

stripping of the asphalt cement from the aggregate. A summary of findings that support this conclusion are as follows:

1. Design 5 and the portion of design 2 placed after the winter had a lower field moisture content than the rest of the project. This was due to (a) both sections had higher densities although the density of design 5 was substantially higher, (b) neither design section was exposed during the winter, and (c) both design sections were covered soon after being placed in the spring.

2. The densities of design 5 and the portion of design 2 placed after the winter were significantly higher than for the rest of the project.

3. The tensile strengths and the portion of the tensile strength retained after being subjected to moisture were much greater for design 5. This is attributed to the increased density which produced lower voids, higher strengths, and reduced moisture penetration. The Hveem stabilities on the cores for design 5 were higher than for designs 1 and 2. There were essentially no differences among Hveem stabilities of laboratory-prepared, job control specimens.

4. The Texas freeze-thaw pedestal test values and the retained tensile strength after moisture conditioning indicated that all aggregates are highly susceptible to moisture damage.

5. All laboratory tests and field observations indicated that the antistripping agent was not effective in preventing moisture damage.

EPILOGUE

During July 1982, an extensive amount of this roadway was removed by a cold milling operation. After the top 1 to 2 in. was removed, the underlying materials were almost devoid of asphalt indicating almost total stripping of the binder course.

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The contents of this paper reflect our views and we 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 Texas State Department of Highways and Public Transportation. This paper does not constitute a standard, specification, or regulation.

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Availability of Sulfur for Sulfur-Extended Asphalt Paving in Washington State

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The availability and pricing of sulfur with respect to sulfur-extended asphalt paving mixtures are assessed. The assessment includes a review of past and current trends as well as estimates of the availability of sulfur up to the year 2000 for the United States and specifically the state of Washington.

CURRENT RESEARCH

The current research related to sulfur in the state of Washington examines the potential of using sulfur for partially replacing or extending the asphalt cement in asphalt concrete. The first field experimental work was sponsored by the Washington State Department of Transportation (WSDOT). The results were reported in a study entitled "Sulfur Extended Asphalt Binder Evaluation." In this experiment, sulfur-extended asphalt (SEA) paving mixtures were placed in August 1979 at two test sites near Pullman,

Washington (1). One site was an existing state highway (SR 270) and the other was the Washington State University (WSU) Test Track.

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

1. Further evaluate the applicability and desirability of using SEA paving mixtures in the state of Washington.

2. Develop design criteria that will improve the utilization of SEA mixtures.

3. Assess the availability and pricing of sulfur in the state of Washington.

The third goal is addressed in this paper.

4. Plastic and synthetic products covers a wide range of synthetics including acetate, cellophane, rayon, viscose products, fibers, and textiles. Together they accounted for 4 percent.

5. Paper products accounted for 3 percent. The largest single demand was for the manufacture of wood pulp by the sulfite process.

6. Paints accounted for 3 percent.

7. 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 before further processing. This category accounted for 1 percent in the form of sulfuric acid.

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

9. 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.

SOURCES

Sulfur is widely distributed 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. Sulfur deposits are generally classified as follows (3,4):

1. 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. Usually 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 USSR, and Iraq. These salt domes and evaporites are the principal sources of mined elemental sulfur, and it is usually extracted by the Frasch process. The majority of the volcanic sulfur deposits are located on the Pacific rim. These deposits have furnished a small portion of the world's sulfur supply.

2. 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, because of 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.

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

4. Natural gas. Hydrogen sulfide is a component of sour natural gas deposits and must be removed before marketing. As a coproduct, the recovered elemental sulfur is the major source of elemental sulfur. Deposits of sour natural gas are located in Canada, the Middle East, the United States, France, the Federal Republic of Germany, Venezuela, and the USSR.

5. 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 that is potentially recoverable on a large scale. The Athabasca tar sands in Canada also represent an important future sulfur source.

6. 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; however, they are a 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 shown in Table 2. Table 3 shows 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 because the sulfur must be removed from the prime product before marketing. The assessments for nonferrous metals, petroleum, and tar sands are based on the use of current technology. The other category is defined as sulfur potentially recoverable from identified deposits using current technology at higher price levels.

The vast sulfur resources in coal and oil shale deposits are specifically excluded from Tables 2 and 3 because of the uncertainty in projecting 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; coal reserves in the rest of the world contain approximately 80 billion metric tons (88 billion tons).

Similarly, in Tables 1 and 2 the large sulfur resources in gypsum and anhydrite deposits are limited 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 most of the identified gypsum and anhydrite deposits that underlie large areas of every continent. With improved technology these deposits would provide essentially unlimited sulfur sources.

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 (7). 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 involun-

Table 2. Identified world sulfur resources (3) (million metric tons).

Country	Reserves	Other	Total
North America			
United States	175	155	330
Canada	350	2,000	2,350
Mexico	90	60	150
Other	5	—	5
Total	620	2,215	2,835
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	650
China: Mainland	25	50	75
Other	50	200	250
Total	485	740	1,225
Oceania	20	10	30
World Total	1,865	4,670	6,535

Note: 1 metric ton = 1,102.3 tons.

Table 3. Identified U.S. sulfur resources (3) (million metric tons).

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

Note: 1 metric ton = 1,102.3 tons.

tary sulfur is that produced in Canada from sour natural gas.

The more important processes currently used to recover sulfur are summarized below (3):

1. **Frasch process.** In this process, developed by Dr. Herman Frasch in Louisiana in 1891 (8), large quantities of hot water are injected through wells drilled into buried deposits of native sulfur. The heat from the hot water is transferred to the formation and melts the sulfur. The liquid sulfur, which is heavier than water, accumulates at the bottom of the well. Compressed air is used to raise the liquid sulfur to the surface. The injected water migrates through the formation and is eventually extracted through the bleed-water wells located on the flanks of the structure away from the mining area. The cost of heating the water is the major operating expense; however, the cost of the water must also be considered.

2. **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 methods, including melting, distillation, agglomeration, flotation, and solvent extraction. The latter methods are extremely costly and are used only under exceptional circumstances.

3. **Pyrite processes.** Pyritic ores of 40 to 50 percent sulfur are generally roasted to produce sulfur dioxide gas which is then converted to sulfuric acid. This process is important in countries that do not have access to other inexpensive sources of elemental sulfur or that contain pyritic deposits.

4. **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 content in the fluctuating gas streams. The location of most nonferrous metal smelters limits the amount of sulfuric acid that can be marketed because of transportation and storage costs [market should be within a 400-km (250-mile) radius of the plant (8)]. Therefore, this process is generally used only to satisfy environmental emission requirements. The principal nonferrous metal sulfides and their associated sulfur content were compiled by Marshall (9) and are given below:

Mineral	Metal	Sulfur Content (%)
Chalcocopyrite	Copper	35
Chalcocite	Copper	20
Bornite	Copper	26
Enargite	Copper	33
Sphalerite	Zinc	33
Galena	Lead	13

5. **Natural gas and petroleum processes.** In sour natural gas, sulfur occurs in the hydrogen sulfide (H_2S). In petroleum, sulfur occurs in organic sulfur compounds. These compounds are converted to hydrogen sulfide during the refining process. In both instances, 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.

6. **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 to produce either elemental sulfur or sulfuric acid.

These methods are rather costly, even when the value of the coproduct is taken into consideration. Therefore, they are used only in England and Europe on a limited basis. As discussed previously, however, the deposits of gypsum and anhydrite are large; and under favorable economic and technological conditions, these deposits could provide an almost unlimited source of sulfur.

7. **Coal processes.** The sulfur content in coal varies between 1 and 14 percent and generally occurs as the sulfide mineral, pyrite; however, the 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 by-product (10); hence, the potential conversion of hydrogen sulfide to elemental sulfur. However, large-scale coal gasification systems are still under development.

GLOBAL SULFUR SUPPLY AND DEMAND

The world has historically consumed sulfur in all forms at a growth rate of about 4 percent per year (11). 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 at a rate of about 5 to 5.7 percent.

During the 1950s and early 1960s voluntary sulfur producers supplied most of the world's 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 and demand relationship. However, this situation changed during the 1960s 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 leverage in the world sulfur market depended mainly on 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. Because Canada's market price was not controlled by its production costs and it initially viewed sulfur as an undesirable by-product, Canada was able to expand its share of the sulfur market rapidly during the 1960s to more than 30 percent of the international trade by 1968.

Before 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 States' historical price leadership. The rapid growth rate of stockpiles in Alberta invariably resulted in lower prices. This pricing policy greatly reduced the effectiveness of the world's voluntary producers, and voluntary production growth began to decline. However, because 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 (11). Their sponsored research quickly revealed several potential uses for sulfur, a number 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-1960s 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 of sulfur was not meeting the demand. Some forecasters who had only 4 years earlier predicted a serious world oversupply of sulfur began to show concern about 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 had caused the unexpected uncertainty in the sulfur market. 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, reducing the uneconomic pyrite production, 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, the United States' sulfur markets had also experienced several major changes (3). Frasch sulfur production had steadily declined as a percentage of the total U.S. production, and 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 and demand relationship in markets where 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 by-product sulfuric acid sectors had 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 assist in visualizing the effect of this period on the historical sulfur production and demand in the United States, a comparison of the sulfur production and demand from 1915 to 1981 is shown in Table 4.

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 USSR 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 percent), Mexico (43.4 percent), and other minor sources (0.6 percent) (12). Africa, South America, Australia, the Far East, and Western Europe were also net importers and all depended on Canadian imports. The world demand for sulfur continued to be greater than the supply; world production was 54 million metric tons (59.5 million tons) and consumption was 52.5 million metric tons (57.9 million tons).

Of the 54 million metric tons produced, 53 percent was involuntary sulfur which is nondiscretionary and cannot be directly adjusted to meet demand. In addition to this complex marketing situation, the sulfur supply and 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 because of the lack of sulfur. Also in 1979 sulfur tanker accidents (with subsequent dry-docking and repairs) and the tug-boat strike on the east coast of the United States affected the world sulfur markets. These incidents, and those in 1978, demonstrate that one cannot rely on one source for a

Table 4. Comparison of U.S. domestic sulfur production and demand, 1915-1981 (3,6,12,13).

Year	Demand (thous. metric tons)	Production (thous. metric tons)	Year	Demand (thous. metric tons)	Production (thous. metric tons)
1915 ^a	350	520	1966	9,292	9,288
1925 ^a	1,250	1,400	1967	9,399	9,267
1935 ^a	1,200	1,600	1968	9,217	9,891
1944 ^a	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 ^a	13,300	12,400

Note: 1 metric ton = 1.1023 tons.

^aApproximate.

Table 5. Time-price relationships for sulfur, 1915-1981 (3,6,12).

Average Annual Prices (dollars per metric ton)			Average Annual Prices (dollars per metric ton)		
Year	Actual Prices	Based on 1981 Dollars	Year	Actual Prices	Based on 1981 Dollars
1915 ^a	17.00	127.82	1967	32.12	86.58
1925 ^a	15.00	75.76	1968	39.49	103.92
1935 ^a	18.00	117.65	1969	26.62	67.39
1944 ^a	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 ^a	111.00	111.00
1966	25.36	68.54			

^aApproximate.

supply of sulfur. To understand the commodity, it must be viewed in a global context.

Effect of Price on Supply

Although world sulfur resources are virtually unlimited, their availability is in part a function of price; therefore, an examination of past pricing trends and their relationship to the supply and demand balance is appropriate.

Table 5 provides the time-price relationship for U.S. domestic sulfur from 1915 to 1981 in terms of actual and constant 1981 dollars per metric ton (3,6), and Figure 1 shows a graphical representation of this relationship. These prices are based on the average reported prices for elemental sulfur (Frasch and recovered) (free on board) (f.o.b.) mine or 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. This stability was possible because the market was able to respond directly to the demand and there were

ample Frasch stockpiles to supplement the market during temporary shortages.

This period was followed by one of short supply in the market countries; the deficit was made up from U.S. stockpiles. The short supply coupled with increased growth in the fertilizer industry resulted in abnormally high sulfur prices in 1967 and 1968. In response to the increased demand and prices, voluntary producers increased production. This increase coupled with the new large supply of Canadian involuntary sulfur resulted in an 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; this continued through 1973.

As shown in Table 5, sulfur prices rose significantly from 1972 to 1981, an increase of about 560 percent. As discussed previously, in this period the growth rate of world sulfur production declined and was partially the cause of increased prices. However, the factors listed below also influenced the price increases.

1. Rapid expansion in the fertilizer industry,
2. High profitability of the fertilizer industry which passed the increased sulfur prices on to its consumers,

Figure 1. Time price relationship for sulfur, 1915-1981.

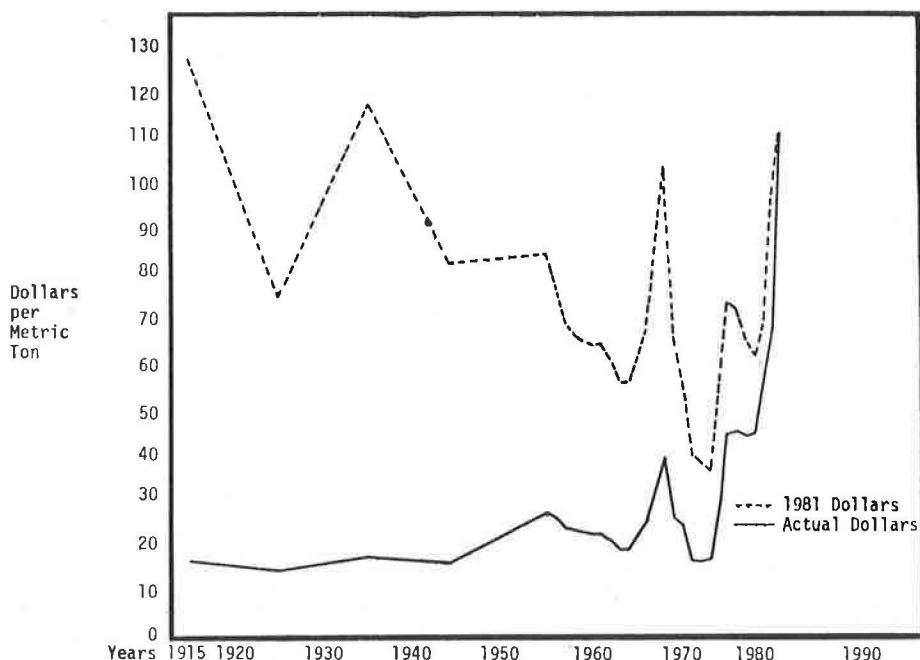


Table 6. Summary of sulfur production and demand forecasts for the United States, Canada, Mexico, and the free world.

Country	Production (million metric tons)			Demand (million metric tons)		
	1980	1985	2000	1980	1985	2000
United States (12, 13)	11.8	15.1 ^a	25.0	13.6	16.2 ^a	24.1 ^b (34.0)
Canada (14, 15)	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 ^c	40.0	48.0	70.0 ^c

Note: 1 million metric tons = 1,1023 million tons.

^aBased on assumption of linear increase from 1980 to 2000.

^bDemand 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.

^cOriginal estimate by Manderson (17) for 1992 at 56.0 million metric tons (61.7 million tons) (production) and 58.0 million metric tons (63.9 million tons) (demand). These values are linearly scaled for the year 2000.

3. Dependence upon Frasch sulfur for large future demands,

4. Substantial increase in Frasch production costs, and

5. Logistical problems that hampered the deliveries of Canadian sulfur.

The sulfur availability-price relationship is also apparent in the case of voluntary sulfur producers because the major constraints to voluntary production are long periods of depressed prices and continued increases in fuel prices. Although the sulfur availability-price relationship for involuntary sulfur is more complex and indirect than for voluntary sulfur, it exists as a choice between producing sulfur in a sellable form or discarding it as a waste material. The producer may have to produce a sellable sulfur product to decrease the expense of complying with the environmental laws.

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 its two principal suppliers of sulfur, Canada and Mexico. Also included are similar estimates for the free world. Forecasts of this type generally have little precision; however, the interesting trend is that sulfur supply and demand will approximately balance for the next 20 years. If this balance holds, the price of sulfur will probably remain high relative to prior historical values. One production and demand forecast (13) indicates that widespread use of sulfur in construction materials would potentially cause demand to be larger than production.

Any number of factors could result in significantly altered estimates for production and demand. For example, demand may be increased by recent research indicating that the direct use of sulfur for agricultural applications may have a greater benefit than previously recognized (18). Application rates of up to 78 kg/hectare (70 lb/acre) have been used.

AVAILABILITY OF SULFUR IN THE STATE OF WASHINGTON

The success of SEA paving mixtures in Washington state will depend on three major factors: the quality of the SEA paving mixtures compared to other asphalt concrete mixtures, the availability of sulfur in the state of Washington, and a reasonable price for sulfur. The latter two factors will be briefly examined.

Western Canadian Sources

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 Canadian sulfur production was projected to be 6.2 million metric tons (6.8 million tons) (19). 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 because of heavy offshore export demands of about 6.0 million metric tons (6.6 million tons) per

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 and paper	103.50 ^a
Allied Chemical	Anacortes, WA	Sulfuric acid	—	—	—	—
ASARCO	Tacoma, WA	Sulfuric acid	100	Same	Stauffer chemical	—
		Liquid sulfur	120-150	Same	Virginia chemical	—
		Dioxide	—	—	—	—
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 and paper	—
Shell Oil	Anacortes, WA	Hydrogen sulfide	—	—	Allied Chemical	—
Texaco Oil	Anacortes, WA	Hydrogen sulfide	—	—	Allied Chemical	—
		Molten sulfur ^b	—	50 ^c	—	—

^aCost is freight allowed. ^bPlant on line middle of 1983. ^cMaximum capacity.

year, exports to the United States, and domestic Canadian consumption.

It appears that Canada can provide an adequate supply of sulfur to the state of Washington now and into the future (as many as 20 years); however, it appears that the price will be comparable to sulfur sources elsewhere because of the high export demand.

In an effort to assess the 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.

1. All were receptive to supplying sulfur for paving projects.

2. The majority had the capability to provide both molten and slate sulfur.

3. Several will deliver molten sulfur to the project site. The f.o.b. price at the project site would vary depending on the quantity of sulfur ordered and the actual location in the state of Washington. Several requested that the tankers be kept on site no longer than 3 days. Contractors may keep the tankers on site for longer periods if special arrangements are made.

4. Construction contractors may 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. Molten 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 the handling and environmental points 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, and 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 available within the state. One source is natural deposits which

currently are not commercially viable. The second source is refining of crude oil and metal ores.

Refining companies (crude oil and metals) are the primary in-state sulfur source. An attempt has been made to identify all such companies in the state as well as a few out-of-state companies (Table 7). The type or form of sulfur produced, current and future production plans, current buyers, and cost are also 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 forms are liquid sulfur and sulfuric acid. Currently about 45,000 metric tons (50,000 tons) of liquid sulfur are produced per year 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.

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 production is in elemental form, and nearly all of it 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 a by-product 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 1960s, most of the world's sulfur supply was the result of voluntary sulfur production. At that time, however, the advent of sour gas production in Alberta, Canada, resulted in the production of large quantities of involuntary sulfur, and Canada entered 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 1970s renewed interest in sulfur-extended asphalt paving mixtures occurred.

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

Conclusions

1. The current and anticipated future production of sulfur in the state of Washington is small 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 in the state of Washington 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.

3. Unless the price of asphalt cement rises substantially in relation 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.

4. States that use or plan to use SEA paving mixtures in substantial quantities should consider conducting similar, locally oriented sulfur availability studies.

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