
Geismar	Borden Inc., Borden Chem. Div., Petrochems.	300
Lake Charles	Jupiter Chems., Inc.	125(g)
Lake Charles	Olin Corp., Olin Chems. Group	476
Luling	Monsanto Co., Monsanto Agricultural Products Co.	813(h)
New Orleans	Air Products and Chems., Inc.	225
New Orleans	American Cyanamid Co., Agricultural Div.	--
New Orleans	American Cyanamid Co., Plant Food Div.	615
New Orleans	Houston Natural Gas Corp., Liquid Carbonic Corp., subsid., I/M Div.	--
Pollock	Famland Indust., Inc.	410
Sterlington	Internat'l Minerals & Chem. Corp., IMC Chem. Group, Inc., subsid.	790
Taft	Occidental Petroleum Corp., Hooker Chem. Corp., subsid., Occidental Chem. Co., subsid., Jefferson Lake Sulphur Co., div.	90
Piaquemine	Georgia-Pacific, Inc., Chemical Div.	185
Gramercy	Kearney Chemical, Inc.	17

TABLE 1.2. (contd)

State/City	Company	Production Capacity (in thousands of short tons/yr)
<u>Minnesota</u>		
St. Paul	Koch Indust., Inc., Koch Refining Co., subsid.	--
<u>Mississippi</u>		
Columbus	Car-ren	66 ⁽ⁱ⁾
Pascagoula	Mississippi Chem. Corp.	187
Pascagoula	Standard Oil Co. of California, Standard Oil Co. (Kentucky), subsid.	475
Yazoo City	Mississippi Chem. Corp.	350
<u>Missouri</u>		
Joplin	Tyler Corp., Atlas Powder Co., subsid.	129
Louisiana	Hercules Inc., Indust. Systems Dept.	71
<u>Nebraska</u>		
Beatrice	Phillips Petroleum Co., Fertilizer Div.	211
Fremont	CF Indust., Inc., Fremont Nitrogen Complex	41
Hastings	Famland Indust., Inc.	158
Omaha	Allied Chem. Corp., Agricultural Div.	200
<u>New Jersey</u>		
Gibbstown	Allegheny Ludlum Indust., Inc., Chemetron Corp., subsid., Carbon Dioxide Div.	--
<u>New Mexico</u>		
Bueyeros	S.E.C. Corp.	--
Carlsbad	Baker Indust. Corp.	190
Carlsbad	N-Ren Corp., N-Ren Southwest, Inc., subsid.	66
Solano	S.E.C. Corp.	--
Lovington	Tipperary Corp.	99
<u>New York</u>		
Olean	Agway Inc.	--
Olean	Felmont Oil Corp.	86
<u>North Carolina</u>		
Tunis	CF Indust., Inc., North Carolina Nitrogen Complex	170 ^(j)
<u>Ohio</u>		
Green Springs	Allegheny Ludlum Indust., Inc., Chemetron Corp., subsid., Carbon Dioxide Div.	--
Lima	The Standard Oil Co. (Ohio), Vistron Corp., subsid., Chems. Dept.	470 ₉ ^(k)
Middletown	Armco Steel Corp.	220
South Point	Allied Chem. Corp., Specialty Chems. Div.	220
Toledo	Allegheny Ludlum Indust., Inc., Chemetron Corp., subsid., Carbon Dioxide Div.	--

TABLE 1.2. (contd)

State/City	Company	Production Capacity (in thousands of short tons/yr)
<u>Ohio (contd)</u>		
Toledo	Houston Natural Gas Corp., Liquid Carbonic Corp., subsid., I/M Div.	--
Toledo	The Standard Oil Co. (Ohio), Vistron Corp., subsid. Chems. Dept.	--
<u>Oklahoma</u>		
Enid	Farmiland Indust., Inc.	820
Enid	S.E.C. Corp.	--
Pryor	Ensearch Corp., Nipak, Inc., subsid.	100
Pryor	N-Ren Corp., Cherokee Nitrogen Div.	83
Tulsa	Carbonic Gas Co.	--
Verdigris	The Williams Companies, Agrico Chem. Co., subsid.	820
Woodward	Bison Nitrogen Products	--
Woodward	Oklahoma Nitrogen Co.	410
<u>Oregon</u>		
Portland	Pennwalt Corp., Inorganic Chem. Div.	8
St. Helens	Reichhold Chems., Inc.	85
<u>Pennsylvania</u>		
Clairton	United States Steel Corp., USS Agri-Chemicals Div.	408
Newell	Allied Chem. Corp., Indust. Chems. Div.	--
Palmerton	Gulf + Western Indust. Inc., The New Jersey Zinc Co., div.	36
Philadelphia	Houston Natural Gas Corp., Liquid Carbonic Corp., subsid., I/M Div.	--
Philadelphia	Publicker Indust. Inc.	--
<u>Tennessee</u>		
Memphis	W.R. Grace & Co., Agricultural Chems. Group	399
Tyner	Carbonic Indust. Corp	--
Tyner	CF Indust., Inc., Chattanooga Nitrogen Complex	136 ^(j)
Woodstock	Allegheny Ludlum Indust., Inc., Chemetron Corp., subsid., Carbon Dioxide Div.	--
<u>Texas</u>		
Beaumont	I.E. du Pont de Nemours & Co., Inc., Elastomer Chems. Dept.	341
Beaumont	Esmark Inc., Swift Agricultural Chems. Corp.	372
Beaumont	Mobil Corp., Mobil Oil Corp., Unites States Div.	--
Borger	Cominco American Inc.	400
Corpus Christi	PPG Indust., Inc., Chem. Group, Chem. Div.-U.S.	--
Deer Park	Liquid Air Corp. of North America, Southwestern Region	--

TABLE 1.2. (contd)

State/City	Company	Production Capacity (in thousands of short tons/yr)
<u>Texas (contd)</u>		
Deer Park	Rohm and Haas Co., Rohm and Haas Texas Inc. subsid.	47(j)
Dimmitt	Goodpasture, Inc.	61
Dumas	Diamond Shamrock Corp., Oil and Gas Unit	160
Fort Stockton	Coastal States Gas Corp., Colorado Interstate Corp., subsid.	--
Freeport	Dow Chemical U.S.A.	--
Kerens	Ensearch Corp., Nipak, Inc., subsid.	115
Mitchell	Northern Natural Gas Co.	120
Odessa	El Paso Natural Gas Co., El Paso Products Co., subsid.	117
Pasadena	Houston Natural Gas Corp., Liquid Carbonic Corp., subsid., I/M Div.	--
Pasadena	Tenneco Inc., Tenneco Chems., Inc.	200
Plainview	Occidental Petroleum Corp., Hooker Chem. Corp., subsid. Jefferson Lake Sulphur Co., div.	56
Texas City	Houston Natural Gas Corp., Liquid Carbonic Corp., subsid., I/M Div.	--
Texas City	Standard Oil Co. (Indiana), Amoco Oil Co., subsid.	477
Trinidad	Allegheny Ludlum Indust., Inc., Chemetron Corp., subsid., Carbon Dioxide Div.	--
Victoria	E.I. du Pont de Nemours & Co., Inc., Plastic Products and Resins Dept.	100
Victoria	Liquid Air Corp. of North America, Southwestern Region	--
Big Spring	W.R. Grace & Co.	100
<u>Utah</u>		
Geneva	United States Steel Corp., USS Agri-Chemicals Div.	70
Salt Lake City	Carbo Chem. Co.	--
Wellington	Dye Carbonic, Inc.	--
<u>Virginia</u>		
Hopewell	Airco, Inc., Airco Indust. Gases Div.	--
Hopewell	Allied Chem. Corp., Fibers Div.	350
<u>Washington</u>		
Finley	Phillips Pacific Chem. Co.	150
Kennewick	Gas-Ice Corp.	--
Seattle	Houston Natural Gas Corp., Liquid Carbonic Corp., subsid., I/M Div.	--
Seattle	Coyne Chemical Co.	150

TABLE 1.2. (contd)

State/City	Company	Production Capacity (in thousands of short tons/yr)
<u>Washington (contd)</u>		
Tacoma	Occidental Petroleum Corp., Hooker Chem. Corp., subsid., Hooker Chems. and Plastics Corp., subsid., Electrochemical and Specialty Chems. Div.	--
<u>West Virginia</u>		
Belle	E.I. du Pont de Nemours & Co., Inc., Biochems, Dept.	339
Marmet	Liquid Air Corp. of North American, Southeastern Region	--
Natium	PPG Indust., Inc., Chem. Group, Chem. Div. U.S.	33
South Charleston	FMC Corp., Indust. Chem. Group	22
<u>Wyoming</u>		
Cheyenne	Coastal States Gas Corp., Colorado Interstate Corp., subsid., Wycon Chem. Co., subsid.	139 23,500 (rounded)

- (a) Ammonia plant owned by town, leased to Agrico.
 (b) May be closed.
 (c) Ammonia plant 47% owned by California Ammonia Co.
 (d) Operated by Farmland Industries, Inc., for Cooperative Farm Chemicals
 Assoc. (owned 75% by Farmland).
 (e) Not currently operating.
 (f) Ammonia plant owned by Gulf Oil Co., leased to Agrico.
 (g) Operated by Terra Chemical.
 (h) Newest plant (372 thousand tons per year on stream in 1977) is a joint
 venture with Chevron Chemical Co.
 (i) May be sold.
 (j) Operated by CF Industries for Farmers Chemical Associations, a co-op member
 of CF.
 (k) Coke-oven by-product.

Source: 1978 Directory of Chemical Producers using data from Chemical Economics Handbook to update
 production figures to 1982.

foreign producers, 2) industry uses alternative feedstocks such as coal, or
 3) energy consumption for ammonia from natural gas is significantly reduced (A.
 Little 1976).

The National Fertilizer Development Center in Muscle Shoals, Alabama, has already completed a plant to produce hydrogen from coal (U.S. Dept. of Commerce 1982). The price is high because investment in industrial hydrogen from coal exceeds costs for the current process by a factor of two. In addition, high costs for transporting coal to major refinery centers make coal a more expensive alternative than natural gas. Nevertheless, continuing shortages of natural gas make alternative fuels look more and more attractive. Exxon projected that by the year 2000 as much as 40% to 50% of industrial hydrogen will be from coal (Corneil 1977). However, conservative new forecasts indicate that alternative fuels will get little use until after the turn of the century ("Progress ...", 1982).

During the period from 1960 to 1970, growth in U.S. domestic consumption of fertilizer averaged 10% (A. Little 1976). The recent performance of nitrogen fertilizer (4% growth rate) casts more doubt on future growth rates. Decline in net farm income along with research to improve nitrogen efficiency in the soil has caused a slowdown in the predicted growth of domestic consumption. U.S. exports to developing nations will become more vulnerable because other countries are boosting their own industries as well as increasing barter with regions that have abundant natural gas ("Fertilizer...", 1982). An annual growth rate of only 1.7% was predicted for North American ammonia production by Leonties (1977). Earlier sources indicate that since there is a fundamental need for increasing quantities, a growth of 6% per year through 1985 was considered realistic (A. Little 1976).

Non-fertilizer uses of ammonia are also expanding at a rate of 1.5% to 3.5% per year (Blue and Landels 1977). An average value of 2.0% will be extrapolated until 2000.

Since there are so many factors influencing the U.S. ammonia capacity, three scenarios are described: an optimistic, a pessimistic, and a most likely. In the pessimistic scenario, a growth rate of 1.7% for fertilizer uses of ammonia is used. Fifty percent of new construction uses gasified coal as a feedstock. A year 2000 production rate of 27 million tons of ammonia is derived with natural gas plants accounting for 19 million tons.

The optimistic scenario assumptions are that because of government regulations in 1985 it will be possible to sell ammonia despite high prices. After 1985, ammonia production for fertilizer capacity grows at 4%/year. Only 10% of the plants use coal as a feedstock and are built primarily for demonstration purposes. A demand of 33 million tons is derived and, of that amount, 30 million tons (90%) is produced using natural gas feedstock.

A most likely scenario is also proposed in which the growth rate of fertilizer and non-fertilizer production averages about 2% and by the year 200, only 10% of the new ammonia plants use coal gas as a feedstock. A production rate of 25 million tons/year of ammonia from natural gas and 2.5 million tons from alternative feedstocks is projected.

Based on the three scenarios, ammonia production using natural gas as a feedstock will be between 19 and 30 million tons of ammonia with a probable value of 25 million tons. Coal will be a feedstock for between 2.5 and 8 million tons of ammonia with a probable value of 2.5 million. We assumed each plant produces about 450 tons NH_3 /day with an 80% capacity factor, which was the average in 1980. Thus, in 2000, there will be a most likely value of 186 ammonia plants that use natural gas as a feedstock and 19 that use coal.

1.4 FUEL CONSUMPTION DEMAND

Fuel consumption is derived from both 1980 and 2000, assuming that the process methodology remains the same and future production ranges from 19 to 30 million tons with a probable value of 25 million tons. Only two types of fuel, natural gas and electricity are used in the synthesis step. Based on 1980 production and energy-use data, approximately 5.5×10^{14} Btu of natural gas and 8.8×10^{11} Btu of electricity were used in the ammonia synthesis step. In the year 2000, a most likely value of 9.4×10^{11} Btu of electricity will be required, and 7.3×10^{14} Btu of natural gas. Fuel consumption is calculated based on the assumptions described below.

The boiler requires 5.22×10^6 Btu/ton NH_3 of natural gas to generate superheated steam (600°F, 4000 psi) from 300°F saturated steam. Actual energy to the boiler must consider efficiency, thus there are $5.22 \times 10^6/0.8$ or 6.5×10^6 Btu of natural gas burned per ton of NH_3 produced.

Natural gas is the feedstock for conventional ammonia plants. Approximately 22.9×10^6 Btu is required per ton of ammonia produced. Feedstock energy accounts for 78% of the energy used for ammonia synthesis. Total fuel consumption is calculated as follows:

$$\frac{\text{Total Fuel Consumption}}{\text{Fuel Consumption}} = \text{Fuel Consumption/Ton NH}_3 \text{ Produced} \times \text{Production Rate}$$

Electricity is used to drive the pump that supplies cooling water to the ammonia separations step. We assumed each of 175 ammonia plants had a capacity of approximately 400 tons NH_3 /day. The cooling water pump used 106 Btu (150 hp) or 3.3×10^9 Btu/yr to pump water at a rate of 2300 gpm. Total energy consumption for the ammonia industry is then calculated as follows:

$$\frac{\text{Total Fuel Consumption}}{\text{Fuel Consumption}} = \frac{\text{Annual Energy Consumption}}{\text{Efficiency}} \times \frac{\text{Number of Plants}}{\text{Plants}}$$

The development of a more active catalyst could save a substantial amount of energy in ammonia synthesis. Ideally, industry could use atmospheric pressure during the ammonia synthesis step because ammonia conversion would be almost instantaneous. This would save 6.55×10^6 Btu/ton of ammonia of natural gas used to manufacture steam for the compressor. As much as 1.2×10^{14} Btu/yr in 1980 or 1.6×10^{14} Btu/yr in 2000 could be saved. This is 22% of the energy used in the synthesis step.

A biocatalytic process to produce ammonia from biomass would allow the 22.4×10^6 Btu/ton NH_3 produced of natural gas feedstock to be used on other sectors of the economy. Natural gas is a premium fuel because of limited domestic sources,

1.5 PRODUCT ACTIVITY LEVEL

A discussion of factors influencing the market for ammonia and the capacity of the U.S. industry is found in Section 1.3. Approximately 21 million tons of ammonia capacity existed in 1980. The industry was operating at 90% of capacity, so actual production was about 19 million tons. We calculated a most likely production rate of 25 million tons of NH_3 from natural gas in the year 2000 ("Key Chemicals" 1981). If we assume a 90% capacity factor, as was the case in 1980, actual production capacity will be 28 million tons.

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