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Sulfur Extended Asphalt Availability Of Sulfur

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SULFUR EXTENDED ASPHALT
AVAILABILITY OF SULFUR

by

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The contents of this report reflect the views of the authors who are responsible for the facts and the accuracy of the data presented herein. The contents do not necessarily reflect the official views or policies of the Washington State Department of Transportation. This report does not constitute a standard, specification, or regulation.

CHAPTER I
INTRODUCTION

CURRENT SULFUR RESEARCH IN WASHINGTON

The current sulfur related research in the State of Washington is being used to examine the potential of using sulfur for partially replacing or extending the asphalt cement in asphalt concrete. The first field experimental work was accomplished in a Washington State Department of Transportation (WSDOT) sponsored study entitled "Sulfur Extended Asphalt Binder Evaluation". This project was a cooperative effort between WSDOT, the University of Washington (UW), Washington State University (WSU), the Federal Highway Administration (FHWA), the Sulphur Development Institute of Canada (SUDIC) and the Asphalt Paving Association of Washington. The study involved the placement (August 1979) of sulfur extended asphalt (SEA) paving mixtures at two test sites near Pullman, Washington [1]. One site is on an existing state highway (SR 270) and the other was the WSU Test Track. Evaluation of the SR 270 test site will continue through August 1982.

Based on initial findings from the first SEA project, a second study was initiated by WSDOT with UW entitled "Sulfur Extended Asphalt Laboratory Investigation". The stated goals of this study are:

1. Further evaluate the applicability and desirability of using SEA paving mixtures in the State of Washington.
2. Develop design criteria which will improve the utilization of SEA mixtures.
3. Assess the availability and pricing of sulfur in the State of Washington.

It is the latter goal which this report addresses. The SEA studies conducted in this state and others are being used to examine the strength and durability of these paving mixtures. The added question is whether enough sulfur will be available at an acceptable price to use in the replacement or extension of asphalt cement.

As the price of sulfur decreased in the early 1970's, it appeared that sulfur could become at least a partial replacement or extender of asphalt cement resulting in a materials related savings and conserving a commodity which eventually was in short supply (asphalt cement). Thus, the majority of the research related to SEA paving materials has been oriented toward the structural aspects. However, economic and supply situations have continued to change over the last few years. Currently, from a strictly economic view, the concept of extending asphalt concrete mixtures with sulfur does not appear to be advantageous

or at best is marginal. Thus, this report is used to present an overview of the sulfur supply and pricing situation from the perspective of past, present and forecasted future conditions. It is clear that the potential users of SEA materials must know whether they can or cannot expect an economically attractive material in the future.

If the sulfur supply predictions prove adequate, how much asphalt might be saved by using SEA mixtures? Table 1 has been prepared to provide an estimate of this amount for the State. The table was prepared for various percentages of SEA mixtures as a function of the total annual hot-mix production for the State (estimated at 4.5 million metric tons (5.0 million tons)). If all of the hot-mix production were SEA mixtures with a 30/70 ratio, the State of Washington requirement for sulfur would be slightly less than 90,000 metric tons (97,500 tons) with a corresponding asphalt savings of 45,400 metric tons (50,000 tons). If we use a current asphalt price of \$190 per metric ton (\$170 per ton), then the break even price for sulfur is about \$95 per metric ton (\$85 per ton). However, price is only one issue. If asphalt is placed on an allocation system, price may be delegated to a somewhat secondary issue. If all hot-mixes produced in the state were SEA mixtures, about 1.5 percent of the total sulfur production of Alberta would be utilized for this purpose.

SULFUR SUPPLY AND DEMAND

Sulfur is one of the most important of the industrial raw materials. To quote the Kirk-Othmer Encyclopedia of Chemical Technology:

"Sulfur, one of the most versatile and essential elements on this planet, is the chemical industry's most widely used raw material. In fact, its applications are so widespread that sulfur consumption is often used as a measure of a nation's economic activity".

Historically, an adequate supply of sulfur was available to meet the demand at an annual growth rate of 4 to 4.5 percent. However, in 1974-1975, the supply of sulfur decreased and the sulfur market became tight with regard to supply and demand. The market continued to be tight through 1976, and a debate as to whether the world would experience a glut or shortage of sulfur in the next ten to twenty years occurred. This lack of consensus was summarized in an article published in 1976 [2] and two paragraphs from that article are as follows:

"On the glut side: existing world stockpiles of a record 26 million metric tons (28.6 million tons) of surplus sulfur; the likelihood of large tonnages of recovered sulfur being produced in the Middle East as a result of sweetening operations at natural-gas-exploitation projects underway there; the probability of more sulfur being recovered as a result of the U.S.

Table 1. Estimates of Sulfur Use for Various Percentages of SEA Paving Mixtures.*

Percent of Total Hot-Mix in State of Washington Using Sulfur Extended Asphalt (30/70 ratio)	Total Amount of Required Sulfur (tons)	**Total Asphalt Savings (tons)
5	4,900	2,500
10	9,750	5,000
25	24,400	12,500
50	48,800	25,000
75	73,100	37,500
100	97,500	50,000

1 metric ton = 1.1023 tons

*Based on annual hot-mix production of 5 million tons (4.5 million metric tons).

**Based on assumption that "optimum" contents require same volume of binder. Binder content for conventional hot-mix assumed to be 5.5% (by weight of total mix) and 6.5% (by weight of total mix) for sulfur extended asphalt (30/70 ratio).

and Western European environmental legislation targeted at power-plant stack-gas emissions; the virtual certainty that more high-sulfur crude will be processed in the U.S.; and the expected growth of recovered sulfur supplies following commercialization of projects for synthetic natural gas, coal liquefaction, shale oil and other alternative energy sources.

On the shortage side: predicted declines in sulfur associated with dwindling gas-fields in currently strong producing areas such as France and Canada; doubts about the rate of recovered sulfur in the next decade; lack of strong economic incentives for continued growth of Frasch (mined) sulfur production in the U.S.; reservations about the marketability of small tonnages of recovered sulfur from scattered individual sources; and rapidly inflating capital costs for Frasch facilities, recovery units and shipping and transportation."

The sulfur market supply and demand situation has remained tight and the lack of agreement regarding future sulfur availability continues. Numerous individuals in several organizations continue to analyze historical data, projected world trends, and technological improvements in sulfur recovery to resolve the uncertainty of sulfur's future availability. The motivation for examining this future availability of sulfur is extensive ongoing research into the potential use of sulfur as a construction material.

This report provides background regarding the uses of sulfur, types of sulfur deposits, identified sulfur reserves, current sulfur recovery technology, and the importance of price in maintaining an adequate future supply of sulfur. The report is concluded with projected sulfur supply and demand trends for the world, the United States, and the State of Washington.

USES OF SULFUR

Sulfur is unusual when compared with most major mineral commodities since it is largely used as a chemical reagent rather than as a finished product component. This predominant use generally requires that prior to its initial use in industry it first be converted to an intermediate chemical product. Sulfuric acid is the most important of these intermediate products and in 1978 approximately 85 percent of the sulfur consumed in the United States was either converted to or produced directly in this form.

The distribution of U.S. sulfur consumption in 1978 by end-use

categories may be broadly summarized as follows [3]:

Agriculture. This category was by far the most important and accounted for more than 60 percent of the domestic sulfur demand.

Petroleum Refining. This category includes petroleum refining and associated chemical processes where process streams may serve both the refinery and the chemical complex. Sulfuric acid requirements for these processes accounted for 8 percent of the U.S. sulfur demand.

Nonferrous Metal Production. This category, which includes the leaching of copper and uranium ores with sulfuric acid, accounted for 6 percent of the domestic sulfur consumption.

Plastic and Synthetic Products. This category covers a wide range of synthetics including acetate, cellophane, rayon, viscose products, fibers, and textiles. Together, they accounted for 4 percent of the U.S. sulfur demand.

Paper Products. This category accounted for 3 percent of the U.S. sulfur demand, with the largest single demand being in the manufacture of wood pulp by the sulfite process.

Paints. This category accounted for 3 percent of U.S. sulfur consumption.

Iron and Steel Production. Sulfuric acid can be used as a pickling agent to remove mill scale, rust, dirt, and grease from the surface of steel products prior to further processing. Consumption of sulfur for this category in the form of sulfuric acid accounted for 1 percent of domestic demand.

Other Uses. This general category covers a wide variety of end uses, including intermediate chemical products, which were largely in the form of sulfuric acid, but included some quantities of elemental sulfur. They accounted for approximately 13 percent of the U.S. sulfur consumption.

New Uses. Recent research efforts have included plasticization of sulfur, sulfur-coated urea, sulfur coatings, sulfur in structural and construction materials, sulfur extended asphalt pavements, civil engineering applications of sulfur-based materials, cold-region testing of sulfur foams and coatings, and lithium sulfur and sodium sulfur battery applications.

SULFUR SOURCES

Sulfur is widely distributed throughout nature and constitutes approximately 0.06 percent of the earth's crust. However, only a small portion of the sulfur exists in sufficiently concentrated amounts to justify the economic costs of mining or recovery. These sulfur deposits are generally classified as follows [3,4]:

Elemental (Native) Sulfur Deposits. These include deposits in limestone rock formations overlying salt domes, gypsum evaporite basin formations, and volcanic rocks. Large deposits over salt domes are currently being exploited in the gulf coast regions of the United States and Mexico. Within the limestone formation, the sulfur may exist as crystals in the rock voids, as veins or as fine particles disseminated in dense rock. Normally, the sulfur is dispersed irregularly throughout the rock mass and rarely occurs in pure layers of appreciable thickness. Deposits in evaporites are currently being mined in Texas, Poland, the U.S.S.R., and Iraq. These salt domes and evaporites are the principal sources of mined elemental sulfur with the sulfur generally extracted through the utilization of the Frasch process (refer to Chapter II). The majority of the volcanic sulfur deposits are located on the Pacific rim. These deposits have furnished only a limited portion of the world's sulfur supply.

Metal Sulfide Deposits. These include deposits of ferrous sulfides (pyrites and pyrrhotite), recovered and processed for their sulfur content, and nonferrous metal sulfides, processed for their nonferrous metal content with the recovery and processing of sulfur as a coproduct. Pyrite deposits served as the primary source of sulfur in the late 19th and early 20th centuries. However, due to the large amounts of energy required in the recovery process, these deposits have become less important. Concurrently, the nonferrous metal sulfides have provided a rapidly increasing coproduct sulfur supply.

Sulfate Deposits. Bedded deposits of gypsum and anhydrite represent perhaps one of the largest sulfur resources. These deposits have been virtually untapped since the economics of recovering the sulfur are currently unfavorable. However, in Europe such deposits are being processed on a limited scale for the production of sulfuric acid.

Natural Gas. Hydrogen sulfide is a component of sour natural gas deposits and must be removed prior to marketing. As a coproduct, the recovered elemental sulfur is the major source of elemental sulfur used in the world. Deposits of sour natural gas are located in Canada, the Middle East, the United States, France, the Federal Republic of Germany, Venezuela, and the U.S.S.R.

Petroleum and Tar Sands. Complex organic sulfur compounds constitute 0.1 to 14 percent by weight of petroleum and tar sands [5]. During the refining process, these compounds are partially removed. The vast petroleum reserves in the Middle East contain high percentages of sulfur which is potentially recoverable on a large scale. The Athabasca tar sands in Canada represent an important future sulfur source.

Coal and Oil Shale. Ferrous sulfides (pyrite) and organic sulfur compounds are components of coal and oil shale in varying concentrations. To date, little sulfur from these sources has been recovered. They present a future potential resource for the United States.

An assessment of the world sulfur reserves and identified resources, as developed by the U.S. Bureau of Mines, is provided in Table 2. Table 3 provides a similar assessment for the United States by type of deposit.

"Reserves" (as used in Tables 2 and 3) are defined as elemental, pyrite, and sulfate sulfur deposits that are recoverable at present price levels using current technology [3]. The assessment of coproduct sulfur deposits is more complex. Coproduct sulfur is in some cases recovered at considerably lower than present price levels due to the requirement that the sulfur must be removed from the prime product prior to marketing. The assessments for nonferrous metals, petroleum, and tar sands are based on the employment of current technology.

The "other" category is defined as sulfur potentially recoverable from identified deposits using current technology at higher price levels.

In Tables 2 and 3 the vast sulfur resources in coal and oil shale deposits are specifically excluded due to the uncertainties in their projected recovery technologies. These virtually untapped resources are significant. For example, the identified coal reserves in the United States contain approximately 20 billion metric tons (22 billion tons) of sulfur. The coal reserves in the rest of the world contain approximately 80 billion metric tons (88 billion tons) of sulfur. Similarly, the large sulfur resources contained in gypsum and anhydrite deposits are limited in the tables to 50 million metric tons (55 million tons) in the United States and to 100 million metric tons (110 million tons) in Europe. These quantities represent only those deposits which have been identified as high purity gypsum and are suitable for sulfur production using current technology. Further, the tables exclude the majority of the identified gypsum and anhydrite deposits which underlie large areas on every continent and which, with improved technology, would provide essentially unlimited sulfur sources.

Table 2. Identified World Sulfur Resources
(million metric tons) [3].

Country	Reserves	Other	Total
North America			
United States	175	155	330
Canada	350	2,000	2,250
Mexico	90	60	150
Other	5	-	-
Total	520	2,215	2,735
South America	30	30	60
Europe:			
U.S.S.R.	250	450	700
Poland	150	450	600
France	30	10	40
Germany, Federal Republic of	30	5	35
Spain	30	450	480
Italy	15	25	40
Other	185	285	470
Total	690	1,675	2,365
Africa	20	-	20
Asia			
Japan	10	40	50
Iraq	150	50	200
Near East	250	400	600
China: Mainland	25	50	75
Other	50	200	250
Total	485	740	1,228
Oceania	20	10	30
World Total	1,765	4,670	6,435

1 metric ton = 1.1023 tons

Table 3. Identified U.S. Sulfur Resources
(million metric tons) [3].

Type of Deposit	Reserves	Other	Total
Salt domes and evaporites	90	25	115
Nonferrous metal sulfides	55	30	85
Natural gas	20	10	30
Petroleum	10	10	20
Pyrite	-	50	50
Volcanic	-	20	20
Tar sands	-	10	10
Total	175	155	330

1 metric ton = 1.1023 tons.

CHAPTER II

SULFUR RECOVERY TECHNOLOGY

Sulfur recovery processes are categorized as either voluntary or involuntary depending on whether sulfur is the primary product or a coproduct from other processes [6]. Examples of voluntary or primary sources include pyrite, native sulfur, and gypsum deposits. Involuntary sulfur, as the term implies, is a coproduct arising from the abatement of sulfurous emissions associated with the processing or combustion of fossil fuels and the roasting and smelting of base metal ores. An example of involuntary sulfur is that produced in Canada from sour natural gas.

The more important individual processes currently utilized to recover sulfur are summarized [3]:

Frasch Process. In this process, developed by Dr. Herman Frasch in Louisiana in 1891 [7], large quantities of hot water are injected through wells drilled into buried deposits of native sulfur. Figure 1 is a sketch of a typical Frasch sulfur production well. The outer pipe, which extends to the bottom of the sulfur zone, carries a flow of hot water which is forced out through holes into the sulfur-bearing formation. The heat from the hot water is transferred to the formation and melts the sulfur. The liquid sulfur, being heavier than water, accumulates at the bottom of the well. The smaller interior pipe carries compressed air which serves as an airlift and raises the liquid sulfur to the surface through the next larger pipe. The injected water migrates through the formation and is eventually extracted through the bleed-water wells which are located on the flanks of the structure away from the mining area.

The cost of heating the process water is the major operating expense. However, the economy of water usage is also important and must be considered. This process is employed almost exclusively for the mining of permeable native sulfur deposits that are enclosed within impermeable formations. These conditions ensure the retention of the liquid sulfur within the area being mined and the migration of the hot process water away from the production area with the release of the residual heat to formations that will be mined at a later period.

Other Native Sulfur Processes. Native sulfur ores not recoverable by the Frasch process may be treated by various methods. Ores of high and medium sulfur content are often roasted directly and the resultant sulfur dioxide gas is converted to sulfuric acid. Medium and low-grade ores may be treated by a wide variety of ore-dressing and chemical

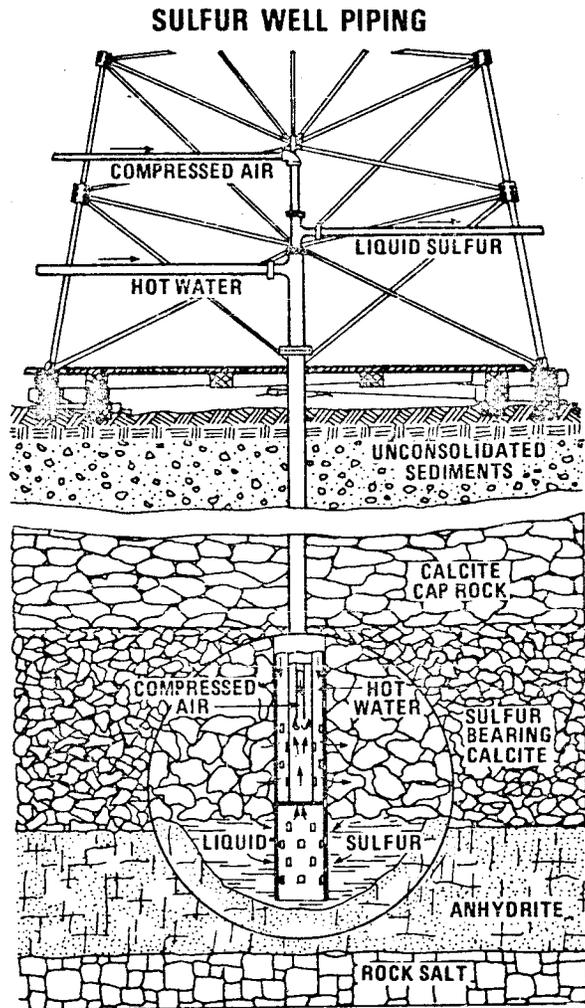


Figure 1. Frasch Process for Mining Sulfur [3].

methods including: melting, distillation, agglomeration, floatation, and solvent extraction. These latter methods are extremely costly and are used only under exceptional circumstances.

Pyrite Processes. Pyritic ores of 40 to 50 percent sulfur are generally roasted for the production of sulfur dioxide gas which is then converted to sulfuric acid. This process is of importance in countries that do not have access to other inexpensive sources of elemental sulfur or that contain pyritic deposits.

Nonferrous Metal Concentrate Processes. Sulfur dioxide gases from nonferrous roasters and smelters, principally those treating copper, lead, zinc, and nickel concentrates, are cleaned of particulate matter and then passed to an acid plant for the production of sulfuric acid. This process is much more difficult than the pyrite process because of the widely varying sulfur contents in the fluctuating gas streams. Due to the locations of most nonferrous metal smelters, the amount of sulfuric acid that can be marketed is limited by transportation and storage costs (market should be within a 400 km (250 mi.) radius of the plant [8]). Therefore, this process is generally used to satisfy environmental emission requirements. A smelter of this type is located in Tacoma, Washington (American Smelting and Refining Co. (ASARCO)) and the principal metal produced is copper. Part of the sulfur emissions generated at this plant are recovered and converted to sulfuric acid and the remainder discharged to the atmosphere [8]. The Puget Sound Air Pollution Control Agency granted ASARCO an air pollution variance until December 31, 1982 on its current sulfur dioxide emissions [14].

The principal nonferrous metal sulfides and their associated sulfur contents are [8]:

<u>Mineral</u>	<u>Metal</u>	<u>Sulfur Content (%)</u>
Chalcopyrite	Copper	35
Chalcocite	Copper	20
Bornite	Copper	26
Enargite	Copper	33
Sphalerite	Zinc	33
Galena	Lead	13

Natural Gas and Petroleum Processes. In the case of sour natural gas, sulfur occurs in the hydrogen sulfide (H_2S). In the case of petroleum, sulfur

occurs in organic sulfur compounds. These compounds are converted to hydrogen sulfide during the refining process. In both cases, the gas streams are passed through an absorbent solution to remove hydrogen sulfide and other gases such as carbon dioxide. The absorbent solution is stripped of its hydrogen sulfide content, yielding a concentrated hydrogen sulfide gas. The hydrogen sulfide is then converted to elemental sulfur by the Claus process.

Figure 2 provides a one-line diagram of a typical Claus sulfur converter process. Hydrogen sulfide gas is burned in the reaction furnace and approximately one-third of the gas is oxidized to sulfur dioxide. These two gases undergo a chemical reaction and liquid sulfur is produced. The hydrogen sulfide and sulfur dioxide which are not consumed in the chemical reaction are passed through one or more activated bauxite catalyst converters to complete the reaction. The waste gas from the reactions is passed through an incinerator to ensure complete conversion of the remaining hydrogen sulfide to sulfur dioxide. The sulfur dioxide is then released to the atmosphere. This process, utilizing three converters, is capable of recovering 98 percent of the sulfur in the feed stream.

Gypsum Processes. These processes are linked with the coproduct recovery of calcium (lime), which is used in the manufacture of cement. Gypsum and anhydrite are decomposed by chemical and pyrometallurgical processes for the production of either elemental sulfur or sulfuric acid.

These methods are rather costly, even with the consideration of the coproduct value of the cement production. Accordingly, they are used only in England and Europe on a limited basis. However, as discussed previously, the identified deposits of gypsum and anhydrite are large, and under favorable economic and technological conditions, these deposits could provide an almost unlimited source of sulfur.

Coal Processes. The sulfur content in coal varies between 1 and 14 percent and generally occurs as the sulfide mineral, pyrite. Present ore-dressing techniques can recover a portion of the pyrite. However, these processes have limited use. An additional small amount of sulfur may also be produced as elemental sulfur and sulfuric acid during the coal-coking operations.

Catalytic coal gasification techniques can produce hydrogen sulfide as a byproduct [9]; hence, the potential conversion of hydrogen sulfide to elemental sulfur. However, large scale coal gasification systems are still under development.

TYPICAL CLAUS SULFUR CONVERTER PROCESS

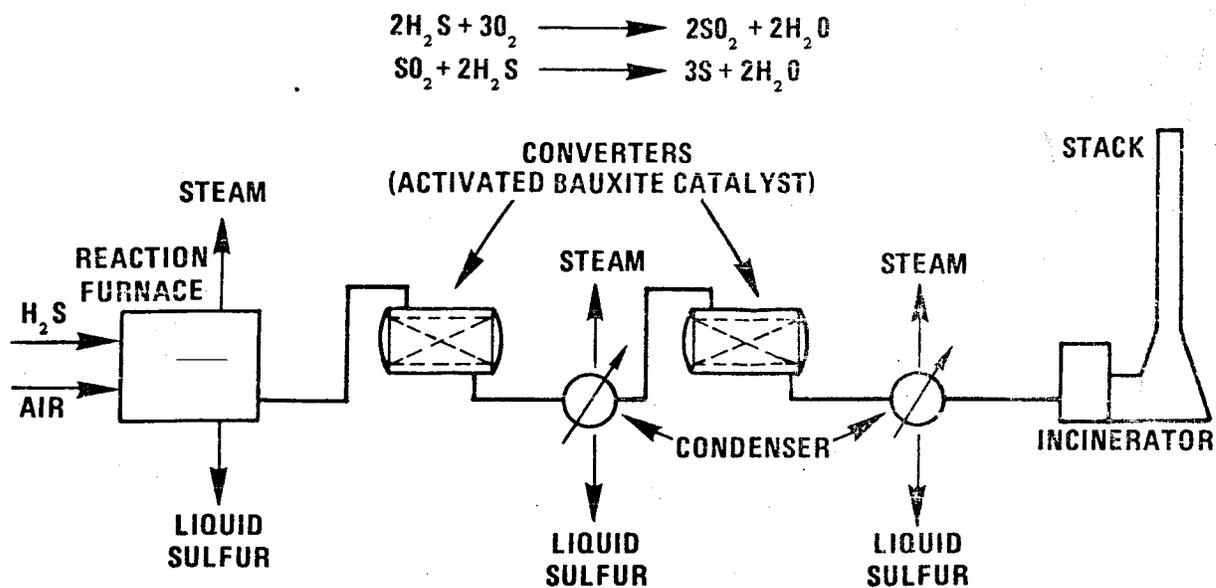


Figure 2. Typical Claus Sulfur Converter Process [3].

CHAPTER III

GLOBAL SULFUR SUPPLY AND DEMAND

The world has historically consumed sulfur in all forms at a growth rate of about 4 percent per year [10]. More specifically, the industrialized countries of North America and North Western Europe have consumed sulfur at an annual growth rate of 3 percent and the developing nations have increased their consumption at a rate of about 5 to 5.7 percent.

During the 1950's and early 1960's voluntary sulfur producers supplied the majority of world sulfur. During this period, sulfur production costs determined the lower price limit and the going market price was linked directly to the generally recognized supply/demand relationship. However, this situation changed during the 1960's when sour gas production and processing boomed in Alberta, Canada and Canada progressed from a net importer of sulfur to a major exporter.

Canada's considerable new leverage in the world sulfur market depended principally upon the abundance of low-priced coproduct elemental sulfur in a world of few significant producers. Except for France, whose production was also the coproduct of sour natural gas processing, the other major suppliers were voluntary sulfur producers. Since Canada's market price was not controlled by its production costs and it initially viewed sulfur as an undesirable byproduct, it was able to expand its sulfur market share rapidly during the 1960's to over 30 percent of the international trade by 1968.

Prior to 1968, price leadership in sulfur had been maintained by producers in the United States. The oversupply situation that developed in 1968, and persisted until early 1972, eliminated the United State's historical price leadership. The rapid growth rate of stockpiles in Alberta and Canada's continued view of sulfur as an undersirable product, resulted in Canadian producers invariably leading sulfur prices downward. This predatory pricing greatly reduced the effectiveness of the world's voluntary producers and voluntary production growth began to decline. However, since the Canadian sulfur producers continued to supply 30 percent of the world sulfur supply and their production rate continued to increase, the decline in voluntary sulfur production was not readily apparent.

By 1971 a world oversupply of sulfur was developing. The Canadian National Research Council, prompted by its concern about the oversupply situation, established the Sulphur Development Institute of Canada

(SUDIC), a joint federal-provincial-industry sponsored organization, whose primary purpose was to fund research and to coordinate the development of new uses for sulfur [10]. Their sponsored research quickly revealed several potential uses for sulfur, the majority of which were in the area of construction.

The world oversupply situation for sulfur continued through 1972. However, this began to change in 1973 when Canada's annual sulfur production peaked at 7 million metric tons (7.7 million tons), thereafter declining. This decline was caused by the lack of significant sour gas discoveries in Alberta after the mid-1960's and the continual pumping of millions of cubic feet per day of sweet gas back into the reserve formations which, over time, resulted in the dilution of the sour gas reserves. This decline in production, coupled with the continual decline in voluntary sulfur production since 1968, resulted in a significant reduction in the sulfur production growth rate for 1974.

The decline in the world sulfur production growth rate continued and by 1975 the world supply/demand situation had become tight and some forecasters, who had only four years earlier predicted a serious world oversupply situation, began to show concern over a sulfur shortage in the near future. A controversy as to whether the world would face an oversupply or shortage of sulfur developed. Many questioned what events had caused the new unexpected sulfur market situation. Some felt the causes were principally: the declining reserves of sulfur from natural gas, the depressed prices as a result of Canada's leadership as a price setter, the increased energy-cost constraints on Frasch sulfur mining, the closing of substantial uneconomic pyrite capacity, a general slowdown in the investment in new metal mining and smelting capacity, certain logistical constraints, and a general lack of investor confidence in sulfur.

Concurrently, during the 1968-1975 time period, when the world sulfur markets had gone from an oversupply to a shortage situation, the United States' sulfur markets had also experienced several major changes [3]. Frasch sulfur production, as a percent of the total U.S. production, had steadily declined, while recovered coproduct sulfur had risen. Imports had become an increasingly important source of sulfur. In addition, the United States had undergone a progressive regionalization of the sulfur industry and each sector of the industry developed its own supply/demand relationship in markets in which it could best compete. The Frasch industry had gradually constricted its marketing to the southern and eastern states and to export. The recovered coproduct sulfur and byproduct sulfuric acid sectors had progressively obtained larger shares of markets in the western and central states and began penetration of the markets in

the southern states. Canada continued to dominate the million-ton market in the north central and western states, whereas Mexican imports of Frasch sulfur served Florida and east coast markets. To summarize and assist in visualizing this period's effect on the historical sulfur production and demand relationship in the United States, a comparison of the sulfur production and demand from 1915-1981 is shown in Table 4 and Figure 3.

In 1976, the controversy still existed as to whether there would be a shortage or oversupply of sulfur in the near future. An increasing number of individuals began to shift their support from the forecasted oversupply situation to that of a tight or shortage market situation. Many Canadians began to feel that the oversupply prognosis had turned out to be too pessimistic and that corrective action under the original parameters for the establishment of SUDIC should be relaxed. SUDIC's role was modified to include that of increasing the returns for Canadian sulfur through higher value new uses and through more efficient transportation and handling to traditional markets [10].

By 1978, over 60 countries produced commercial sulfur in one or more of the principal forms [6]. Of these countries, only Canada, Poland, Mexico and the Middle East were significant net exporters. Canada continued as the world's largest exporter and accounted for 35 percent of the world total. Poland was second at 27 percent. The U.S.S.R. and the United States, the largest producers, did not meet their domestic requirements. For example, the U.S. production totaled 11.2 million metric tons (12.3 million tons) and consumption totaled 12.6 million metric tons (13.9 million tons), thus a net importation of sulfur was required. U.S. imports currently are obtained from Canada (56.0%), Mexico (43.4%) and other minor sources (0.6%) [13]. Africa, South America, Australia, the Far East, and Western Europe were also net importers and all depended on Canadian imports. The world sulfur market continued to be tight, with world production at 54 million metric tons (59.5 million tons) and consumption at 52.5 million metric tons (57.9 million tons).

Of the 54 million metric tons (59.5 million tons) produced, 53 percent was involuntary sulfur which is nondiscretionary and cannot be directly adjusted to demand. In addition to this complex marketing situation, the sulfur supply/demand balance in 1978 was aggravated by several world situations: the revolution in Iran, mine flooding in Poland, severe weather in North America and labor disruptions in Canada.

In 1979, several major sulfur consumers in Europe, India, and Pakistan had to shut down or advance their annual shutdowns due to the lack of sulfur. Also in 1979, sulfur tanker incidents with subsequent dry-docking and repairs, and the tug-boat strike on the east coast of the United States

Table 4. Comparison of U.S. Domestic Sulfur Production and Demand, 1915-1981 [after Ref. 3, 11, 12, 13]

Year	Demand (1000 metric tons)	Production (1000 metric tons)	Year	Demand (1000 metric tons)	Production (1000 metric tons)
1915*	350	520	1966	9,292	9,288
1925*	1,250	1,400	1967	9,399	9,267
1935*	1,200	1,600	1968	9,217	9,891
1944*	2,900	3,200	1969	9,316	9,698
1954	4,992	6,782	1970	9,375	9,710
1955	5,715	7,140	1971	9,320	9,734
1956	5,836	7,943	1972	10,012	10,382
1957	5,643	7,116	1973	10,399	11,096
1958	5,347	6,240	1974	10,991	11,602
1959	6,012	6,267	1975	10,773	11,440
1960	5,956	6,768	1976	10,941	10,879
1961	5,988	7,287	1977	11,657	10,727
1962	6,344	6,865	1978	12,600	11,175
1963	6,713	6,730	1979	13,739	12,101
1964	7,371	7,201	1980	13,635	11,839
1965	8,109	8,328	1981*	13,300	12,400

*Approximate

1 metric ton = 1.1023 tons

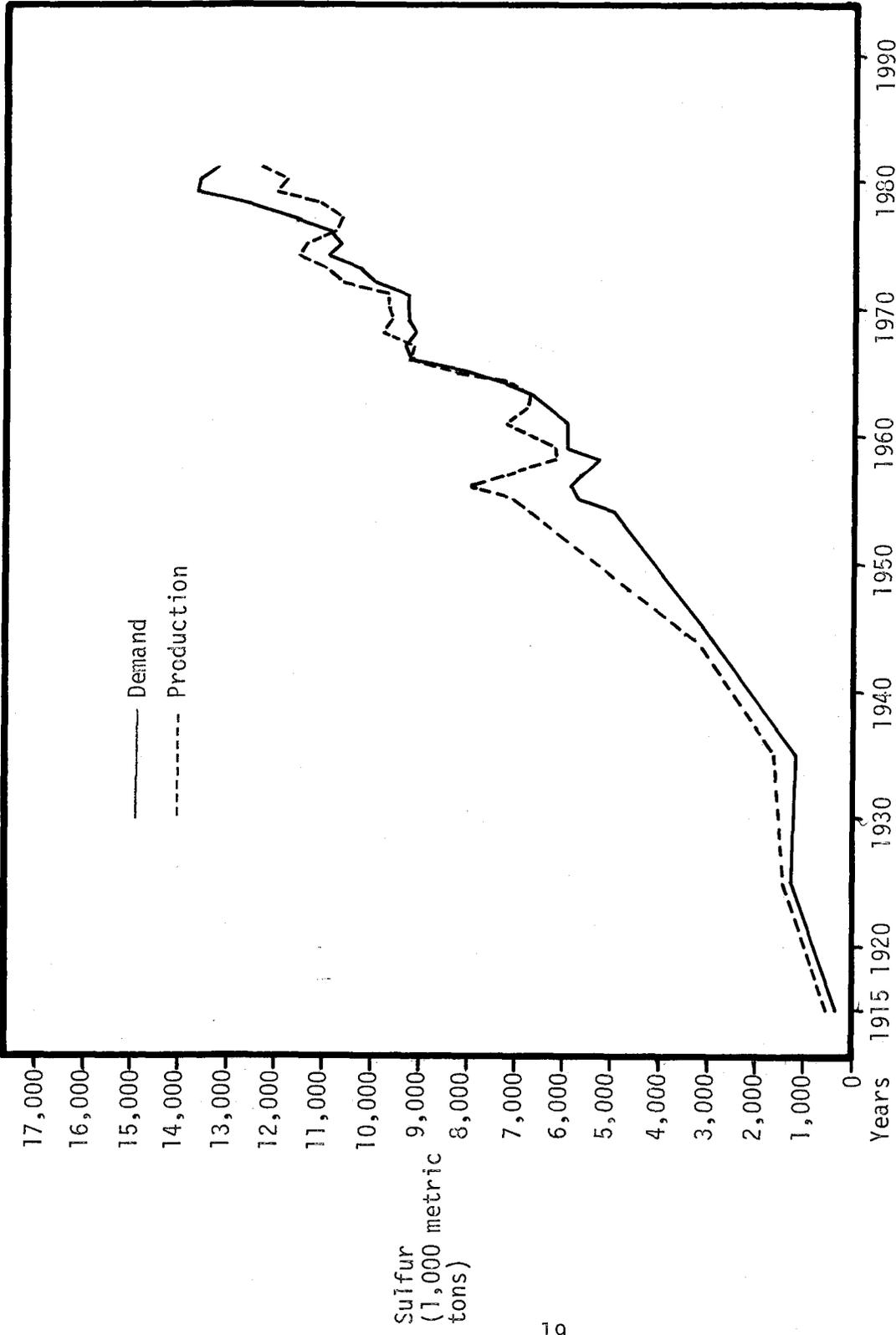


Figure 3. Domestic Sulfur Production and Demand, 1915 - 1981

greatly affected the world sulfur markets. These incidents, and those in 1978, demonstrated that one cannot deal with sulfur in isolation as Canadian, American, etc. To understand the commodity, one must view it in a global context.

PRICE EFFECTS

As previously discussed, world sulfur resources are virtually unlimited. However, their availability is a function of price; therefore, an examination of past pricing trends and their relationship to the supply/demand balance is appropriate.

Table 5 provides the time-price relationship for U.S. domestic sulfur from 1915-1981 in terms of actual and constant 1981 dollars per metric ton [3, 11] and Figure 4 shows a graphical representation of this relationship. These prices are based on the average reported prices for elemental sulfur (Frasch and recovered) f.o.b. mine/plant and reflect about 90 percent of the shipments of sulfur in all forms during this period.

Prior to 1955, sulfur prices (in 1981 dollars) were about what they are today. Between 1955 and 1965 the time-price relationship reflects the general stability of the sulfur market, which was based on the dominance of the Frasch sulfur supply. The stability of the market was the result of its ability to respond directly to supply/demand pressures and by the existence of ample Frasch stockpiles to supplement the market during temporary shortages.

This period was followed by one of short supply in the market countries. This deficit was made up by U.S. stockpiles. This, coupled with increased growth in the fertilizer industry, resulted in abnormally high sulfur prices in both 1967 and 1968. In response to the increased demand and prices, voluntary producers increased production. However, this increase in production, coupled with the new large supply of Canadian involuntary sulfur, resulted in a serious oversupply in 1968. The effects were further magnified by a retrenchment in the fertilizer sector and a weakening of export prices. Supply became more and more unrelated to demand and all of these factors led to a general collapse of the sulfur market, which continued through 1973.

As shown in Table 5, sulfur prices rose dramatically from 1972 to 1981, an increase of over 650 percent. As discussed previously, this period of time experienced a decline in the growth rate of world sulfur production and the increased prices were partially in response to the increasingly tight market situation. However, several other factors also influenced the price increases and included:

Table 5. Time-Price Relationships for Sulfur, 1915-1981
 [after Refs. 3, 11, 13]

Year	Average Annual Prices (dollars per metric ton)		Year	Average Annual Prices (dollars per metric ton)	
	Actual Prices	Based on Constant 1981 Dollars		Actual Prices	Based on Constant 1981 Dollars
1915*	17.00	127.82	1967	32.12	86.58
1925*	15.00	75.76	1968	39.49	103.92
1935*	18.00	117.65	1969	26.62	67.39
1944*	16.50	82.91	1970	22.77	55.67
1955	27.50	84.62	1971	17.19	40.83
1956	26.07	77.59	1972	16.76	38.62
1957	24.02	69.42	1973	17.56	37.05
1958	23.44	66.78	1974	28.42	51.96
1959	23.09	65.78	1975	44.91	74.11
1960	22.76	64.66	1976	45.72	72.34
1961	22.75	65.00	1977	44.38	65.94
1962	21.41	61.00	1978	45.17	62.22
1963	19.67	56.20	1979	55.75	69.08
1964	19.87	56.61	1980	88.93	97.19
1965	22.12	61.79	1981*	111.00	111.00
1966	25.36	68.54			

*Approximate

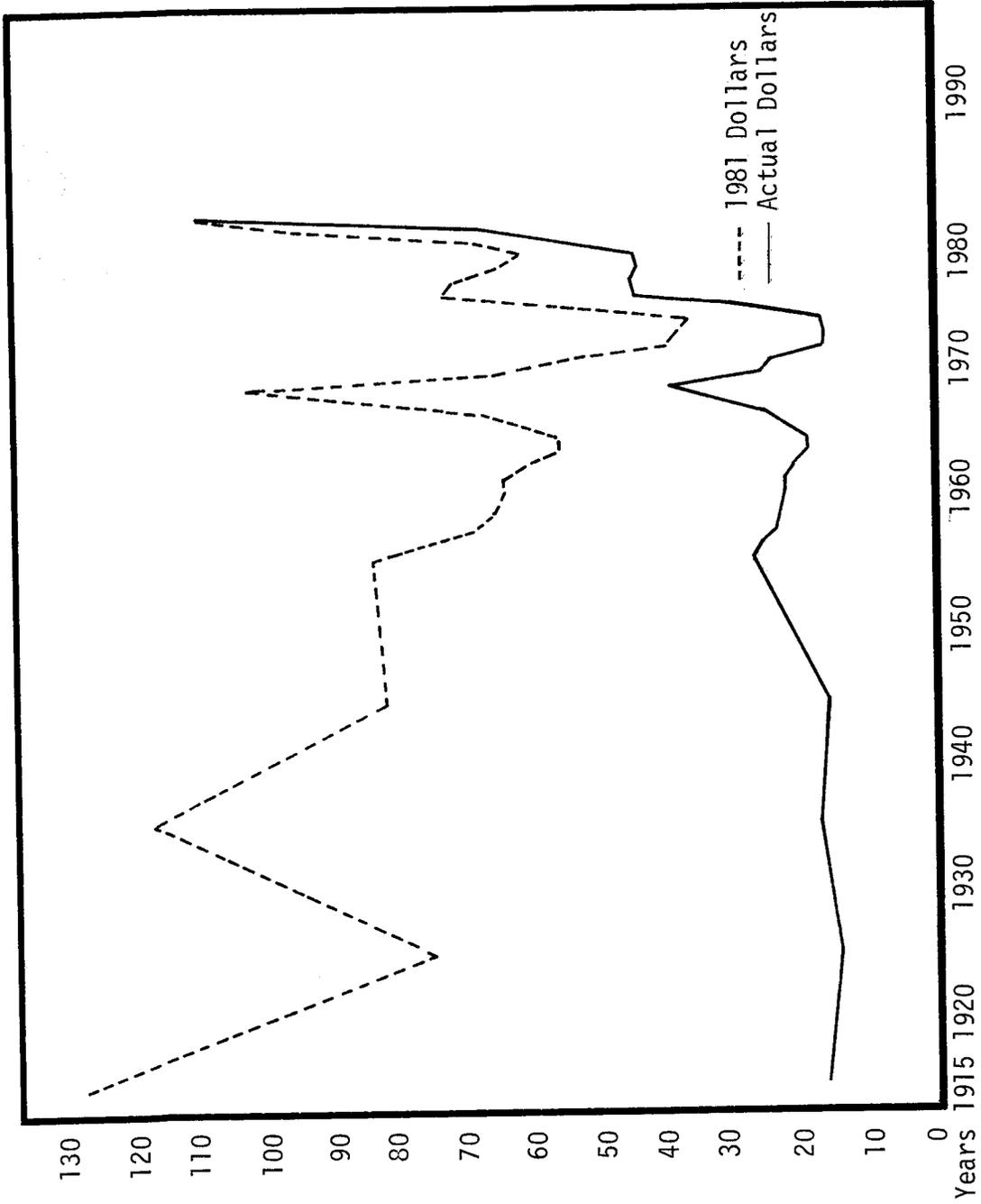


Figure 4. Time Price Relationship for Sulfur, 1915-1981.

1. the rapid expansion in the fertilizer industry;
2. the high profitability of the fertilizer industry which passed the increased sulfur prices on to its consumers;
3. the dependence upon Frasch sulfur for large future demands;
4. the substantial increase in Frasch production costs; and
5. logistical problems which had hampered the deliveries of Canadian sulfur.

The sulfur availability-price relationship is somewhat apparent in the case of voluntary sulfur producers, since the major constraints to voluntary production are long periods of depressed prices and continued increases in fuel prices. Though the sulfur availability-price relationship for involuntary sulfur is more complex and indirect, the relationship exists as a choice between producing sulfur in a saleable form or discarding it as a waste material. The producer may have to produce a saleable sulfur product in order to decrease environmental compliance expenses. A discussion of prices on individual sulfur sources follows [10]:

Pyrite. At one time the world's major source of sulfur, pyrite has markedly declined in use because of the rise in involuntary sulfur output, the effect of depressed prices for a 10 year period, and the cost advantages enjoyed by elemental sulfur in transportation. Pyrite is currently being stockpiled and at the right price it could be revived as a source of sulfur. If shortfalls of any duration should occur in the future, this source would be called upon to fill the gap.

Gypsum and Anhydrite. Production of sulfur compounds from gypsum and anhydrite has been principally confined to Europe. Given suitable supply/price conditions and the value of coproduct cement, sulphate rock could however emerge as an essentially unlimited source of sulfur. Specifically, the enormous stockpiles of waste artificial gypsum from phosphate fertilizer manufacture (presently in excess of 240 million metric tons (275 million tons) in Florida alone) could become attractive. Using current technology, prices above \$82.50 (1981 dollars) per metric ton (\$74.85 per ton) would have to prevail before sulfur production from sulphates would become economical.

Sour Natural Gas and Petroleum. The estimated world reserves of sulfur from petroleum and natural gas are approximately 1,250 million metric (1,378 million tons) of sulfur (equivalent to a 100 year supply for the

United States), of which 70 percent occurs in the Middle East. It is also estimated that only one half of the Middle East's known reserves will have been tapped by the year 2000.

Sulfide Ores (excluding pyrite). A major percentage of the world's smelting capacity is in areas where sulfur markets are small. Since sulfuric acid is difficult to store, a percentage of that produced is used to leach oxide ores, some is marketed, but a significant amount is neutralized and discarded. Significant amounts of sulfur are lost to the atmosphere as sulfur dioxide during the production process. A price increase is required to enable industry to meet the future emission requirements for sulfur dioxide.

Utility Stack Gases. It is estimated that 100 million metric tons (110 million tons) of sulfur dioxide are emitted annually, or approximately 50 million metric tons (55 million tons) of sulfur (about equivalent to the annual global supply consumed). The burning of fossil fuels for thermal power generation accounts for 70 percent of this total. The United States alone produces approximately 12 million metric tons (13 million tons) of pollutant sulfur annually; however, the recovery of this sulfur is difficult. Of the recovery processes currently used, the most economic appears to be stack gas scrubbing using limestone, which results in an inert product requiring disposal. Only two coal burning power plants in the United States are known to produce elemental sulfur as of August, 1981 [12].

Coal Gasification. The amount of energy that can be developed from coal gasification is limited by capital, equipment, and manpower. Accordingly, sulfur production from this source is limited for the present. However, during 1982, the Tennessee Valley Authority will start a coal gasification plant capable of producing 181,000 metric tons (200,000 tons) of sulfur annually [12].

Oil Shale. Research and development of this energy source has recently been stepped up in response to the energy crisis; however, little sulfur is expected from oil shale for the near term.

Athabasca Tar Sands. The Athabasca Tar Sands in Canada contain approximately 1,750 million metric tons (1,930 million tons) of sulfur; however, this sulfur will become available slowly.

Low-cost sulfur operations produced the majority of the sulfur during times of low market prices and higher-cost sulfur production operations have been deferred. The lack of success in finding new salt-dome deposits in the United States, and the likelihood of the continued need for volun-

tary sulfur production indicate that higher cost operations will make up a larger proportion of the voluntary sulfur production in the future. So, future sulfur production, regardless of sources, will respond with increasing prices to meet future supply/demand pressures. Even though involuntary sulfur production costs, in certain situations, may be considered to be zero by allocating them to the primary product, the producers will normally seek the best sulfur price attainable. Thus, the future price of involuntary sulfur will continue to bear some relationship to the costs of voluntary sulfur production [10].

PROJECTIONS OF FUTURE SULFUR AVAILABILITY

Table 6 provides estimates of sulfur production and demand for the years 1980, 1985 and 2000. These estimates are for the United States and the two principal countries from which the United States receives imports, Canada and Mexico. Also included are similar estimates for the "free world". Forecasts of this type generally have little precision or accuracy; however, the interesting trend is that sulfur supply and demand will approximately balance for the next twenty years. If this balance holds, the price of sulfur will probably remain high relative to prior historical values. One production/demand forecast [12] indicates that widespread use of sulfur in construction materials would cause potential unbalancing (demand larger than production).

Any number of factors could result in significantly altered estimates for both production and demand. For example, on the demand side, recent research has shown that the direct use of sulfur for agricultural applications may have a greater benefit than previously recognized [19]. Application rates of up to 78 kg/hectare (70 lbs/acre) have been used. Additionally, sulfur also can increase agricultural production yields due to increased plant uptake of nitrogen, phosphorus and potassium.

Table 6. Summary of Sulfur Production and Demand Forecasts for the United States, Canada, Mexico and the Free World.

Country	Production (million metric tons)			Demand (million metric tons)		
	1980	1985	2000	1980	1985	2000
United States [12, 13]	11.8	15.1 (1)	25.0	13.6	16.2 (1)	24.1 (2) (34.0)
Canada [15, 18]	6.2	7.3	7.2	0.8	1.0	-
Mexico [16]	2.3	3.2	-	0.8	1.9	-
Free World [17]	38.0	45.0	68.0 (3)	40.0	48.0	70.0 (3)

(1) Based on assumption of linear increase from 1980 to 2000.

(2) Demand of 24.1 million metric tons (26.6 million tons) without provision for SEA paving mixtures or sulfur concrete. Demand estimated to be 34.0 million metric tons (37.5 million tons) with provision for SEA and sulfur concrete.

(3) Original estimate in Ref. 17 for 1992 at 56.0 million metric tons (61.7 millions tons) (production) and 58.0 million metric tons (63.9 million tons) (demand). These values linearly scaled for the year 2000.

1 million metric tons = 1.1023 million tons.

CHAPTER IV

AVAILABILITY OF SULFUR IN THE STATE OF WASHINGTON

The future success of SEA paving mixtures in Washington State will depend upon three major factors: the quality of the paving mixtures compared to "normal" asphalt concrete mixtures, the future availability of sulfur in the State of Washington, and a reasonable price level for sulfur to ensure the SEA mixture's economic advantages over "normal" asphalt concrete paving mixtures. The latter two factors will be briefly examined.

WESTERN CANADA SOURCES

As previously discussed Canada has dominated the Pacific Northwest sulfur markets for a number of years. As of 1981, 18.4 million metric tons (20.3 million tons) of sulfur were stored in stockpiles in Alberta and total Western Canada sulfur production was projected to be 6.2 million metric tons (6.8 million tons) [15]. Estimated production in the year 2000 is 7.3 million metric tons (8.0 million tons). The stockpiled sulfur (primarily in Alberta) is expected to be depleted by 1990 due to heavy offshore export demands of about 6.0 million metric tons (6.6 million tons) per year, exports to the United States and domestic Canadian consumption.

It appears that Canada can provide an adequate supply of sulfur in the State of Washington now and into the future (as much as twenty years); however, it appears that the price will be comparable to sulfur sources elsewhere due to the high export demand.

To overview sulfur delivery from Western Canada to the State of Washington, several sulfur producers were contacted in July, 1980. A summary of their comments assists in illustrating the situation though slightly dated (comments relating to price deleted):

1. Of the sulfur producers contacted, all were receptive to supplying sulfur for paving projects.
2. The majority of those contacted had the capability of providing both molten sulfur and slate sulfur.
3. Several of those contacted will deliver molten sulfur to the project site. The f.o.b. price at the project site would vary depending upon the quantity of sulfur ordered and the actual location in the State of Washington. Several of those con-

tacted also requested that the tankers not be used as temporary storage facilities and kept on site longer than three days. Contractors could keep the tankers on site for longer periods of time if special arrangements were made with the producers.

4. Construction contractors could purchase the sulfur f.o.b. the plant and make their own delivery arrangements.
5. The Canadian Sulphur Export Company, known as Cansulex, is the marketing arm for approximately 55 percent of the Western Canada sulfur industry and coordinates all off-shore exports through the Port of Vancouver, British Columbia. Molton sulfur is not available through this source; currently 95 percent of the sulfur shipped through the Port is slate sulfur.

As a related matter, slate sulfur is dusty and presents problems from both a handling and an environmental point of view. Prompted by this concern, the Western Canadian sulfur producers established the Sulphur Industry Forming Committee in 1976 to develop new acceptable quality standards for an improved form of export sulfur. The committee recommended in 1978 that production be in the form of prills or pellets, spherical in shape, generally between 2.0 and 6.0 mm (0.079 and 0.236 in.) in diameter. It is anticipated that by 1985 most of Western Canada's slate sulfur will be replaced by prills or pellets [20].

WASHINGTON SOURCES

Two principal sources of sulfur are produced or otherwise available within the state. One source is naturally occurring deposits which currently are not commercially viable. The second source is refining of crude oil and metal ores. Both will be briefly discussed.

The following locations have been identified within the state for naturally occurring deposits of sulfur [21]:

1. King County:
 - (a) White River: Located near logging railroad bridge over White River in SE 1/4 SW 1/4 Sec 33. Sulfur described as occurring in landslide boulders and as veinlets and cavity fillings in brecciated granites. Probably insufficient amount for commercial operation.
 - (b) 110-Line: Near center NW 1/4 sec 33. A core hole drilled in 1937 penetrated 15.2 m (50 ft) of andesite then 42.7 m (140 ft) of rock containing 20 to 30 percent sulfur. Quantity unknown.

2. Okanogan County: Minnie prospect located E 1/2 Sec. 23. A small amount of native sulfur occurs in a zone of leached quartz. Quantity described as being below that required for commercial requirements.
3. Pierce County: White River Secs 3 and 4. Located in railroad cuts south of the river. Described as native sulfur. Quantity unknown.
4. Yakima County: Mount Adams near the summit. Sulfur and alum occur as cavity fillings, veinlets, and cementing material in breccia and tuff. Quantity estimated to be 760,000 metric tons (840,000 tons) of 46 percent sulfur (estimated by core borings). Location eliminates further consideration.

The description of the above locations is provided only for local interest since none of the locations identified to date have potential for sulfur production.

Refining companies (crude oil and metals) are the second source. An attempt has been made to identify all such sources in the state as well as a few select out-of-state sources (Table 7). Additionally, the type or form of sulfur produced, current and future production plans, current buyers and cost are provided if known. This information was obtained via telephone interviews during April, 1982.

A review of the data contained in Table 7 reveals that sulfur is produced in the state in several forms, the primary ones being liquid sulfur and sulfuric acid. For the liquid sulfur form, about 45,000 metric tons (50,000 tons) per year currently is produced and about 62,000 metric tons (68,000 tons) will be produced in the near future. Also, it appears that most if not all of the available sulfur production has existing, developed markets. Further, there is no expectation that additional sulfur will be available for new markets in the near-term.

Table 7. Sulfur Production in Washington and Other Selected Locations.

Company	Plant Location	Type of Sulfur	Production		Distribution	Cost FOB Plant (April 1982) (\$/long ton)
			Current (tons/day)	Near-Term Future (tons/day)		
ARCO	Bellingham, WA	Molten Sulfur	120-130	same	Pulp & Paper	103.50 ⁽¹⁾
ALLIED CHEMICAL	Anacortes, WA	Sulfuric Acid	-	-	-	-
ASARCO	Tacoma, WA	Sulfuric Acid Liquid Sulfur Dioxide	100 120-150	same same	Stauffer Chemical Virginia Chemical	- -
CHEVRON	Richmond, CA	Molten Sulfur	180	same	Phosphate Producers	75.00
CHEVRON	Salt Lake City, UT.	Molten Sulfur	3-4	same	Phosphate Producers	90.00
MOBIL OIL	Ferndale, WA	Molten Sulfur	12	same	Pulp & Paper	-
SHELL OIL	Anacortes, WA	Hydrogen Sulfide	-	-	Allied Chemical	-
TEXACO OIL	Anacortes, WA	Hydrogen Sulfide Molten Sulfur ⁽²⁾	-	- 50 ⁽³⁾	Allied Chemical -	- -

1. Cost is freight allowed

2. Plant on line middle of 1983

3. Maximum capacity

CHAPTER V

SUMMARY AND CONCLUSIONS

SUMMARY

Sulfur, one of the world's most important industrial raw materials, is distributed throughout the world. More than half of the world's sulfur output is in elemental form, nearly all of which is obtained from native sulfur deposits and natural gas. Fertilizer manufacture accounts for approximately 60 percent of all sulfur consumed, followed by chemicals, pigments, and pulp and paper.

Sulfur production is categorized as either voluntary or involuntary, depending on whether it is the primary product or a by-product from other sources. Voluntary sources include pyrite, native sulfur, and gypsum. Native sulfur is usually recovered either by conventional mechanical mining or the Frasch process. Involuntary sulfur is essentially a byproduct arising from abatement of sulfurous emissions associated with processing or combustion of fossil fuels and the roasting and smelting of base metal ores. Involuntary sources include coal, oil shale, natural gas, petroleum, tar sands, and metal ore processing.

Until the 1960's, the majority of the world's sulfur supply was the result of the voluntary sulfur production. However, the advent of sour gas production in Alberta, Canada resulted in the production of large quantities of involuntary sulfur and entry into the world marketplace. By 1968, an oversupply developed, sulfur prices weakened, and a retrenchment in the fertilizer sector occurred. This led to a decline in the price of sulfur which continued through 1973. Also in the early 1970's renewed interest in sulfur extended asphalt paving mixtures occurred.

Currently, the supply and demand situation for sulfur is about balanced both worldwide and in the United States; a tight supply situation has however resulted in significantly increased prices. The trend of approximately balanced supply and demand for sulfur is expected to continue to the year 2000, but a number of factors could change this balanced situation in either direction (increased recovery of sulfur from coal and increased use of sulfur in agriculture to identify two of the more uncertain, major factors).

Table 8 provides an overview of how the break even price of sulfur in SEA paving mixtures is influenced by the cost of the principal ingredients in hot-mix (asphalt cement and aggregate). For a range of possible costs (low and high estimates), the maximum sulfur price so that "typical" SEA paving mixtures break even with conventional asphalt concrete is heavily influenced by the price of asphalt cement. The SEA ratio has little influence on these price effects. Essentially the maximum price for sulfur is linearly related to the price of asphalt

Table 8. Equivalent Sulfur Price (\$/ton) Required to Break Even with Conventional Asphalt Concrete*

Asphalt Cement (\$/ton) SEA Ratio (Sulfur Asphalt) Aggregate (\$/ton)	100		150		175		200		300					
	2.0%/80	4.0%/60	3.0%/70	4.0%/60	3.0%/70	4.0%/60	3.0%/70	4.0%/60	2.0%/80	4.0%/60				
5	60	55	57	82	85	103	95	99	118	108	113	177	161	168
10	62	58	60	92	84	106	97	101	121	111	115	179	164	170

*Only material costs evaluated - not additional costs due to plant operation, placement and compaction.

**Basic assumptions: optimum binder contents: 5.5% (0/100 SEA)
6.0% (20/80 SEA)
6.4% (30/70 SEA)
6.7% (40/60 SEA)

cement by a factor of about 1.7 - 1.8, e.g., the market price for asphalt cement can be no less than about 1.7 - 1.8 times larger than the market price for sulfur.

CONCLUSIONS

The following conclusions are appropriate:

1. The current and anticipated future production of sulfur in the State of Washington is modest and probably not sufficient to provide substantial quantities of elemental sulfur for SEA paving mixtures.
2. The sulfur required for substantial production of SEA paving mixtures would be obtained from Canada (specifically Alberta). The current and anticipated price levels probably will be high relative to the break even price for asphalt cement. This cost trend is expected to continue into at least the near future.
3. Unless the price of asphalt cement rises substantially with respect to the price of elemental sulfur, the production of SEA paving mixtures is not currently economical in the State of Washington. This conclusion is based in part on the assumption that SEA mixtures are not superior to conventional asphalt concrete and in part on the assumption that current and future price levels of sulfur will remain above the break even price with asphalt cement.

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APPENDIX A
SELECTED DEFINITIONS

SELECTED DEFINITIONS

This report addresses several classifications of sulfur deposits and chemical by-products which occur in the recovery and processing of elemental sulfur. To assist readers in understanding these terms, the following selected definitions are provided [after Ref. 3]:

1. Anhydrite: A mineral consisting of anhydrous (free of water) calcium sulfate (CaSO_4) and is usually white or slightly colored.
2. Bright sulfur: Sulfur free of discoloring impurities and bright yellow in color.
3. Brimstone: Synonymous with elemental sulfur.
4. Broken sulfur: Solid sulfur crushed to minus 20 cm (8 inch) size.
5. Calcite: A mineral consisting of calcium carbonate (CaCO_3). Examples include common limestone, chalk, and marble.
6. Coke: The residue of coal left after destructive distillation.
7. Dark sulfur: Sulfur discolored by minor quantities of hydrocarbons ranging up to 0.3 percent carbon content.
8. Elemental sulfur: Processed sulfur in the elemental form produced from native sulfur or combined sulfur sources, generally with a minimum sulfur content of 99.5 percent.
9. Gypsum: Hydrated calcium sulfate ($\text{CaSO}_4 \cdot 2\text{H}_2\text{O}$).
10. Liquid sulfur dioxide: Purified sulfur dioxide compressed to the liquid phase.
11. Native sulfur: Sulfur that occurs in nature in elemental form.
12. Prilled sulfur: Solid sulfur in the form of pellets produced by cooling molten sulfur with air or water.
13. Pyrite: Common mineral consisting of iron disulfide (FeS_2). Burned in making sulfur dioxide and sulfuric acid.
14. Slated sulfur: Solid sulfur in the form of slate-like lumps that are produced by allowing molten sulfur to solidify on a moving belt.

15. Sulfate: A salt of sulfuric acid (SO_4). Formed by replacement of part or all of acid hydrogen by a metal or radical acting like a metal.
16. Sulfide: A compound of sulfur analogous to an oxide (such as H_2O) with sulfur in place of the oxygen (hence hydrogen sulfide is H_2S).
17. Sulfite: A salt of sulfurous acid (SO_3). Formed similarly to sulfate.
18. Sulfur or sulphur: Derived from the Latin word sulphur. A non-metallic element that occurs either free or combined especially in sulfides and sulfates. It is used in the chemical and paper industries, in rubber vulcanization, and in medicine for treating skin diseases.
19. Sulfuric Acid: A heavy, corrosive, strong acid (H_2SO_4) containing 32.69 percent sulfur.
20. Sulfurous Acid: Weak, unstable acid (H_2SO_3).

APPENDIX B
ECONOMIC CONVERSION FACTORS

ECONOMIC CONVERSION FACTORS

Year	Index A (1967=100)	Index B (1981=1.00)	Year	Index A (1967=100)	Index B (1981=1.00)
1913 ¹	36.0	0.133	1948	82.8	0.307
14	35.2	0.130	49	78.7	0.292
15	35.8	0.133	50	81.8	0.303
16	44.1	0.163	51	91.1	0.338
17	60.6	0.225	52	88.6	0.328
18	67.6	0.250	53	87.4	0.324
19	71.4	0.265	54	87.6	0.325
20	79.6	0.295	55	87.8	0.325
21	50.3	0.186	56	90.7	0.336
22	49.9	0.185	57	93.3	0.346
23	51.9	0.192	58	94.6	0.351
24	50.5	0.187	59	94.8	0.351
25	53.3	0.198	60	94.9	0.352
26	51.6	0.191	61	94.5	0.350
27	49.3	0.183	62	94.8	0.351
28	50.0	0.185	63	94.5	0.350
29	49.1	0.182	64	94.7	0.351
30	44.6	0.165	65	96.6	0.358
31	37.3	0.138	66	99.8	0.370
32	33.6	0.124	67	100.0	0.371
33	34.0	0.126	68	102.5	0.380
34	38.6	0.143	69	106.5	0.395
35	41.3	0.153	70	110.4	0.409
36	41.7	0.154	71 ²	113.7	0.421
37	44.5	0.165	72	117.2	0.434
38	40.5	0.150	73	127.9	0.474
39	39.8	0.148	74	147.5	0.547
40	40.5	0.150	75	163.4	0.606
41	45.1	0.167	76	170.6	0.632
42	50.9	0.189	77	181.7	0.673
43	53.3	0.198	78	195.9	0.726
44	53.6	0.199	79	217.7	0.807
45	54.6	0.202	80	247.0	0.915
46	62.3	0.231	81	269.8	1.000
47	76.5	0.284			

1. 1913 - 1970: All Commodities Total Index, Wholesale Price Index, by Major Product Groups, 1967 = 100.
 Published by: Bureau of Labor Statistics
 Title: Bicentennial Edition, Historical Statistics of the United States, Colonial Times to 1970.
 Author: U.S. Department of Commerce, Bureau of the Census.

2. 1971 - 1981: Producer Price Index
Published by: Bureau of Labor Statistics
Published Name: Economic Indicators

*Index B = Index A ÷ 269.8 (Index A in 1981). Prices in 1981 dollars
are obtained by dividing actual prices by Index B.