

SULFUR

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After nearly a century of world dominance in the production of native sulfur, the U.S. Frasch industry shuttered its last mine as a result of low sulfur prices, which were caused by weakened demand for phosphate processing, continually increasing competition from low-cost recovered sulfur producers, escalating production costs, and technical problems. Worldwide, production of native sulfur and pyrites continued to decline as environmental regulations forced increased sulfur recovery to limit atmospheric emissions of sulfur dioxide. Growth in sulfur recovery continued to outpace sulfur demand, resulting in increased stocks worldwide.

Through its major derivative, sulfuric acid, sulfur ranks as one of the more important elements used as an industrial raw material. It is of prime importance to every sector of the world's industrial and fertilizer complexes. Sulfuric acid production is the major end use for sulfur, and consumption of sulfuric acid has been regarded as one of the best indices of a nation's industrial development. More sulfuric acid is produced in the United States every year than any other chemical; 39.9 million metric tons (Mt), equivalent to about 13.1 Mt of elemental sulfur, were produced in 2000, slightly less than that in 1999 (U.S. Census Bureau, 2001).

Domestic production of sulfur in all forms was 9% lower; shipments, consumption, imports, and prices decreased (table 1; figures 1, 2). The United States maintained its position as the leading world producer and consumer of sulfur and sulfuric acid. The quantity of sulfur recovered during the refining of

petroleum and the processing of natural gas continued the upward trend established in 1939. Sulfur produced by using the Frasch process was 50% lower than that of 1999 because of the closure of the last mine. Frasch production data were estimated by the U.S. Geological Survey (USGS) based on company reports and other public information. Production of recovered sulfur from petroleum refineries and natural gas processing operations was slightly higher than in 1999, although production from petroleum refining increased and natural-gas recovery remained about the same. Because shipments were higher than production, stocks decreased by 54%.

Byproduct sulfuric acid from the Nation's nonferrous smelters and roasters, produced as a result of laws restricting sulfur dioxide emissions, supplied a significant quantity of sulfuric acid to the domestic merchant (commercial) acid market. Production from this sector decreased by 22% because the three copper smelters that closed in 1999 were not reopened.

World sulfur production changed little in 2000 (table 1). Frasch production was lower because of continued production cutbacks in the United States. Elemental sulfur production from recovered sources, primarily during the processing of natural gas and petroleum products, increased slightly. Approximately 86% of the world's elemental sulfur production came from recovered sources; the quantity of sulfur supplied from these sources was dependent on the world demand for fuels, nonferrous metals, and petroleum products, not for sulfur.

World sulfur consumption remained about the same with

Sulfur in the 20th Century

In 1900, Herman Frasch was trying to perfect his hot water melting process for producing sulfur. Domestic production was about 3,200 metric tons of sulfur valued at \$88,100. Native sulfur deposits in Louisiana, Nevada, Texas, and Utah were mined with conventional mining methods. Domestic sulfur production, including mined elemental sulfur and pyrites, supplied about one-quarter of the U.S. sulfur demand of about 415,000 tons. Most sulfur and pyrites, domestic and imported, were used to produce sulfuric acid that was consumed in many different industries. Virtually all elemental sulfur imports came from the Italian island of Sicily, and pyrite imports were from unspecified locations. Pyrites remained a significant raw material for sulfuric acid until 1982. When the Frasch process was successfully commercialized in 1903, the U.S. sulfur industry took a turn for the better. By about 1915, the United States surpassed Italy as the world's leading producer of sulfur, a situation that continued throughout the century, during which eight companies produced nearly 340 million tons of sulfur from 36 mines in Louisiana and Texas. Frasch sulfur production hit its peak in 1974 when 12 mines produced 8 million tons.

Domestic production of elemental sulfur recovered as a byproduct of natural gas processing and oil refining was first reported in 1938 and grew steadily from that time. Recovered sulfur overtook Frasch as the primary domestic sulfur source in 1982. Sulfur also was recovered in the form of byproduct sulfuric acid from nonferrous metal smelters; production data were published for the first time in 1911.

In 2000, domestic sulfur production totaled 10.3 million tons, 81% from recovered operations, 9% from one Frasch mine, and 10% as byproduct acid from nonferrous metal smelters. Consumption was 12.5 million tons, including 2.8 million tons of imported sulfur and sulfur contained in sulfuric acid. The end uses did not change significantly during the century, although consumption in 2000 was nearly 4,000 times higher than it was in 1900. About 90% of domestic sulfur consumption was converted to sulfuric acid and then used, in decreasing order, in phosphate fertilizer and other agricultural chemical production, in oil refining, in copper ore leaching, and in many other industrial uses. Elemental sulfur was used as a plant nutrient, in synthetic rubber production, in pulp and paper products, and in other inorganic chemicals.

about 50% used in fertilizer production and the remainder in myriad other industrial uses. World trade of elemental sulfur increased slightly from the levels recorded in 1999. Worldwide inventories of elemental sulfur were higher.

Legislation and Government Programs

The U.S. Environmental Protection Agency (EPA) issued the final rule for reduced sulfur content of gasoline early in 2000, as part of tier 2 of the Clean Air Act Amendments of 1990. The standards were nationwide standards, with the implementation time extended for some States and for some refining facilities. By 2006, the sulfur content in gasoline must average 30 parts per million (ppm) with an upper limit of 80 ppm. States in the Rocky Mountain region and Alaska were given until 2007 to reach standards, because those States generally had better air quality than other parts of the country. Small refineries with fewer than 1,500 employees or less than 155,000 barrels per day (bbl/d) of processing capacity were required to meet interim goals until 2008, when the national limits would be imposed. The 2008 deadline could be delayed until 2010 if the refiners could demonstrate a severe economic hardship. Small refineries received special consideration because the installation of new equipment in small facilities could be economically damaging (Oil & Gas Journal, 2000b).

The EPA began the process for new sulfur standards for diesel fuel by proposing new limits for sulfur, reducing the allowable content from 500 ppm to 15 ppm, a 97% decrease. The final rule was announced in December, although implementation of the new rule was delayed for further review. The EPA reduced diesel sulfur levels in a first step to clean up emissions from heavy-duty trucks and buses. In addition to reducing sulfur dioxide emissions from diesel engines, changes were made because new emission control apparatus needed to reduce particulate emissions from these vehicles could not operate effectively unless sulfur levels in the fuel were significantly reduced. The agency estimated the cost of diesel regulations at 4 to 5 cents per gallon (Oil & Gas Journal, 2001).

The petroleum refining industry was concerned, however, that the cost of compliance might be significantly higher than the EPA estimated, in the range of 15 to 50 cents per gallon. Costs that high could make it economically unfeasible for some facilities to install the necessary apparatus, forcing closure of refining capacity, and perhaps causing shortages in supply (Chemical Market Reporter, 2001). Low-sulfur diesel presented more technological challenges than low-sulfur gasoline, requiring more substantial investments for high-pressure hydrotreating facilities. The sulfur compounds found in diesel are more difficult to remove than those found in gasoline (Moyse, 2000). Refineries had several options for reducing sulfur levels to meet new regulations. The least expensive choice was using advanced catalysts in desulfurization units. Not all refineries would be able to use this alternative (Garritsen and others, 2000). Other more expensive treatment options for producing low-sulfur fuels were known (Moyse, 2000).

Other concerns about the new regulations addressed the issues of timing and transportation. Implementation of the new regulations was required on approximately the same time frame as those for gasoline. Questions were raised as to whether the refining industry would be able to make the required upgrades to diesel and gasoline facilities simultaneously without compromising the availability of either product. In addition,

most diesel fuel is transported via pipelines that also transport home heating oil for which no new sulfur requirements were enacted. Industry officials believed that it would be difficult to prevent diesel product contamination from the pipelines that also carried the higher sulfur heating oil (Hess, 2000).

Production

Elemental Sulfur.—Production statistics were collected on a monthly basis and published in the USGS monthly sulfur Mineral Industry Surveys. All of the 120 operations to which survey requests were sent responded, representing 100% of the total production shown in table 1. In 2000, production was 7% lower than that of 1999. Shipments decreased by 3%, and the value of shipments was 35% lower owing to a decrease in the average unit value of elemental sulfur. Trends in sulfur production are shown in figure 2.

Frasch.—Native sulfur associated with the caprock of salt domes and in sedimentary deposits was mined by the Frasch hot-water method, in which the native sulfur was melted underground and brought to the surface by compressed air. Freeport-McMoRan Sulphur Inc., a subsidiary of McMoRan Exploration Co., was the last remaining Frasch producer in the United States. After announcing plans in July to close its Main Pass Mine by the end of the year, Freeport abruptly closed the mine 4 months early, at the end of August, citing low sulfur prices and increased operating expenses, especially natural gas prices, for the early closure (Fertilizer Markets, 2000c). An example of the scope of increased costs was the price of natural gas, a major constituent of Frasch production cost, which nearly doubled from the beginning of the year to July, with additional increases set for September (McMoRan Exploration Co., 2000b).

The mine also was closed ahead of schedule because a geologic and tectonic study revealed significant stability problems in a subsurface brine cavity. Continued production would have been impossible without substantial investment to remediate the problem. Because drilling activities had already been curtailed and mining was to be suspended at the end of the year, the company decided to close the mine rather than to incur the expense necessary to alleviate the technical problems (Green Markets, 2000).

Main Pass was a mine operated on a salt dome sulfur deposit in the Gulf of Mexico, about 51 kilometers (km) (32 miles) from the coast of Louisiana. The Main Pass offshore complex, which was more than 1.6 km (1 mile) long and was the largest structure in the Gulf, had a production capacity of more than 5,500 metric tons per day (t/d) (McMoRan Exploration Co., 2000a). Production began in 1991 at a development cost of \$880 million (Chemical & Engineering News, 2000).

When Freeport announced plans to close its mine, it proposed to concentrate on its sulfur transportation and marketing business and to continue meeting its supply contracts through purchases of recovered sulfur. The company later offered the sulfur logistics business for sale, expecting about \$80 million for the deal. By yearend, a buyer had not been identified (Fertilizer Markets, 2001). In addition to the mine, Freeport's operations included facilities for forming, loading, remelting, and transporting sulfur in Galveston, TX; Port Sulphur, LA; and Tampa, FL.

Recovered.—Recovered elemental sulfur, a nondiscretionary byproduct from petroleum refining, natural gas processing, and

coking plants, was produced primarily to comply with environmental regulations that were applicable directly to emissions from the processing facility or indirectly by restricting the sulfur content of the fuels sold or used by the facility. Recovered sulfur was produced by 39 companies at 117 plants in 26 States and 1 plant in the U.S. Virgin Islands. Most of these plants were small, with 33 reporting production exceeding 100,000 metric tons per year (t/yr). By source, 76% of recovered elemental sulfur production came from petroleum refineries or satellite plants treating refinery gases and coking plants. The remainder was produced at natural gas treatment plants. The largest recovered sulfur producers, in descending order of production, were Exxon Mobil Corp. (ExxonMobil), BP p.l.c., Chevron Corp., and Motiva Enterprises LLC. The 35 plants owned by these companies accounted for 50% of recovered sulfur output during the year. Recovered sulfur production by State and region is listed in tables 2 and 3.

Five of the 15 largest refineries in the world are in the United States. They are, listed by declining refining capacity, Hovensa LLC's St. Croix, U.S. Virgin Islands, refinery; ExxonMobil's Baytown, TX, and Baton Rouge, LA, refineries; and BP's Texas City, TX, and Whiting, IN, refineries (Chang, Thi, 2000), all of which were significant sulfur producing facilities. Refining capacity does not necessarily mean that these refineries are the largest producers of refinery sulfur. Sulfur production depends on installed sulfur recovery capacity, as well as the types of crude that are refined at the specific refineries. Large refineries that process low-sulfur crudes may have relatively low sulfur production.

Consolidation in the petroleum industry reduced the number of companies operating sulfur recovery operations, although the number of sulfur plants remained about the same. In 1998, Amoco Co. and British Petroleum Co., p.l.c., merged to form BP Amoco p.l.c. (BP Amoco p.l.c., 1999). On November 30, 1999, the U.S. Federal Trade Commission (FTC) approved the merger of Exxon Corp. and Mobil Corp. to form ExxonMobil (Chang, Joseph, 1999).

In April, the FTC approved the merger of BP Amoco p.l.c. with Atlantic Richfield Co. (ARCO). In order to receive approval, the companies agreed to sell all of ARCO's Alaska operations to Phillips Petroleum Co. The new company was called BP Amoco ARCO p.l.c., but the name was quickly simplified to BP p.l.c. (Oil & Gas Journal, 2000a).

Chevron Corp. and Texaco Inc. announced plans to merge to form ChevronTexaco Corp. The companies planned to merge in order to be better able to develop new oilfields and sources of energy (Hoffman, 2000). The new company will be the third largest oil and gas producer in the United States after ExxonMobil and BP. Some divestitures were likely to be required by the FTC before approval. Of particular interest were Texaco's refining and marketing joint ventures with Shell Oil Co. and Saudi Arabian Oil Co. (Westervelt, 2000). In response to the proposed merger of Chevron and Texaco, Shell considered buying Texaco's share of the Shell/Texaco alliances formed in 1997. This arrangement could eliminate many of the regulatory hurdles the Chevron/Texaco merger faced (PentaSul North America Sulphur Review, 2000a).

Mergers were becoming more common in the natural gas industry also. Duke Energy Corp. merged with Phillips Petroleum's gas gathering, processing, and marketing unit to form Duke Energy Field Services, LLC, owned 70% by Duke Energy and 30% by Phillips Petroleum (Duke Energy Corp.,

2001, p. 12). El Paso Energy Corp. was in the process of acquiring The Coastal Corp. (North America Sulphur Service, 2000a). The El Paso Energy/Coastal merger was completed early in 2001, and the name was changed to El Paso Corp. (El Paso Energy Corp., 2001; El Paso Corp., 2001).

Several refining companies were in the process of upgrading their facilities to produce low sulfur fuels from higher sulfur crude oil. ExxonMobil was building a 40,000 bbl/d coker at its Baytown, TX, refinery in order to handle 530,000 bbl/d of Mexican sour crude from Petróleos Mexicanos S.A. de C.V. (Pemex). The upgrades were designed to increase the quality of the fuels produced at Baytown. Sulfur production at the plant was likely to increase to between 350,000 to 360,000 t/yr from about 300,000 t/yr (North American Sulphur Service, 2000c). Marathon Ashland Petroleum LLC was upgrading and adding sulfur recovery capacity at its Garyville, LA, refineries to handle imports from Pemex (Cunningham, 1999b). The Premcor Refining Group Inc.—formerly Clark Refining & Marketing, Inc.—was upgrading its Port Arthur, TX, refinery to handle more heavy crude. New sulfur recovery capacity was being installed to increase production to more than 200,000 t/yr from 130,000 t/yr (North America Sulphur Service, 2000e).

Other companies were involved in joint ventures in which upgraded sour crude producers contributed financing for the upgraded facilities. Phillips Petroleum and Petróleos de Venezuela, S.A. (PdVSA), completed installation of a new vacuum distillation unit and a coker at the Phillips Sweeny, TX, refinery to enable the facility to handle heavy crudes like those produced by PdVSA from the Venezuelan Orinoco Basin (Oil & Gas Journal, 2000c). Shell Oil Co. and Pemex were expanding their joint-venture Deer Park, TX, refinery to 340,000 bbl/d from 280,000 bbl/d. Maya crude will make up 65% of the throughput. Additional sulfur recovery capacity was to bring sulfur capacity to about 200,000 t/yr (North America Sulphur Service, 1999a).

Byproduct Sulfuric Acid.—Sulfuric acid production at copper, lead, molybdenum, and zinc roasters and smelters (table 4) accounted for about 10% of the total domestic production of sulfur in all forms, down from 12% in 1999. Four acid plants operated in conjunction with copper smelters, and six were accessories to lead, molybdenum, and zinc smelting and roasting operations. Even with the cutbacks at copper smelters, the four largest acid plants were all associated with copper mines and accounted for 81% of the output. The largest producers—ASARCO Incorporated, Kennecott Utah Copper Corp., and Phelps Dodge Corp.—operated a total of four copper smelters.

Byproduct acid decreased by 22% from that of 1999, because three of the seven copper smelters in the United States remained closed during the year. The 1999 closures resulted from a serious slump in the world copper industry, with adjusted copper prices lower than they had been at any time in the 20th century (McCoy, 1999).

Consumption

Apparent domestic consumption of sulfur in all forms was 7.0% lower than that of 1999 (table 5). Of the sulfur consumed, 77.6% was obtained from domestic sources, such as elemental sulfur (69.9%) and byproduct acid (7.7%), compared with 77.4% in 1999 and 79.2% in 1998. The remaining 22.4% was supplied by imports of recovered elemental sulfur (18.7%) and

sulfuric acid (3.7%). The USGS collected end-use data on sulfur and sulfuric acid according to the standard industrial classification of industrial activities (tables 6, 7).

Sulfur differs from most other major mineral commodities in that its primary use is as a chemical reagent rather than as a component of a finished product. This use generally requires that it be converted to an intermediate chemical product prior to its initial use by industry. The largest sulfur end use, sulfuric acid, represented 77% of reported consumption with an identified end use. Some identified sulfur end uses were tabulated in the "Unidentified" category because these data were proprietary. Data collected from companies that did not identify shipment by end use also were tabulated as "Unidentified." A significant portion of the sulfur in the "Unidentified" category may have been shipped to sulfuric acid producers or exported, although data to support such an assumption were not available.

Because of its desirable properties, sulfuric acid retained its position as the most universally used mineral acid and the most produced and consumed inorganic chemical, by volume. Based on USGS surveys, reported U.S. consumption of sulfur in sulfuric acid (100% basis) decreased by 7.5% and total sulfur consumption was 4.9% lower than that of 1999.

Agriculture was the largest sulfur-consuming industry, although it decreased to 8.6 Mt compared with 9.2 Mt in 1999. Reported consumption in phosphatic fertilizers was 8.5% lower than that of 1999, a result of decreased production of phosphoric acid. Based on export data from the U.S. Census Bureau, the estimated quantity of sulfur needed to manufacture exported phosphatic fertilizers increased by 16% to 4.8 Mt.

The second largest end use for sulfur was in petroleum refining and other petroleum and coal products. Producers of sulfur and sulfuric acid reported a slight increase in the consumption of sulfur in that end use. Because oil refineries had operated near capacity in 1999 and 2000, little change was expected.

Demand for sulfuric acid in copper ore leaching, the third largest end use, decreased by 7.6%. This use of sulfuric acid decreased for the second consecutive year as a result of downturns in the copper industry. Planned expansions at copper leach operations, however, were expected to cause increased consumption for this use by 2001. All copper producers, even companies that closed smelter operations, continued to operate their solvent extraction-electrowinning (SX-EW) operations in which weak sulfuric acid dissolves copper as it percolates through specially prepared beds of copper minerals. The copper is then concentrated through a solvent extraction process, and the concentrated solution undergoes an electrowinning process that produces 99.99% copper cathode (Phelps Dodge Corp., 1999).

Phelps Dodge was converting its Morenci, AZ, site to the SX-EW process. Upon completion, the 45% increase in SX-EW capacity should require a comparable increase in sulfuric acid consumption for the process. The company's copper smelter near Chino, NM, initially was expected to supply a portion of the necessary acid with the remainder being purchased (Sulfuric Acid Today, 1999). The decreased byproduct acid production resulting from the closed smelters and the expansion of solvent extraction operations in the same area presented the potential for reduced acid supplies for the new SX-EW capacity. Phelps Dodge was considering the option of installing a sulfur burner at its shuttered Hidalgo, NM,

sulfuric acid plant. The company would be able to meet its requirements for its leach operations with virgin acid from Hidalgo (North America Sulphur Service, 2000b). Poorer than expected financial results for the company in the first half of 2000 delayed action on the sulfur burner plan (North America Sulphur Service, 2000d). A new solvent extraction copper operation was planned for development in Utah that would use byproduct sulfuric acid produced at Kennecott Utah Copper's smelter (Sulphur, 2000a).

The U.S. Census Bureau reported 5.73 Mt of sulfuric acid was produced as a result of recycling spent and contaminated acid from petroleum alkylation and other processes (U.S. Census Bureau, 2001). This material was recycled by companies that produced acid for consumption in their own operations and also recycled acid used in their plants. The petroleum refining industry was believed to be the largest source and consumer of recycled acid for use in its alkylation process.

Stocks

Yearend inventories held by Frasch and recovered elemental sulfur producers decreased to 208,000 metric tons (t), about 54% less than those of 1999 (table 1). Based on apparent consumption of all forms of sulfur, combined yearend stocks amounted to about a 6-day supply, compared with a 12-day supply in 1999, a 7-day supply in 1998, a 20-day supply in 1997, and a 17-day supply in 1996. Yearend stocks were lower than they had been since Frasch production became profitable early in the 20th century (Haynes, 1959, p. 61). Final stocks represent 4% of the quantity held in inventories at the end of 1976, when sulfur stocks peaked at 5.65 Mt, a 7.4-month supply at that time (Shelton, 1978, p. 1296). In October, Freeport shipped nearly all the sulfur it had in stocks as it was attempting to exit the sulfur business. In most cases, it was difficult for recovered sulfur producers to accumulate any significant stockpiles. Many recovered operations did not have sufficient space for storing excess sulfur, and in many locations, environmental regulations did not allow stockpiling to occur. Without Frasch production, domestic sulfur stocks were expected to remain relatively stable.

Prices

The contract prices for elemental sulfur, at terminals in Tampa, FL, reported weekly in Green Markets, began the year at \$61 to \$64 per metric ton. Prices quickly decreased to between \$56 to \$59 per ton and remained steady until the end of October, when they increased to between \$62 to \$66 per ton, where they remained throughout the rest of the year.

Based on total shipments and value reported to the USGS, the average value of shipments for all elemental sulfur was \$24.73 per ton, which was 35% lower than that of 1999. Prices varied greatly on a regional basis, causing the discrepancies between Green Markets prices and USGS prices. Tampa prices were usually the highest prices reported because of the large sulfur demand in the central Florida area. U.S. West Coast prices were \$0 to \$1 per ton, though, in reality, West Coast producers often faced negative values as a result of costs incurred at forming plants. These costs were necessary to make solid sulfur in acceptable forms, often known as prills, to be shipped overseas. The majority of West Coast sulfur was sent to prillers

who may have been subsidized by the refineries, and the formed sulfur was shipped overseas (Green Markets, 1999c).

Foreign Trade

Exports of elemental sulfur from the United States, including the U.S. Virgin Islands, were 11% higher in quantity than those of 1999 and 50% higher in value, as listed in table 8, because the average unit value of U.S. export material increased. The average unit value of exported elemental sulfur increased to \$70 per ton from \$52 per ton, which was 35% higher than in 1999. Exports from the West Coast were 659,000 t, or 86% of total U.S. exports.

The United States continued to be a net importer of sulfur—imports of elemental sulfur exceeded exports by 1.6 Mt. Recovered elemental sulfur from Canada and Mexico delivered to U.S. terminals and consumers in the liquid phase furnished about 94% of all U.S. sulfur import requirements. Total elemental sulfur imports decreased by about 10% in quantity and decreased by 24% in value; imports from Canada, mostly by rail, were 3% higher; and waterborne shipments from Mexico were 10% lower than those of 1999 (table 10). Imports from Venezuela were estimated to account for about 6% of all imported sulfur.

The most unusual detail concerning imports was that one shipment of about 46,000 t of formed Canadian sulfur was transported by ship from Vancouver, British Columbia, to Galveston, TX. Because the closure of Main Pass raised questions about possible sulfur supply shortages by yearend, Freeport imported one shipload of solid sulfur from Canada. Unlike most Canadian imports that entered the United States as molten sulfur by rail into the northern States and went cross-country to Florida, Freeport's shipment was transported by ship from Vancouver to Galveston, where Freeport operated remelting facilities. Freeport also bought formed sulfur from Hovensa LLC in St. Croix, U.S. Virgin Islands, for remelting to meet their supply contracts (PentaSul North America Sulphur Review, 2000b).

With the decreased supplies and some concern of price increases at yearend, several Florida fertilizer companies were pursuing necessary permits to build a terminal south of Tampa to handle formed sulfur. After several unexpected delays late in 2000, Big Bend Transfer Station Co. (BBTC) received from the Hillsborough County Commission approval for its sulfur melting plant south of Tampa early in 2001. The joint venture formed by Cargill Inc.; CF Industries, Inc.; and IMC Global Inc. planned to build a facility for remelting formed sulfur as a means of diversifying their supply options. The project needed an air quality permit from the county's Environmental Protection Commission. Upon successful completion of the permitting process, BBTC planned to install facilities for handling 1.5 million tons per year (Mt/yr) of sulfur, with possible expansions to 2 Mt/yr (Green Markets, 2001). This would enable BBTC to buy formed sulfur at the best prices available, perhaps from foreign producers.

In addition to elemental sulfur, the United States also had significant trade in sulfuric acid. Sulfuric acid exports were 23% higher than those of 1999 (table 9). Acid imports were more than seven times greater than exports (tables 9, 11). Canada was the source of 57% of U.S. acid imports, most of which were probably byproduct acid from smelters. Canadian shipments to the United States came by rail, and the remainder

of imports came primarily by ship from Europe, Latin America, and Japan. The tonnage of imports of sulfuric acid was 3.5% more than that of 1999, but the value of imported sulfuric acid decreased by 34%.

World Review

The global sulfur industry remained divided into two sectors—discretionary and nondiscretionary. In the discretionary sector, the mining of sulfur or pyrites is the sole objective; this voluntary production of native sulfur or pyrites is based on the orderly mining of discrete deposits, with the objective of obtaining as nearly a complete recovery of the resource as economic conditions permit. In the nondiscretionary sector, sulfur or sulfuric acid is recovered as an involuntary byproduct, the quantity of output subject to demand for the primary product irrespective of sulfur demand. Nondiscretionary sources represented nearly 87% of the sulfur in all forms produced worldwide as listed in table 12.

With the termination of Frasch production in the United States, Poland was the only country that produced more than 1 Mt of native sulfur by using either the Frasch or conventional mining methods (table 12). Small quantities of native sulfur were produced in Asia, Europe, and South America. The importance of pyrites to the world sulfur supply has significantly decreased; China was the only country in the top 15 sulfur producers whose primary sulfur source was pyrites. About 71% of all pyrites production was in this country.

Of the 25 countries listed in table 12 that produced 400,000 t or more of sulfur, 18 obtained the majority of their production as recovered elemental sulfur. These 25 countries produced 94% of the total sulfur produced worldwide. The international sulfur trade was dominated by a limited number of exporting countries, which, in descending order of importance, were Canada, Russia, Saudi Arabia, Japan, and the United Arab Emirates; these countries exported more than 1 Mt of elemental sulfur each and accounted for 64% of total sulfur trade. Major sulfur importers, in descending order, were China, Morocco, the United States, India, Tunisia, and Brazil, all with imports of more than 1 Mt.

World production of sulfur was virtually the same in 2000 as it was in 1999; consumption was believed to be slightly higher. Statistics compiled by CRU International Ltd. showed 1998 to be the seventh consecutive year in which sulfur supplies exceeded demand. Although complete data for 1999 and 2000 were not available, it could be assumed that 2000 represented the ninth consecutive year of excess sulfur supplies (Kitto, 2000).

Prices in most of the world were believed to have averaged higher throughout the year, but with a slight decrease at yearend. Production of native sulfur was 20% lower than that of 1999 as a result of termination of mining in the United States. Frasch production in Poland increased by 17%, the first increase there since 1995. Recovered sulfur production increased slightly and byproduct sulfuric acid production decreased by about 4% from those of 1999. Supply continued to exceed demand; worldwide sulfur inventories increased, much of which was stockpiled in Canada. Globally, sulfur from pyrites decreased by 13%, much of which was a result of the continued decline in China and the conversion of a pyrite-based sulfuric acid plant in Spain to a sulfur burner.

Statistics compiled by the Oil & Gas Journal showed the

United States producing 20% of the world's total refining capacity and 42% of the world's sulfur recovery capacity derived from oil refineries. The publication listed 742 oil refineries in 114 countries; only 54 of these countries were reported to have sulfur recovery capacity (Stell, 2000, p. 67-68). Although the sulfur recovery data appeared to be incomplete, analysis of the data showed that most of the countries reporting no sulfur recovery at refineries were small, with developing economies and limited refining industries. In general, as refining economies improve and the refining industries mature, additional efforts are made to improve sulfur recovery and atmospheric emissions.

Mergers of major oil producers were not limited to the United States. Following the merger in 1999 of France's Total and Belgium's Compagnie Financière Belge des Pétroles (PetroFina) to form TotalFina, the new company merged with Société Nationale Elf Aquitaine to form Total Fina Elf S.A. (TotalFinaElf). The deal formed the world's fourth largest oil company. For approval by the European Commission, TotalFina was required to divest some of its assets in France. TotalFinaElf owned 55% of France's refining capacity (Chemical Market Reporter, 2000a).

Regulations were enacted in many countries limiting the amount of sulfur allowable in fuels and the quantity of sulfur dioxide emitted into the atmosphere. Many of these regulations will result in increased sulfur recovery. Bulgaria, Canada, China, the European Union (EU), Thailand, and the United States set or proposed significant, although varied, reductions in the sulfur content of motor fuels sold in those countries. Suppliers were required to meet these new standards by between 2005 and 2011. Germany, already covered under EU regulations, accelerated the timetable for new EU guidelines to be met in Germany to 2001 and was pushing for more stringent limitations in the EU's next round of rulemaking (Sulphur, 1999d). Based on Germany's urgings, European oil industry experts expected sulfur in gasoline to be reduced to 10 ppm by 2003. Germany was suggesting sulfur-free fuels throughout the European Union by 2007 (Cunningham, 2000b, p. 14). The Japanese auto industry proposed further cuts to the sulfur level of motor fuels in Japan. Allowable sulfur in gasoline was 100 ppm with reduction to 50 ppm set for 2005. The new proposal suggested limiting sulfur to 5 to 10 ppm. No timeframe for implementation was established (Sulphur, 2000k). At the 2000 European Oil Refining Conference, discussions addressed additional legislation to further limit sulfur in fuels. Legislation enacted in 1999, which would take effect in 2000, reduced the allowable sulfur in nonmotor heavy fuel oils to 1% (Cunningham, 2000b, p. 13).

European refineries faced challenges in upgrading to meet new fuel specifications. Premium prices charged for cleaner fuels were not expected to make up for the poorer yields and higher processing costs resulting from deeper desulfurization. Upgrading a typical refinery in Europe was estimated to cost more than \$100 million (Packer, 2000). Total cost estimates of new European fuel specifications, including reduced sulfur content, could approach \$9 billion. Increased costs would include expenditures needed for installing new facilities; modifying existing plants; increased operating expenses; new maintenance, insurance, and overhead charges; and storage fees for seasonal products (Richardson and du Preez, 2000). A European petroleum industry expert estimated that the total worldwide cost of producing low-sulfur motor fuels could

approach \$2.5 trillion (Sulphur, 2001).

The next targets for this type of legislation were expected to be marine bunker fuels, fuels used by ocean going vessels. The International Maritime Organization—the international governing organization for shipping—had set a 4.5% sulfur specification for these heavy fuel oils. The average sulfur content of bunker fuels was considerably less at about 3%; but even at that level, the emissions from bunker fuel were around 4 Mt/yr of sulfur in sulfur dioxide. The European Union was considering the imposition of more stringent sulfur restrictions on fuels used in ships traveling in the English Channel, the Baltic Sea, and the North Sea because shipping has become the source of an increasingly large portion of sulfur dioxide emissions in Europe. From 1990 to 2000, the shipping portion of European sulfur dioxide emissions increased from 10% to 30%. The major factor contributing to this increase was that emissions from motor vehicles had decreased. Negotiations for establishing worldwide marine fuel requirements were expected to be contentious and time-consuming. Local restrictions were likely to be imposed prior to international agreements being reached. After bunker fuels were addressed, more controversy was expected when the sulfur content of jet fuel was debated (Sulphur, 2001b). The U.S. Air Force and the U.S. Department of Energy were assessing the reduction of the sulfur content of jet fuels as a first step toward decreasing sulfur dioxide emissions from advanced propulsion systems. The research was aimed at understanding how sulfur compounds in jet fuels affect engines and emission control systems before mandating reduced sulfur levels in jet fuels (Sulphur, 2000e).

In many countries, companies were installing additional capacity for recovering sulfur and byproduct sulfuric acid, as well as producing low-sulfur fuels in advance of new government mandates and/or before legal requirements of existing laws took effect. Firms in Canada, Egypt, Germany, the Netherlands, Russia, the United Arab Emirates, the United States, and Uzbekistan were reducing sulfur dioxide emissions at their facilities. Low-sulfur fuels were offered years in advance of legal requirements in Bahrain, Kuwait, the United Kingdom, and the United States.

Not all of these developments caused significant increased production, but most created at least incremental additions to sulfur supplies. These increases in sulfur recovery, coupled with the widespread trend toward higher sulfur content in crude oils, promised continued growth in worldwide production of recovered sulfur and byproduct sulfuric acid. Only discretionary sulfur production was expected to decrease.

Australia.—Technical problems seemed to be resolved for most of Australia's nickel laterite projects using a pressure acid leach process (PAL). The PAL represented a potential demand for large quantities of sulfur to produce the sulfuric acid needed for the process. In PAL operations, nickel laterite ore slurries were leached with sulfuric acid at up to 250° C, in a titanium clad autoclave. Sulfuric acid consumption could be up to 30 t of acid per ton of metal produced—enough to justify the installation of a sulfur-burning sulfuric acid plant (Sulphur, 2000i).

QNI Pty. Ltd. and Comet Resources Ltd. planned a PAL project in Western Australia (QNI Pty. Ltd., 2000). Anaconda Nickel Ltd. was working on three PAL projects. The Murrin Murrin project achieved design capacity during the year and proceeded with its second stage of development. The company's Mount Margaret project was under development and

expected to quickly achieve design capacity taking advantage of the lessons learned at Murrin Murrin. Mount Margaret was to begin construction early in 2001, with commissioning and production beginning in 2003. A third operation, Cawse, was planned to begin in 2004 (Cunningham, 2000a).

The world's largest single-stage sulfuric acid plant provided all the acid required for stage I at Murrin Murrin. Additional acid would be required from another acid plant or byproduct acid from local sources to meet requirements for stage II. Sulfuric acid plants were planned for the other projects (Cunningham, 2000a).

Estimates placed the sulfur requirements for each planned acid plant at between 500,000 to 750,000 t/yr of sulfur. Total requirements for the Anaconda projects were expected to be between 2.5 to 3 Mt/yr of elemental sulfur within 5 years. Anaconda was considering the development of a phosphate fertilizer project in the same region to make better use of the infrastructure built to support the nickel projects. The phosphate project would require an additional 400,000 to 500,000 t/yr of sulfur. Canada has provided much of the sulfur for the new Australian demand, but diversified markets were being pursued, with Middle Eastern sulfur likely offering competition for Canadian suppliers (Cunningham, 2000a).

Bahrain.—Bahrain Petroleum Co. planned to update its refinery to produce diesel fuel containing between 50 to 500 ppm sulfur. Hydrogen cracking would reduce sulfur from 7,500 ppm. Bahrain processed crude oils from its own oilfields, from off-shore operations shared with Saudi Arabia, and from Saudi Arabian crudes (Sulphur, 2001c).

Canada.—Second only to the United States in sulfur production in all forms, Canada led the world in the production of byproduct sulfur, exports of elemental sulfur, and stockpiled material. The majority of the sulfur production came from natural gas plants in Alberta where sulfur inventories reached 13.2 Mt (PentaSul North America Sulphur Review, 2001).

In addition to the large reserves of high-sulfur natural gas, Alberta has huge deposits of oil sands with estimated reserves of 300 million barrels of recoverable crude oil that also contain 4% to 5% sulfur (Stevens, 1998). As traditional petroleum production in Canada declined, oil sands were becoming a more important source of petroleum for the North American market (Cunningham, 2001). The Athabasca oil sands were a mixture of sand, water, clay, and bitumen, a naturally occurring viscous mixture of heavy hydrocarbons. Because of its complexity, bitumen was difficult or impossible to refine at most oil refineries. It was upgraded to a light-oil equivalent before further refining or was processed at facilities specifically designed for processing bitumen. Oil sands with more than 10% bitumen were considered rich; those with less than 7% bitumen were not economically attractive (Oil & Gas Journal, 1999).

Shallow deposits were amenable to strip mining, but deeper deposits required in situ technology whereby the bitumen was separated underground from the matrix that contained it with steam injection. Bitumen was separated from the oil sands matrix by mixing it with heated water. With in situ operations, steam assisted gravity drainage flushed the hydrocarbon out of the matrix, forming a pool that was pumped from the ground and transported to an upgrader via pipeline. During upgrading, the very large hydrocarbon molecules were reduced, creating molecules that are more easily processed. Furnace treatment produced petroleum coke that was used in other industries.

Hydrogen addition or hydrogen conversion inserted additional hydrogen atoms into the bitumen molecules and, in the process, broke them down into smaller compounds and removed much of the sulfur. The simplified hydrocarbon, known as synthetic crude oil, was then processed at traditional refineries (Cunningham, 2001).

Three surface operations were in production or under development in Alberta and at about 75 in situ projects. Surface minable reserves were estimated to be 33 billion barrels (Gtbl) with less than 9.9 Gtbl under development. Estimates for reserves appropriate for in situ processes were 142 Gtbl. Production of sulfur from oil sands could approach 2 Mt/yr by 2015 based on projections for oil sands production. Where the sulfur was actually produced depended on the type of upgrader chosen. If a coker was installed, the sulfur could be contained in the petroleum coke product and recovered at the location where the coke was consumed. If hydrocracking was used, then the sulfur was recovered on site (Cunningham, 2001).

Syncrude Canada Ltd. began production at its Aurora Mine in August. The company's second oil sands mine, about 35 km from its existing operation near Fort McMurray, Alberta, was the first such operation to be remote from most necessary processing facilities. Syncrude used newly developed technology that allowed partial processing of the mine output before transporting bitumen froth by pipeline to the company's Mildred Lake operation for further upgrading. Syncrude used a its newly developed low energy extraction process that removed the bitumen from the sand at much lower temperatures than that required by more traditional processing techniques, cutting energy consumption by about 40% (Syncrude Canada Ltd., 2000). The company stored the sulfur recovered at the upgrading facility (Syncrude Canada Ltd., [undated], Sulphur and nitrogen removal, accessed June 27, 2001, via URL <http://www.syncrude.com>). Logistical problems at Fort McMurray made it difficult and costly to get the sulfur produced to market. Rail lines did not connect to the plant site, necessitating the trucking of sulfur through the town to reach the railhead (North America Sulphur Service, 2000c). Syncrude provided space for Alberta Sulphur Research Ltd. to test its underground sulfur storage method. The sulfur stocks to be tested were buried in 1999, with several years of environmental evaluation planned (Sulphur, 1999c).

Albian Sands Energy Inc., a joint venture of Shell Canada Ltd. (60%), Chevron Canada Resources Ltd. (20%), and Western Oil Sands Inc. (20%), began construction on all aspects of its Can\$ 3.5 billion oil sands project in northern Alberta. The project included the Can\$1.8 million Muskeg River Mine, 75 km north of Fort McMurray; the Can\$1.7 million upgrade at Shell Canada's Scotford refinery near Fort Saskatchewan, Alberta; and Corridor Pipeline Ltd.'s 450-km dual pipeline system to carry diluted bitumen from the mine to Scotford and transport diluent to the mine. The pipeline project included a 43-km pipeline to carry feedstock from other operations to the upgrader and deliver upgraded material to the refinery and terminals near Edmonton, Alberta (Oil & Gas Journal, 2000d). The construction was proceeding on schedule with production expected to begin by the end of 2002 (Albian Sands Energy Inc., 2000). Albian Sands' plans included production of 500,000 t/yr of molten sulfur that would be recovered at the Scotford Refinery (North American Sulphur Service, 1999b).

Koch Industries, Inc.'s, TrueNorth Energy L.P. subsidiary expanded its Fort Hill oil sands project leases to bring the total

minable reserves at the operation to 2.4 Gbbl. TrueNorth expected to begin producing 95,000 bbl/d of bitumen by 2005. Production at the site could continue at that rate for 60 years. No upgrade was planned for the project (Sulphur, 2001f). Petro-Canada was considering the construction of a bitumen upgrade at its Edmonton, Alberta, refinery to handle production from its McKay River oil sands project near Fort McMurray. The refinery processed synthetic crude at Syncrude Canada Ltd.'s plant at Fort McMurray (Sulphur, 2000o).

Irving Oil Ltd. was spending Can\$1 billion to upgrade its Saint John, New Brunswick, refinery to meet Canada's gasoline sulfur specifications that go into effect in 2005. The upgrade was to reduce sulfur dioxide emissions at the refinery and improve the reliability of environmental controls. Reductions in atmospheric sulfur dioxide emissions were self-imposed. The refinery already met New Brunswick and Canadian regulations (Goodwin, 2000).

Chile.—Corporación Nacional Del Cobre (Codelco) and Finland's Outokumpu Oyj agreed to work together to develop new flash smelting technology to modify Codelco's Chuquicamata smelter. The upgrade at the smelter would significantly decrease sulfur dioxide emissions (Outokumpu Oyj, 2000). Outokumpu also was considering the construction of a copper smelter in Mejillones. Upon completion sometime after 2003, the smelter would have the capacity to produce 350,000 t/yr of copper and 1 Mt/yr of sulfuric acid (Sulphur, 2000c).

Noranda Inc. of Canada was expanding its Altonorte smelter to increase copper production by about 80%. Sulfuric acid production capacity, however, will nearly triple to 700,000 t/yr. The upgrade would make Altonorte more cost competitive and enable the company to capture 90% of the sulfur dioxide released by the smelter. The complete modernization project was expected to be completed in 2003 (Sulphur, 2000n).

China.—One of the few countries whose primary domestic source of sulfur was pyrites, China was working to convert much of its sulfuric acid capacity from pyrites burning to elemental sulfur. Some new elemental sulfur-based acid plants were built, but much of the conversion was through adapting existing pyrites operations to use solid sulfur. The conversions were driven by economic and environmental reasons (Fertilizer Markets, 1999). Environmental awareness was a relatively recent concern in official Government considerations. Pyrite-based sulfuric acid plants in China emitted sulfur dioxide and other pollutants to the atmosphere, discharged pollutants to rivers and contaminated groundwater, and presented solid waste disposal problems. A properly operated sulfur-burner has very limited atmospheric emissions, no water discharge, and no solid waste issues (Sears, 2000).

The Chinese pyrite industry faced additional setbacks when Nanjing Chemical Industry Group, a leading producer of sulfuric acid, announced plans to switch to elemental sulfur burning. The reconstructed plant was to use sulfur recovered from Chinese oil refineries (Sulphur, 2001i). The China Sulphuric Acid Industry Association forecast sulfuric acid production to grow to 28 Mt in 2005 from 23 Mt in 2000, representing an increased sulfur demand of about 1.7 Mt (Sears, 2000).

The Chinese petroleum industry was working to modernize its facilities to reduce sulfur emissions as it increased imports of sour crudes from the Middle East (Sulphur, 2001i). Chinese imports of crude oil have been sweet crudes because of the

country's inadequate sulfur recovery capabilities. Work was progressing to improve sulfur recovery units at several refineries. Additional improvements at smelters were expected to increase availability of byproduct acid (Sears, 2000).

Chinese crude petroleum was relatively sweet with little sulfur recovered at refineries. In fact, only 1 of China's 95 refineries had any sulfur recovery capacity, amounting to just more than 100,000 t/yr. Restructuring of the refining industry included plans for large-scale increases in sulfur recovery capacity. Joint ventures with major oil producers willing to make investments in the Chinese industry were a large part of the strategy for reducing imports of oil products and improving the refining technology (Cunningham, 1999a).

Germany.—As one of the largest sulfur producing countries in Europe, discrepancies existed between official Government production statistics and other sources reporting German production. Other sources showed German production significantly higher than Government sources, with nearly 1 Mt more production of sulfur in all forms than official data. Most German sulfur was sold in European Union markets. Although official U.S. Census Bureau statistics suppressed data regarding United States imports from Germany, the United States was believed to have received sulfur shipments from Germany (Fertilizer Focus, 2001).

Norddeutsche Affinerie AG completed the expansion of its Hamburg copper smelter in November. The upgrade raised the sulfuric acid capacity of the smelter to 1.3 Mt. Production was targeted toward the northwestern European markets (Fertilizer Week, 2000). Norddeutsche Affinerie was considering a further 50% expansion of its copper and sulfuric acid capacity. The expansion would bring the company's total sulfuric acid capacity to nearly 2 Mt/yr. A location for the new operation was not identified (Sulphur, 2001h).

Iran.—Major oil companies were showing increased interest in exploration in Iran. A refinery with sulfur recovery capacity was completed in Iran's Hormuzgan Province. A new gas processing plant to process natural gas from the South Pars gasfield was under construction. The sulfur recovery at the gas plant was expected to be 400 t/d. Eight phases of development were planned for the South Pars field. When development was complete, sulfur output from the field could reach 500,000 t/yr (Cunningham, 2000d). Sulfur producers in Iran were installing forming capacity to improve their competitiveness with other major sulfur exporters (Sulphur, 2000f).

Iraq.—Questions remain about Frasch and other sulfur production in Iraq. Before Iraq invaded Kuwait precipitating Operation Desert Shield in 1990 and Operation Desert Storm (the gulf war) in 1991, Frasch production at the Mishraq Mine was around 1 Mt/yr, with plans to expand capacity to 2 Mt/yr. Some recovered sulfur was also produced in Iraq. Since that time, with the imposition of economic sanctions by the United Nations (UN) and very limited public information of any kind coming from Iraq, little was known of sulfur production in that country. Mishraq was not believed to be damaged during the war and could be operating at or near capacity, although that scenario is doubtful. The most likely situation was that Mishraq produced consistently since 1990 but at a greatly reduced rate. Recovered sulfur production probably continued. With little outlet for any products as a result of the sanctions, significant stocks of sulfur were believed to have accumulated at Mishraq since the imposition of sanctions. Sulfur also was produced at two sour gas processing plants at Kirkuk and Beiji (Fertilizer

Markets, 2000b).

Iraq reached an agreement with Jordan to supply all of Jordan's sulfur requirements starting in late 2000 and through 2001. UN sanctions against Iraq ban most trade with Iraq since Iraq invaded Kuwait in 1990. Jordan invoked an article of the UN charter that allows a UN member state not to implement a sanction if it is against that country's domestic interests. The price of the Iraqi sulfur, probably from the Mishraq Frasch Mine, was estimated to be nearly one-third less than similar material from elsewhere in the Middle East (Sulphur, 2000g). Jordan received 150,000 t of sulfur from Iraq in 2000 with up to 1 Mt expected in 2001 (Fertilizer Markets, 2000b).

Kazakhstan.—The Tengiz oilfield with associated gas on the northeast shore of the Caspian Sea in western Kazakhstan has been operated by Tengizchevroil (TCO) since 1993. In 2000, Chevron Corp. raised its stake in TCO to 50%. Other owners in TCO were Kazakhoil (the Republic of Kazakhstan's national oil and gas company with 20%), ExxonMobil (25%), and LUKARCO (a joint venture between BP and Russian oil company LUKoil with 5%) (Chevron Corp., 2000a). One of the world's largest oilfields, Tengiz contains high-quality oil with 0.49% sulfur and associated natural gas that contains 12.5% hydrogen sulfide (Connell and others, 2000).

In 2000, TCO completed an oil and gas expansion project that included additional sulfur production capacity and further expansions were planned (Chevron Corp., 2000a). TCO was studying the feasibility of reinjecting sour gas into the Tengiz reservoir and reducing the quantity of sulfur recovered at the site (Chevron, 2000b, p. 23). Sulfur production at Tengiz was around 1.3 Mt in 2000 with likely expansion to 2 Mt by 2005 and the potential to reach 3.8 Mt by 2010 (Cunningham, 2000e).

Mexico.—A former Frasch producer from 1954 when mining began at San Cristobal (Larson and Marks, 1955, p. 1136-1137) until 1993 when the Texistepec Mine closed (Ober, 1994, p. 1172), Mexico was the second largest supplier of imported recovered sulfur to the United States. Mexico recovered most of its sulfur from its petroleum refineries and recovered byproduct sulfuric acid at its smelters.

Mexican crude oil was classified in four specific types. With production of 1.5 million barrels per day, maya crude was the type with highest production and lowest quality. Maya crude was heavy, making it difficult to refine at conventional refineries, and had an average sulfur content of 3.4%. Second in production at 950,000 bbl/d, isthmus crude had medium weight and sulfur content of about 1.4%. Marine light contained 1.23% sulfur and production was 721,000 bbl/d. Olmeca, the highest quality Mexican crude with 0.93% sulfur, had the lowest production at 455,000 bbl/d. Pemex refineries processed about 45% of domestically produced crude oil. The remainder was exported; primary customers, in descending order, were the United States, Spain, the Netherlands Antilles, and Japan (Manriquez and others, 2000).

Although Mexico produced about 5% of global crude oil, it did not have the refinery capacity to meet domestic demand for gasoline. The completion of the refinery upgrade at Pemex's Cadereyta refinery brought capacity close to demand. Five additional upgrade projects were planned to transform the country's trade balance for gasoline. Mexican refineries were unable to process heavy maya crude into sufficient quantities of motor fuels. Pemex invested in U.S. refineries in Texas to ensure steady markets for their crude oil but had been unable to find the capital to modernize its own refineries. Revamping at

Cadereyta expanded capacity for diesel, jet fuel, and gasoline. Sulfur production was expected to be about 480 t/d with further expansion of 80 t/d, eventually reaching about 450,000 t/yr. Sulfur production was expected to be similar when the Madero upgrade was completed. Other planned modernization projects include those of Minatitlan, Salamanca, Tula, and Salina Cruz. No details on progress or expected sulfur recovery capacities were available. Additional sulfur supplies were expected from new natural gas processing operations, perhaps more than 500,000 t/yr from a single project (Cunningham, 2000c).

Pemex had long-term supply contracts with U.S. refiners Premcor Inc., ExxonMobil, and Marathon Ashland Petroleum LLC (Cunningham, 1999b). Pemex was involved in a joint venture with Shell at Deer Park, TX (North America Sulphur Service, 1999a).

Netherlands Antilles.—PdVSA's Netherlands Antilles affiliate, Refineria Isla, was upgrading its refinery in Curaçao, including its sulfur recovery unit. Completion was expected in 2002 (Sulphur, 2000v).

Philippines.—Crew Development Corp. of Canada was planning a nickel pressure acid leach project on Mindoro Island in the Philippines. In order to mitigate the costs of sulfur, a high-cost factor in development of the nickel operation, Crew investigated the possibility of mining sulfur from the Pamplona sulfur deposit on Negros Island, also in the Philippines. Reserves at Pamplona were set at 60 Mt with 30.8% sulfur, 13.8% of which was elemental sulfur and 17% was in sulfides (Industrial Minerals, 2000). With sulfur prices at low levels worldwide and no change expected, it seemed unlikely that the Philippine sulfur deposit would be developed. The cost of development and production would need to be very low to allow profitable processing.

Poland.—As in many countries with improving economies, oil refineries in Poland were upgrading their sulfur recovery units to meet air quality regulations forbidding the release of sulfur dioxide into the atmosphere (Sulphur, 1999b). Recovered sulfur, however, remains a secondary source of sulfur in Poland.

Rich sulfur deposits were discovered in Poland in 1954, and production began at the first surface mine late in that decade. Since that time, five native sulfur mines have been developed in Poland. The first two, Piaseczno and Machów, were surface mines that utilized conventional mining methods. The other three mines, Grzybów, Jeziórko, and Osiek, used the Frasch method with modifications to work with the geologic conditions in Poland. At the peak of Polish sulfur production in 1980, more than 5 Mt of sulfur could be produced from three mines, Grzybów, Jeziórko, and Machów. Three of the mines closed and were being recultivated as lakes and other recreation areas, leaving Jeziórko and Osiek operating in 1999 (Karolak, 1997).

Polish sulfur entered the global market in 1961, when the sulfur shipping facilities in Gdańsk were completed. In 1980, about 3.8 Mt (nearly 75%) of Polish production was exported, mostly to other European countries. Since the early 1990s, low global prices have made it extremely difficult for the discretionary sulfur producers to compete in the global market, and those markets have dwindled for the Polish industry (Karolak, 1997). Polish Frasch production increased by 17% in 2000, the first increase since 1995. Domestic consumption and exports were higher than the previous year. Poland's largest sulfur customer was Morocco; Poland had a sulfur-phosphate rock swap agreement with a Moroccan phosphate producer

(Fertilizer Focus, 2001).

Qatar.—Qatar Liquefied Gas Co. was revamping and expanding two sulfur recovery units at Ras Laffan, with completion expected in 2002 (Sulphur, 2000y).

Russia.—The Astrakhan Gas Processing Plant (AGP) was the largest single source of recovered sulfur in the world. During 2000, the operation was producing 3.6 Mt/yr and expansion projects nearing completion promised to bring the total to 4.2 Mt/yr by 2002. Final expansions were expected to be completed in 2003, bringing sulfur production to 4.5 Mt/yr. Formed sulfur from this site was exported through the port of Novorossiysk, at which a liquid sulfur terminal was under consideration. Exports of AGP products from this port were limited to about 1 Mt/yr because the rail line from the plant to the port was unable to handle more than that (Sulphur, 2000m).

Russia's largest natural gas producer, Gazprom, approved a study on the feasibility of building a liquid sulfur terminal at the Black Sea port of Novorossiysk to handle 1 Mt/yr of molten sulfur from Gazprom's Astrakhan natural gas field. North Africa and other locations in the Mediterranean would be logical markets for the material. In 2000, Astrakhangazprom produced about 3.6 Mt with sales of 3.9 Mt of solid sulfur, including sales from stocks (Sulphur, 2000d).

Russian exports were more than 3 Mt in 2000. The 25% increase from the previous year was a result of increased production from Astrakhan and an effort to reduce stocks. Israel was Russia's largest customer. Russian sulfur has displaced material from Canada and the Middle East in important markets in north Africa, southern Europe, and the Mediterranean area (Fertilizer Week, 2001).

Russian industry was beginning to deal with pollution issues, sometimes with foreign assistance. Pernetegas, a major Russian natural gas and oil producer, revamped one of its units to reduce sulfur dioxide emissions (Sulphur, 2000m). The copper smelter at Karabash, one of Russia's five most polluted cities, was renovating the gas cleaning systems to recover sulfuric acid. The Government of Norway was paying for environmental improvements at the Pechanganickel operation owned by Norilsk Nickel Corp. on the Kola Peninsula. Sulfuric acid recovery was to be expanded to reduce the amount of sulfur dioxide released in Russia that contaminates other countries that border Russia (Sulphur, 2001g).

Saudi Arabia.—The Hawiyah gas plant in Saudi Arabia was 4 months ahead of schedule and was expected to begin production in December 2001. Ramp-up was expected to begin in June. This was the first supply plant of Saudi Arabia's master gas system to process gas not associated with crude oil production (Sulphur, 2000u).

Spain.—A new 900,000 t/yr sulfuric acid plant was commissioned by Fertiberia S.A. at Huelva in southern Spain. The new sulfuric acid plant was expected to use about 200,000 t/yr of elemental sulfur from Spanish suppliers and imported sulfur from Canada, France, and Russia (Fertilizer Markets, 2000a). The new sulfuric acid plant replaced three pyrite-based acid plants (Fertilizer Focus, 2001)

Spain's Asturiana de Zinc, S.A., was building a new zinc processing plant in San Juan de Nieva. Included in the project was a sulfuric acid plant (Sulphur, 2000j).

Ukraine.—Ukraine, once a major producer of native sulfur using Frasch and conventional mining methods, has not mined any sulfur for several years. The country planned to flood one of its idle surface mines to be used as a reservoir (Sulphur,

2000m).

Venezuela.—Venezuela's Orinoco Basin was one of the world's largest resources of crude oil. If recent developments in refining technology had not provided the means for upgrading the crude, it could not have been developed (Sulphur, 2000s). Upgraded crude production from the Orinoco Basin could result eventually in the production of 8 Mt/yr of sulfur, with about 5 Mt/yr of that being produced in Venezuela, and the rest, at refineries in other countries, very possibly in the United States (Cunningham, 2000e).

Heavy oil upgrading facilities at the port of Jose progressed. The first of the projects to upgrade high-sulfur Orinoco crude oil was expected to be completed early in 2001. Petrozuata, a joint venture between Conoco Inc. and PdVSA that was designed to produce synthetic crude oil for domestic refining and export, would also produce byproduct petroleum coke and elemental sulfur. The Cerro Negro project, owned by ExxonMobil, PdVSA, and Germany's Veba Oel AG, will produce synthetic crude oil for refining at ExxonMobil's and PdVSA's refinery in Chalmette, LA, and in Germany. Production was expected to begin in 2001. The largest upgrader project at Jose is scheduled for completion in 2002. That operation is owned 47% by TotalFinaElf, 38% by PdVSA, and 15% by Statoil ASA of Norway (Sulphur, 2001e).

Sulfur production from the first heavy oil upgrader project at the Jose complex will undergo a forming process before being shipped overseas. Once the heavy oil upgrading projects are completed at Jose, the terminal will provide an additional 400,000 t/yr of sulfur to the world market (Sulphur, 2000h).

PdVSA also is involved in a joint venture for processing Venezuelan crude at the Phillips refinery in Sweeny, TX. PdVSA and Phillips spent \$540 million to build a coker and a vacuum distillation unit to be operated by Mery Sweeny Limited Partnership (Sulphur, 2001e).

In addition to upgrader projects that will add sulfur recovery capacity in Venezuela, PdVSA was updating existing petroleum crackers to meet new standards for reducing sulfur emissions. The upgrade was designed to raise the recovery at two refineries to 99.2% from a maximum of 94%. Venezuela established new standards of 98.9% recovery (Chemical Market Reporter, 2000b).

Zambia.—Roan Antelope Mining Corp. of Zambia planned to develop of a new SX-EW project at its Muliashi North Mine. The project required construction of an elemental-sulfur-based sulfuric acid plant (Sulphur, 2000t).

Current Research and Technology

Biodesulfurization.—Enchira Biotechnology Corp. received \$900,000 from the U.S. Department of Energy for research to develop a bacterial process for removing sulfur from gasoline. Enchira, formerly Energy Biosystems Corp., was operating a pilot plant in Alaska to remove sulfur from diesel using a similar process. Thus far, the diesel process had struggled to meet cost targets and did not remove sulfur as thoroughly as projected. Enchira has stated that because gasoline is a more powerful solvent than diesel, it may be difficult to adapt the process to gasoline. Genetic modifications to the bacteria enabled faster adaptation to differing environments (Sulphur, 2000b).

Development of a biological process that worked quickly enough to use in an industrial facility had been the major hurdle

to implementation. Biocatalytic desulfurization, when fully developed, was expected to be significantly less costly than more common technology and was identified as a possible way for small refiners to meet more stringent sulfur requirements (U.S. Department of Energy, 2000).

Injection of Sulfur Dioxide.—Alberta Sulphur Research Ltd. was looking into the possibility of developing a process for injecting sulfur dioxide into a sour gas reservoir. The sulfur dioxide would react with the hydrogen sulfide in the deposit to form elemental sulfur and water, the same reaction used in sulfur recovery units. Not only would the process eliminate a sulfur disposal problem for the operation, but it also would produce high quality steam that could be used elsewhere in the operation. This process also could help to eliminate excess stocks of sulfur and at the same time produce electricity for sale to the power grid. Investigation of this new idea for sulfur disposal has just begun; but if it is successfully developed, it could relieve the worldwide oversupply situation (Connock, 2001).

New Processes for Removing Sulfur from Fuels.—BP developed a gasoline desulfurization process called olefinic alkylation of thiophenic sulphur (OATS). OATS was capable of removing 99.5% of the sulfur compounds in a major gasoline blending component, naphtha produced at fluid catalytic cracking units, without significantly reducing the quality of the fuel or reducing the quantity of fuel produced. The OATS process was simple and easily retrofitted to an existing operation. The process involved pretreatment of the feed by washing with acid, neutralization of the spent liquor, the OATS reaction section, the production fractionation section, and a naphtha hydrotreater. Two small demonstration units began operation at BP's Texas City, TX, refinery, and a larger scale trial was completed at the company's joint-venture refinery in Bayern, Germany (Sulphur, 2001d). ExxonMobil has developed a new catalyst for conventional hydrotreating processes, but it minimizes quality degradation of the product (Exxon Mobil Corp., 2000).

Phillips Petroleum developed a process that stripped sulfur from gasoline blending stocks by using a regenerative adsorbent. The benefits of this process as compared with some desulfurizing processes were that the reduction in octane level was limited, the volume loss was low, and the vapor pressure was maintained. The process's first commercial application at Phillips Petroleum's Borger, TX, facility was set to go onstream in early 2001. Phillips Petroleum licensed the technology to Marathon Ashland Petroleum for use at all of its seven refineries (Sulphur, 2000q).

Phillips Petroleum adapted its S Zorb technology to handle diesel fuels. Pilot plant testing of the processes was ongoing at the company's research and development center. The S Zorb technology did not consume significant quantities of hydrogen, a high-cost component of many desulfurization processes (Sulphur, 2000p).

Reinjection of Hydrogen Sulfide.—Reinjection of the sulfur as hydrogen sulfide into an appropriate underground reservoir was an attractive alternative in some instances at some natural gas operations but was seldom feasible at oil refineries. In acid gas reinjection from sour gas processing, the hydrogen sulfide and carbon dioxide were separated from the gas using standard separation techniques and recompressed into a suitable injection zone. The suitability of the injection zone was influenced by its distance from the processing facility and could be a large aquifer, a depleted reservoir, or a zone producing sour fluids. A

depleted reservoir was especially attractive because its size and original pressure were already known, making the determination of its holding capacity easier to determine. The sour gases also could be reinjected into a producing deposit.

Reinjection was being used at many small-scale operations, especially in Canada, but it had not been demonstrated that reinjection would work on a large scale. It was essential that the reinjected gases not escape from the reservoir by migration into adjacent reservoirs or aquifers or into the atmosphere by migration through an outcrop.

With large-scale reinjection schemes, the energy balance would be a large factor in determining its feasibility. Without the sulfur recovery plant that produces energy that can be used elsewhere in the operation, steam production using an external energy source, such as natural gas or electricity, was required. Using natural gas presented the situation of producing carbon dioxide emissions in order to reinject carbon dioxide. A determination on whether the environmental benefit of reinjecting carbon dioxide was canceled out by the carbon dioxide emissions produced for that reinjection was needed.

A feasibility study conducted by Abu Dhabi National Oil Co. showed that a large scale reinjection project should have favorable energy balance greenhouse gas considerations. The technical and operating challenges were yet to be resolved (Connock, 2001).

Sulfuric Acid from Powerplants.—Powerspan Corp. developed a process for converting sulfur dioxide emissions from coal-fired power generation to commercial grade sulfuric acid. A full-scale demonstration project was being installed at FirstEnergy Corp.'s Eastlake, OH, generating plant. The electrocatalytic oxidation process (ECO) was designed to cut nitrogen oxide and sulfur dioxide emissions simultaneously at lower installation and operation costs than similar emission reduction processes. The Eastlake project was expected to cut nitrogen oxide, sulfur dioxide, mercury, and fine particulate matter emissions by more than 70%, 50%, 70%, and 90%, respectively, beginning early in 2001 (Sulphur, 2000r).

Sulfur Paving Materials.—Liquified Gas, a subsidiary of Astrakhangazprom, built a pilot plant to produce materials for trials of sulfur-extended construction materials. The plant will have the capacity to produce 50,000 t/yr of sulfur polymer cement and 32,000 t/yr of sulfur-extended asphalt cement. Other countries of the former Soviet Union that announced plans to pursue the use of sulfur in paving are Turkmenistan and Kazakhstan (Sulphur, 2001a).

Outlook

The sulfur industry continued on its path of increased production, slower growth in consumption, higher stocks, and expanded world trade. U.S. production from petroleum refineries is expected to increase substantially in the next few years as expansions, upgrades, and new facilities at existing refineries are completed, enabling refiners to increase throughput of crude oil and to process higher sulfur crudes. Production from natural gas operations varies but is usually between 2.0 and 2.2 Mt/yr. Output is expected to remain at about that level. Worldwide recovered sulfur should continue to increase. Refineries in developing countries should begin to improve environmental protection measures and eventually approach the environmental standards of plants in Japan, North America, and Western Europe.

Experts from the natural gas industry estimate that the world demand for natural gas will grow by 2.5% per year during the next 20 years, a total 50% increase in demand. Producing 50% more gas means recovering at least an additional 50% in sulfur from that source. Future gas production, however, is likely to come from deeper, hotter, and sourer deposits that will result in even more excess sulfur production unless more efforts are made to develop new, large-scale uses for sulfur. Other alternative technologies for reinjection and long-term storage to eliminate some of the excess sulfur supply will require further investigation in order to handle the quantity of surplus material anticipated (Hyne, 2000).

Byproduct sulfuric acid production will remain depressed in the United States as long as the copper smelters remain idle. With the copper industry's switch to lower cost production processes and producing regions, it could be many years before U.S. byproduct acid production again approaches the level it reached in 1998. Worldwide, the outlook is different. Copper production costs in many countries are lower than in the United States, so that acid production from those countries has not decreased as drastically, and increased production is more likely. Environmental controls have been less of a concern in developing countries in the past. Many copper producers, however, in these and even in developed countries are installing more efficient sulfuric acid plants to limit sulfur dioxide emissions at new and existing smelters. Planned and in-progress improvement projects could increase byproduct acid production to 52 Mt by 2010 or the equivalent of about 17 Mt of sulfur from 10 Mt (3.3 Mt of sulfur) in 1999 (Sulphur, 1999a).

Frasch and pyrites production, however, have little chance of significant long-term increases. Because of the continued growth of elemental sulfur recovery for environmental reasons rather than demand, discretionary sulfur has become increasingly less important. Frasch sulfur has become the high-cost process for sulfur production. Pyrites, with significant direct production costs, are an even higher-cost raw material for sulfuric acid production when the environmental aspects are considered. Discretionary sulfur output should show a steady decline. The decreases will be pronounced when large operations are closed outright for economic reasons such as was the case in 2000.

Sulfur and sulfuric acid will continue to be important in agricultural and industrial applications, although consumption will not equal production. World sulfur demand for fertilizer is forecast to increase at about 2.7% per year for the next 10 years; industrial demand is predicted to grow at 2.3% per year.

The most important changes in sulfur consumption will be in location. Phosphate fertilizer production, where most sulfur is consumed, is projected to increase by about 2.3% per year through 2010. With new and expanding phosphate fertilizer capacity in Australia, China, and India, sulfur demand will grow in these areas at the expense of some phosphate operations elsewhere, thus transferring sulfur demand rather than creating new. The effects were already being felt by the U.S. phosphate industry, reflected in the permanent closure of some facilities and reduced production at others. U.S. phosphate products supply domestic requirements, but a large portion of U.S. production is exported. China and India are primary markets for United States fertilizers. As the phosphate fertilizer industries develop in these countries, some of the markets for U.S. material could be lost. Sulfur will be required for

phosphate production at new operations, and more producers will be competing for those markets.

Use of sulfur directly or in compounds as fertilizer should increase, but this use will be dependent on agricultural economies and increased acceptance of the need for sulfur in plant nutrition. If widespread use of plant nutrient sulfur is adopted, sulfur consumption in that application could be significant; thus far, growth has been slow.

Industrial sulfur consumption has more prospects for growth than in recent years but still less than agriculture and not enough to consume any surplus production. Conversion to or increases in copper leaching by producers, who require significantly more sulfuric acid for the leaching operations than was used in 2000, bode well for the sulfur industry. Nickel PAL operations were demanding increased quantities of sulfur. Changes in the preferred methods for producing oxygenated gasoline, especially in Canada and the United States, might result in additional alkylation capacity that would require additional sulfuric acid. Other industrial uses show less potential for expansion. Estimates show sulfur production exceeding consumption by 3 Mt/yr for the next 20 years, and worldwide inventories reaching 80 Mt by 2020 (Hyne, 1999). The potential exists for involuntary sulfur production of 80 to 100 Mt/yr by 2050, representing a 120% increase in the time period that could be required to develop viable energy alternatives to fossil fuels (Cunningham, 2000e)

Unless significant new uses for elemental sulfur are implemented, the oversupply situation will result in tremendous stockpiles accumulating around the world. In the 1970s and 1980s, research was conducted that showed the effectiveness of sulfur in several construction uses that held the promise of consuming huge quantities of sulfur in sulfur-extended asphalt and sulfur concretes. In many instances, these materials were found to be superior to the more traditional products, but their use has been very limited. Interest in these materials seemed to be increasing but only in additional research. No large-scale projects were announced that would require sizable quantities of sulfur. It may be necessary to revisit these proposals to avoid building mountains of sulfur in the not-too-distant future.

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TABLE 1
SALIENT SULFUR STATISTICS 1/

(Thousand metric tons, sulfur content, and thousand dollars unless otherwise specified)

	1996	1997	1998	1999	2000
United States:					
Production:					
Frasch e/	2,900	2,820	1,800	1,780	900
Recovered 2/	7,480	7,650	8,220	8,220	8,380
Other	1,430	1,550	1,610	1,320	1,030
Total e/	11,800	12,000	11,600	11,300	10,300
Shipments:					
Frasch	W	W	W	W	W
Recovered 2/ 3/	10,400	10,400	10,500	9,800	9,500
Other	1,430	1,550	1,610	1,320	1,030
Total	11,800	11,900	12,100	11,100	10,500
Exports:					
Elemental 4/	855	703	889	685	762
Sulfuric acid	38	39	51	51	62
Imports:					
Elemental	1,960	2,060	2,270	2,580	2,330
Sulfuric acid	678	659	668	447	463
Consumption, all forms	13,600	13,900	14,100	13,400	12,500
Stocks, December 31, producer, Frasch and recovered	646	761	283	451	208
Value:					
Shipments, f.o.b. mine or plant:					
Frasch	W	W	W	W	W
Recovered 2/ 3/	\$355,000	\$375,000	\$306,000	\$371,000	\$239,000
Other	\$85,800	\$98,100	\$77,100	\$66,400	\$55,100
Total	\$441,000	\$473,000	\$383,000	\$437,000	\$295,000
Exports, elemental 5/	\$51,700	\$36,000	\$35,400	\$35,800	\$53,700
Imports, elemental	\$70,200	\$64,900	\$58,400	\$51,600	\$39,400
Price, elemental, f.o.b. mine or plant	\$34.11	\$36.06	\$29.14	\$37.81	\$24.73
World, production of all forms, including pyrites	55,200 r/	57,100	57,100 r/	57,700 r/	57,200 e/

e/ Estimated. r/ Revised. W Withheld to avoid disclosing company proprietary data; included with "Recovered."

1/ Data are rounded to no more than three significant digits, except prices; may not add to totals shown.

2/ Includes U.S. Virgin Islands.

3/ Includes corresponding Frasch sulfur data.

4/ Includes exports from the U.S. Virgin islands to foreign countries.

5/ Includes value of exports from the U.S. Virgin Islands to foreign countries.

TABLE 2
RECOVERED SULFUR PRODUCED AND SHIPPED IN THE UNITED STATES, BY STATE 1/

(Thousand metric tons and thousand dollars)

State	1999			2000		
	Production	Shipments		Production	Shipments	
		Quantity	Value		Quantity	Value
Alabama	336	336	12,700	320	321	7,970
California	1,070	1,070	5,270	1,150	1,140	5,660
Illinois	418	417	11,300	444	444	5,900
Louisiana	1,110	2,590 2/	W	1,070	2,180 2/	W
Michigan and Minnesota	33 r/	33 r/	818	34	34	483
Mississippi	527	528 r/	10,200	525	533	20,100
New Mexico	47	47	253	48	48	(3/)
North Dakota	51	51	487	50	50	(3/)
Ohio	80	80	2,300	112	111	2,210
Texas	2,610	2,770 2/	153,000 2/	2,760	2,770	80,300
Washington	95	96	224	113	110	27
Wyoming	1,080	1,050	21,700	1,030	1,030	16,900
Other 4/	763 r/	736 r/	152,000	717	730	99,800
Total	8,220	9,800	371,000	8,380	9,500	239,000

See footnotes at end of table.

TABLE 2--Continued
RECOVERED SULFUR PRODUCED AND SHIPPED IN THE UNITED STATES, BY STATE 1/

r/ Revised. W Withheld to avoid disclosing company proprietary data; included with "Other."
1/ Data are rounded to no more than three significant digits; may not add to totals shown.
2/ Includes corresponding Frasch sulfur data.
3/ Some sulfur producers in this State incur expenses to make their production available to consumers.
4/ Includes Arkansas, Colorado, Delaware, Florida, Indiana, Kansas, Kentucky, Louisiana (value), Montana, New Jersey, Pennsylvania, Utah, Virginia, Wisconsin, and the U.S. Virgin Islands.

TABLE 3
RECOVERED SULFUR PRODUCED AND SHIPPED IN THE UNITED STATES,
BY PETROLEUM ADMINISTRATION FOR DEFENSE (PAD) DISTRICT 1/

(Thousand metric tons)

District and source	1999		2000	
	Production	Shipments	Production	Shipments
PAD 1:				
Petroleum and coke	228	220	240	246
Natural gas	45	45	43	42
Total	272	265	283	288
PAD 2:				
Petroleum and coke	821	820	882	882
Natural gas	53	53	53	53
Total	874	873	935	935
PAD 3: 2/				
Petroleum	3,880	W	3,890	W
Natural gas	847	W	904	W
Total	4,730	6,350 3/	4,800	5,940 3/
PADs 4 and 5:				
Petroleum	1,280	1,270	1,340	1,320
Natural gas	1,070	1,040	1,020	1,020
Total	2,350	2,310	2,360	2,340
Total petroleum and coke	6,210	W	6,360	W
Total natural gas	2,010	W	2,020	W
Grand total	8,220	9,800 3/	8,380	9,500 3/

W Withheld to avoid disclosing company proprietary data.
1/ Data are rounded to no more than three significant digits; may not add to totals shown.
2/ Includes the U.S. Virgin Islands.
3/ Includes corresponding Frasch sulfur data.

TABLE 4
BYPRODUCT SULFURIC ACID PRODUCED IN THE UNITED STATES 1/ 2/

(Thousand metric tons, sulfur content, and thousand dollars)

Type of plant	1999	2000
Copper 3/	1,130	830
Zinc 4/	124	123
Lead and molybdenum 4/	70	73
Total	1,320	1,030
Value	\$66,400	\$55,100

1/ Includes acid produced from imported raw materials.
2/ Data are rounded to no more than three significant digits; may not add to totals shown.
3/ Excludes acid made from pyrites concentrates.
4/ Excludes acid made from native sulfur.

TABLE 5
CONSUMPTION OF SULFUR IN THE UNITED STATES 1/ 2/

(Thousand metric tons)

	1999	2000
Total elemental:		
Shipments 3/	9,800	9,500
Exports	685	762
Imports	2,580	2,330
Total	11,700	11,100
Byproduct sulfuric acid:		
Shipments 3/	1,320	1,030
Exports 4/	51	62
Imports 4/	447	463
Grand total	13,400	12,500

1/ Crude sulfur or sulfur content.

2/ Data are rounded to no more than three significant digits; may not add to totals shown.

3/ Includes the U.S. Virgin Islands.

4/ May include sulfuric acid other than byproduct.

TABLE 6
SULFUR AND SULFURIC ACID SOLD OR USED IN THE UNITED STATES, BY END USE 1/

(Thousand metric tons, sulfur content)

SIC 3/	End use	Elemental sulfur 2/		Sulfuric acid (sulfur equivalent)		Total	
		1999	2000	1999	2000	1999	2000
102	Copper ores	--	--	726	671	726	671
1094	Uranium and vanadium ores	--	--	8	2	8	2
10	Other ores	--	--	75	44	75	44
26, 261	Pulpmills and paper products	W	W	138	136	138	136
28, 285, 286 2816	Inorganic pigments, paints and allied products, industrial organic chemicals, other chemical products 4/	116 r/	208	174	152	290 r/	360
281	Other inorganic chemicals	-- r/	--	195	202	195	202
282, 2822	Synthetic rubber and other plastic materials and synthetics	--	--	68	68	68	68
2823	Cellulosic fibers, including rayon	--	--	5	5	5	5
283	Drugs	--	--	3	2	3	2
284	Soaps and detergents	--	W	1	1	1	1
286	Industrial organic chemicals	--	--	90	82	90	82
2873	Nitrogenous fertilizers	--	--	210	213	210	213
2874	Phosphatic fertilizers	--	--	7,770	7,110	7,770	7,110
2879	Pesticides	--	--	19	14	19	14
287	Other agricultural chemicals	1,200	1,260	32	29	1,240	1,290
2892	Explosives	--	--	4	8	4	8
2899	Water-treating compounds	--	--	64	52	64	52
28	Other chemical products	--	--	39	22	39	22
29, 291	Petroleum refining and other petroleum and coal products	1,400	1,460	508	497	1,910	1,960
331	Steel pickling	--	--	13	16	13	16
333	Nonferrous metals	--	--	38	38	38	38
33	Other primary metals	--	--	48	8	48	8
3691	Storage batteries (acid)	--	--	11	11	11	11
	Exported sulfuric acid	--	--	9	6	9	6
	Total identified	2,720	2,790	10,200	9,390	13,000	12,200
	Unidentified	1,100	1,190	185	237	1,290	1,430
	Grand total	3,820	3,980	10,400	9,620	14,300	13,600

r/ Revised. W Withheld to avoid disclosing company proprietary data; included with "Unidentified." -- Zero.

1/ Data are rounded to no more than three significant digits; may not add to totals shown.

2/ Does not include elemental sulfur used for production of sulfuric acid.

3/ Standard industrial classification.

4/ No elemental sulfur was used in inorganic pigments and paints and allied products.

TABLE 7
SULFURIC ACID FROM SMELTERS SOLD OR USED IN THE UNITED STATES, BY END USE 1

(Thousand metric tons of 100% H₂SO₄)

SIC 2/	Use	1999	2000
102	Copper ores	2,120	1,950
10	Other ores	W	W
26, 261	Pulp mills and other paper products	W	W
28, 281, 282, 283, 286, 2816	Miscellaneous chemicals	W	W
2873	Nitrogenous fertilizers	W	W
2874	Phosphatic fertilizers	W	W
287, 2879	Pesticides and other agricultural chemicals	100	70
2899	Water-treating compounds	162	W
291	Petroleum refining	W	W
3691	Storage batteries (acid)	W	W
33, 331, 333, 1094	Miscellaneous metal usage	189	62
	Unidentified 3/	865	1,200
	Total	3,440	3,290

W Withheld to avoid disclosing company proprietary data; included with "Unidentified."

1/ Data are rounded to no more than three significant digits; may not add to totals shown.

2/ Standard industrial classification.

3/ Includes exports.

TABLE 8
U.S. EXPORTS OF ELEMENTAL SULFUR, BY COUNTRY 1/ 2/

(Thousand metric tons and thousand dollars)

Country	1999		2000	
	Quantity	Value	Quantity	Value
Argentina	(3/)	9	(3/)	3
Australia	18	452	(3/)	6
Brazil	184	5,160	115	3,780
Canada	36	4,160	46	5,300
Colombia	(3/)	79	(3/)	75
India	44	1,160	(3/)	15
Korea, Republic of	6	5,840	5	6,860
Mexico	132	5,020	178	13,100
Morocco	--	--	210	6,040
Senegal	28	847	126	5,910
Other	237	13,100	82	12,600
Total	685	35,800	762	53,700

-- Zero.

1/ Includes exports from the U.S. Virgin Islands.

2/ Data are rounded to no more than three significant digits; may not add to totals shown.

3/ Less than 1/2 unit.

Source: U.S. Census Bureau.

TABLE 9
U.S. EXPORTS OF SULFURIC ACID (100% H₂SO₄), BY COUNTRY 1/

Country	1999		2000	
	Quantity (metric tons)	Value (thousands)	Quantity (metric tons)	Value (thousands)
Canada	133,000	\$7,220	154,000	\$7,890
China	444	359	5,080	1,240
Dominican Republic	1,830	186	2,760	318
Israel	2,960	815	349	469
Japan	93	120	2,130	324
Korea, Republic of	1	9	45	44
Mexico	1,450	288	3,850	589
Netherlands	66	65	658	104
Netherlands Antilles	509	265	--	--
Panama	--	--	22	13

See footnotes at end of table.

TABLE 9--Continued
U.S. EXPORTS OF SULFURIC ACID (100% H₂SO₄), BY COUNTRY 1/

Country	1999		2000	
	Quantity (metric tons)	Value (thousands)	Quantity (metric tons)	Value (thousands)
Saudi Arabia	2,000	4,150	430	774
Singapore	709	406	777	594
Taiwan	832	452	950	422
Trinidad and Tobago	72	22	4,120	347
United Kingdom	35	85	880	99
Venezuela	190	22	787	90
Other	10,700	2,390	13,300	2,470
Total	155,000	16,800	191,000	15,800

-- Zero.

1/ Data are rounded to no more than three significant digits; may not add to totals shown.

Source: U.S. Census Bureau.

TABLE 10
U.S. IMPORTS OF ELEMENTAL SULFUR, BY COUNTRY 1/

(Thousand metric tons and thousand dollars)

Country	1999		2000	
	Quantity	Value 2/	Quantity	Value 2/
Canada	1,640	12,500	1,690	10,900
Mexico	543	27,000	489	19,200
Other	403	12,100	151	9,300
Total	2,580	51,600	2,330	39,400

1/ Data are rounded to no more than three significant digits; may not add to totals shown.

2/ Declared customs valuation.

Source: U.S. Census Bureau; as adjusted by the U.S. Geological Survey.

TABLE 11
U.S. IMPORTS OF SULFURIC ACID (100% H₂SO₄), BY COUNTRY 1/

Country	1999		2000	
	Quantity (metric tons)	Value 2/ (thousands)	Quantity (metric tons)	Value 2/ (thousands)
Canada	865,000	\$27,100	803,000	\$24,300
Germany	69,600	2,100	24,000	926
Japan	162,000	12,200	97,300	6,040
Mexico	107,000	6,810	328,000	8,720
Spain	8,150	245	16,400	478
Other	157,000	14,100	148,000	1,050
Total	1,370,000	62,600	1,420,000	41,500

1/ Data are rounded to no more than three significant digits; may not add to totals shown.

2/ Declared c.i.f. (cost, insurance, and freight paid by shipper) valuation.

Source: U.S. Census Bureau.

TABLE 12
SULFUR: WORLD PRODUCTION IN ALL FORMS, BY COUNTRY AND SOURCE 1/ 2/

(Thousand metric tons)

Country and source 3/	1996	1997	1998	1999	2000 e/
Australia, byproduct: e/					
Metallurgy	327	474	507	441	654
Petroleum	35	35	35	34 4/	35
Total	362	509	542	475	689
Belgium, byproduct, all sources e/	406	430	428	408	410
Canada, byproduct:					
Metallurgy	1,044	1,072	1,153	1,156	1,200 p/ 4/
Natural gas, petroleum, tar sands	8,446	8,408	8,541	8,960	8,700 p/ 4/
Total	9,490	9,480	9,694	10,116	9,900 p/ 4/
Chile, byproduct, metallurgy e/	587	768	899	1,040	1,100
China: e/					
Elemental	170	200	210	250	250
Pyrites	5,990	6,040	4,490	3,860	3,370
Byproduct, metallurgy	1,100	1,400	1,450	1,580	1,600
Total	7,260	7,640	6,150	5,690	5,220
Finland:					
Pyrites	425	373	430 r/ e/	500 r/ e/	500
Byproduct:					
Metallurgy	291	307	296 e/	300 e/	300
Petroleum	38	50	40 r/ e/	45 e/	50
Total	754	730	766 r/ e/	845 r/ e/	850
France, byproduct: e/					
Natural gas	755	697 4/	600	600	600
Petroleum	235	263 4/	245	250	250
Unspecified	99	100	261	250	260
Total	1,090	1,060	1,110	1,100	1,110
Germany, byproduct: e/					
Metallurgy	20	25	25	25	30
Natural gas and petroleum	1,000	1,085 4/	1,100	1,100	1,110
Unspecified	90	50	50	60	100
Total	1,110	1,160	1,180	1,190	1,240
Iran, byproduct: e/					
Metallurgy	50	50	50	48 r/	50
Natural gas and petroleum	840	850	1,280 r/ 4/	1,302 r/ 4/	1,300
Total	890	900	1,330 r/ 4/	1,350 r/ 4/	1,350
Italy, byproduct: e/					
Metallurgy	216	229	199	193	203
Petroleum	335	380	425	485	490
Total	551	609	624	678	693
Japan:					
Pyrites e/	45	39	23	41	30
Byproduct:					
Metallurgy	1,314	1,331	1,322	1,363	1,400
Petroleum e/	1,790	2,010	2,080	2,060	2,070
Total e/	3,150	3,380	3,430	3,460	3,500
Kazakhstan: e/					
Pyrites	71	--	--	--	--
Byproduct:					
Metallurgy	139	139	212	245	300
Natural gas and petroleum	515	778	933	1,070	1,200
Total	725	917	1,150	1,320	1,500
Korea, Republic of, byproduct: e/					
Metallurgy	260	265	270	280	290
Petroleum	200	200	200	200	200
Total	460	465	470	480	490
Kuwait, byproduct, natural gas and petroleum e/	595	675 4/	665	675	675
Mexico, byproduct:					
Metallurgy	359	417	474	450	450
Natural gas and petroleum	921	923	913	860	860
Total	1,280	1,340	1,387	1,310	1,310

See footnotes at end of table.

TABLE 12--Continued
SULFUR: WORLD PRODUCTION IN ALL FORMS, BY COUNTRY AND SOURCE 1/ 2/

(Thousand metric tons)

Country and source 3/	1996	1997	1998	1999	2000 e/
Netherlands, byproduct: e/					
Metallurgy	119	127	131	129	84
Petroleum	380	450	432	445	428
Total	499	577	563	574	512
Poland: 5/					
Frasch	1,745 r/	1,673 r/	1,348	1,175	1,369 4/
Byproduct: e/					
Metallurgy	200 r/	256	260 r/	260	260
Petroleum	25	44	57	74	70
Gypsum e/	12 r/	12 r/	10 r/	--	--
Total	1,982 r/	1,985 r/	1,675 r/	1,509 r/	1,700
Russia: e/ 6/					
Native	70	50	50	50	50
Pyrites	400	400	254	300	350
Byproduct, natural gas	3,000	2,950	3,940	4,410	4,900
Other	325	350	411	510	600
Total	3,800	3,750	4,650	5,270	5,900
Saudi Arabia, byproduct, all sources e/	2,300	2,400	2,300	2,400	2,400
South Africa:					
Pyrites	184	167	152 e/	141	146 4/
Byproduct:					
Metallurgy	91	37	100 e/	100 e/	100
Petroleum 7/	232	256	178	164	203 4/
Total	507	460	430	406	448 4/
Spain:					
Pyrites	438	424	430	388	115
Byproduct: e/					
Coal (lignite) gasification	2	2	2	2	1
Metallurgy	428	456	461	455	454
Petroleum	75	85	100	110	115
Total e/	943	967	993	955	685
United Arab Emirates, byproducts, natural gas and petroleum e/	780	967	967	1,089 r/ 4/	1,120
United States:					
Frasch e/	2,900	2,820	1,800	1,780	900
Byproduct:					
Metallurgy	1,430	1,550	1,610	1,320	1,030 4/
Natural gas	2,100	2,420	2,160	2,010	2,020 4/
Petroleum	5,370	5,230	6,060	6,210	6,360 4/
Total e/	11,800	12,000	11,600	11,300	10,300
Uzbekistan, byproduct:					
Metallurgy	145	165 e/	170	175 e/	180
Natural gas and petroleum	250	250 e/	275	280 e/	280
Total	395	415 e/	445	455 e/	460
Venezuela, byproduct, natural gas and petroleum	250	319	425	450	450
Other: e/ 8/					
Frasch	25	20	25	23 r/	24
Native	485	471	463	446	398
Pyrites	552 r/	421 r/	290 r/	227 r/	257
Byproduct:					
Metallurgy	661 r/	606 r/	649 r/	617 r/	677
Natural gas	150	130	206	215	255
Natural gas, petroleum, tar sands, undifferentiated	136 r/	148 r/	156 r/	153 r/	156
Petroleum	490 r/	569 r/	587 r/	540 r/	550
Unspecified	750	810	879	887 r/	888
Total	3,250 r/	3,180 r/	3,250 r/	3,110	3,200

See footnotes at end of table.

TABLE 12--Continued
SULFUR: WORLD PRODUCTION IN ALL FORMS, BY COUNTRY AND SOURCE 1/ 2/

(Thousand metric tons)

Country and source 3/	1996	1997	1998	1999	2000 e/
Grand total	55,200 r/	57,100	57,100 r/	57,700 r/	57,200
Of which:					
Frasch	4,670 r/	4,510 r/	3,170	2,980	2,290
Native 9/	725	721	723	746	698
Pyrites	8,100 r/	7,860 r/	6,070 r/	5,460 r/	4,770
Byproduct:					
Coal (lignite) gasification e/	2	2	2	2	1
Metallurgy	8,780 r/	9,670 r/	10,200 r/	10,200	10,400
Natural gas	6,000	6,200	6,900	7,230	7,780
Natural gas, petroleum, tar sands, undifferentiated	13,700 r/	14,400	15,300 r/	15,900 r/	15,900
Petroleum	9,210 r/	9,580 r/	10,400 r/	10,600	10,800
Unspecified	3,970	4,140	4,330	4,510	4,660
Gypsum e/	12 r/	12 r/	10 r/	--	--

e/ Estimated. p/ Preliminary. r/ Revised. -- Zero.

1/ World totals, U.S. data, and estimated data are rounded to no more than three significant digits; may not add to totals shown.

2/ Table includes data available through July 20, 2001.

3/ The term "Source" reflects the means of collecting sulfur and the type of raw material. Sources listed include the following: (1) Frasch recovery, (2) native, comprising all production of elemental sulfur by traditional mining methods (thereby excluding Frasch), (3) pyrites (whether or not the sulfur is recovered in the elemental form or as acid), (4) byproduct recovery, either as elemental sulfur or as sulfur compounds from coal gasification, metallurgical operations including associated coal processing, crude oil and natural gas extraction, petroleum refining, tar sand cleaning, and processing of spent oxide from stack-gas scrubbers, and (5) recovery from the processing mined gypsum. Recovery of sulfur in the form of sulfuric acid from artificial gypsum produced as a byproduct of phosphatic fertilizer production is excluded, because to include it would result in double counting. It should be noted that production of Frasch sulfur, other native sulfur, pyrites-derived sulfur, mined gypsum-derived sulfur, byproduct sulfur from extraction of crude oil and natural gas, and recovery from tar sands are all credited to the country of origin of the extracted raw materials. In contrast, byproduct recovery from metallurgical operations, petroleum refineries, and spent oxides are credited to the nation, where the recovery takes place, which is not the original source country of the crude product from which the sulfur is extracted.

4/ Reported figure.

5/ Official Polish sources report total Frasch and native mined elemental sulfur output annually, undifferentiated; this figure has been divided between Frasch and other native sulfur on the basis of information obtained from supplementary sources.

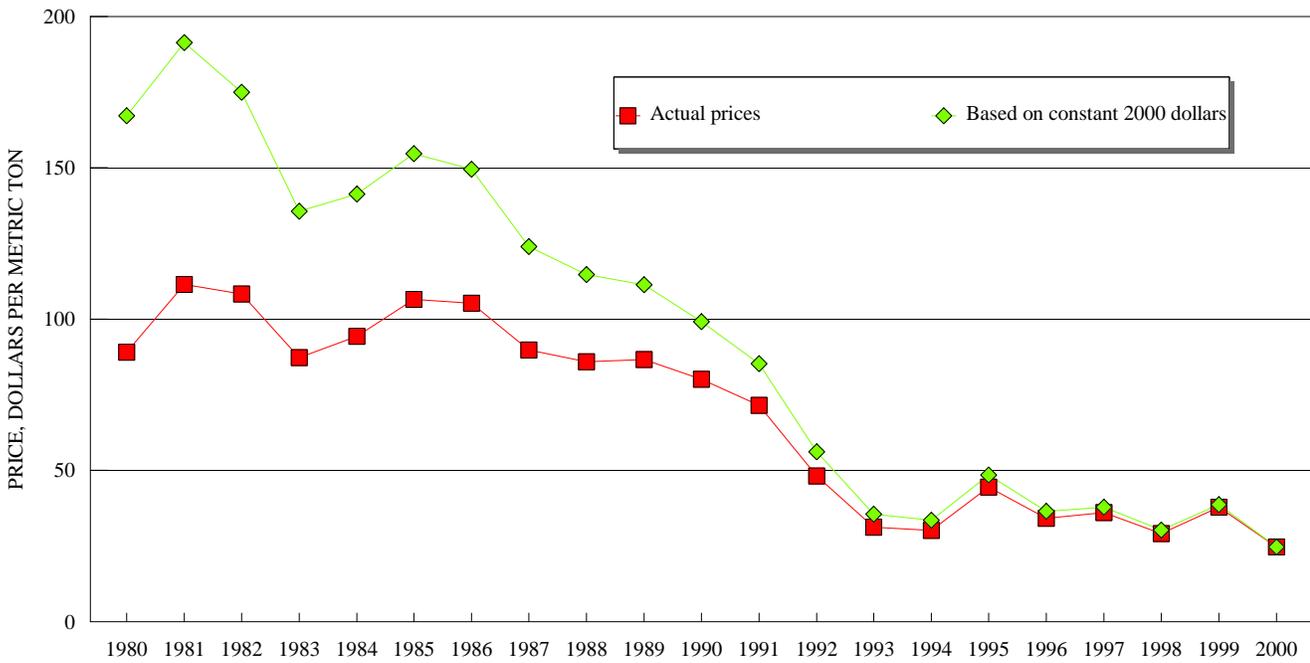
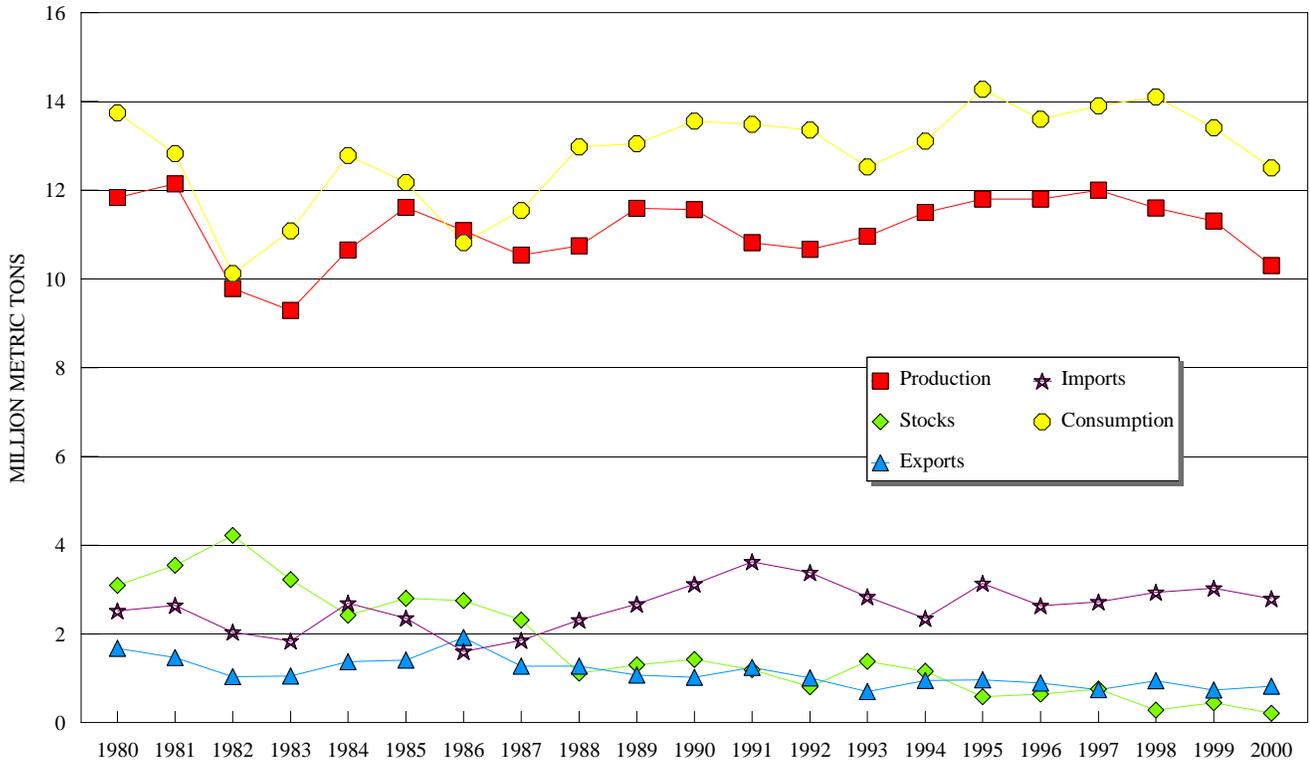
6/ Sulfur is believed to be produced from Frasch and as a petroleum byproduct; however, information is inadequate to formulate estimates.

7/ Includes byproduct production from synthetic fuels.

8/ "Other" includes all countries, except the above mentioned: Australia, Belgium, Canada, Chile, China, Finland, France, Germany, Iran, Italy, Japan, Kazakhstan Republic of Korea, Kuwait, Mexico, Netherlands, Poland, Russia, Saudi Arabia, South Africa, Spain, United Arab Emirates, United States, Uzbekistan, and Venezuela.

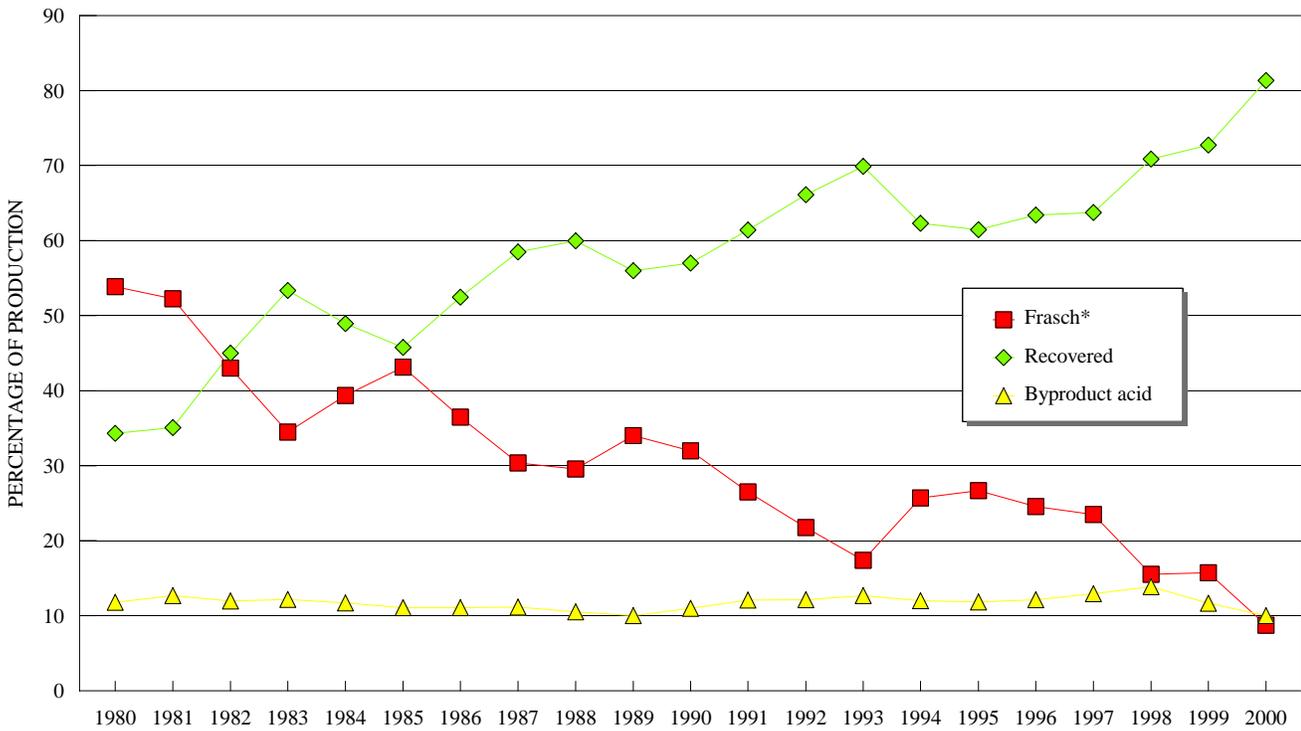
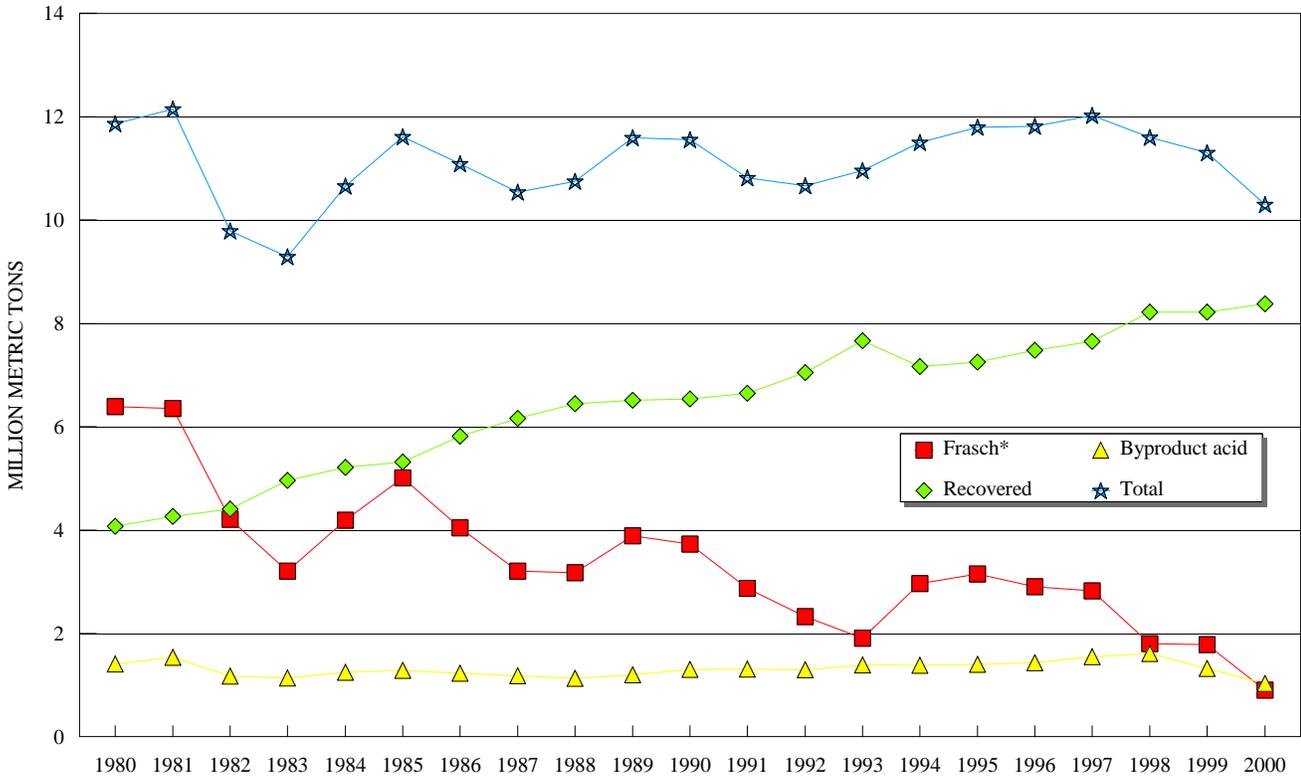
9/ Includes "China, elemental" and "Iraq, elemental, all sources."

FIGURE 1
TRENDS IN THE SULFUR INDUSTRY IN THE UNITED STATES



Based on the average reported values for elemental sulfur (Frasch and recovered), f.o.b. mine and/or plant, these prices reflect about 90% of the shipments of sulfur in all forms from 1980 through 2000.

FIGURE 2
TRENDS IN THE PRODUCTION OF SULFUR IN THE UNITED STATES



*Includes 10 months of Frasch data for 1993; the other 2 months are included with the recovered sulfur data to conform with proprietary data requirements. Data are estimates for 1994 through 2000.