

ENERGY

Conversion of Hydrogen Sulfide in Coal Gases to Liquid Elemental Sulfur with Monolithic Catalysts

Annual Technical Progress Report for the Period
October 1, 2006 to September 30, 2007

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December 2007

Work Performed Under Contract No
DE-FG26-04NT42129

For
U.S. Department of Energy
National Energy Technology Laboratory
Pittsburgh, PA 15236-0940

By
Tuskegee University
Tuskegee, Alabama 36088

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SUMMARY

Removal of hydrogen sulfide (H_2S) from coal gasifier gas and sulfur recovery are key steps in the development of Department of Energy's (DOE's) advanced power plants that produce electric power and clean transportation fuels with coal and natural gas. These plants will require highly clean coal gas with H_2S below 1 ppmv and negligible amounts of trace contaminants such as hydrogen chloride, ammonia, alkali, heavy metals, and particulate. The conventional method of sulfur removal and recovery employing amine, Claus, and tail-gas treatment is very expensive. A second generation approach developed under DOE's sponsorship employs hot-gas desulfurization (HGD) using regenerable metal oxide sorbents followed by Direct Sulfur Recovery Process (DSRP). However, this process sequence does not remove trace contaminants and is targeted primarily towards the development of advanced integrated gasification combined cycle (IGCC) plants that produce electricity (not both electricity and transportation fuels).

There is an immediate as well as long-term need for the development of cleanup processes that produce highly clean coal gas for next generation power plants. To this end, a novel process is now under development at several research organizations in which the H_2S in coal gas is directly oxidized to elemental sulfur over a selective catalyst. Such a process is ideally suited for coal gas from commercial gasifiers with a quench system to remove essentially all the trace contaminants except H_2S .

In the Single-Step Sulfur Recovery Process (SSRP), the direct oxidation of H_2S to elemental sulfur in the presence of SO_2 is ideally suited for coal gas from commercial gasifiers with a quench system to remove essentially all the trace contaminants except H_2S . This direct oxidation process has the potential to produce a super clean coal gas more economically than both conventional amine-based processes and HGD/DSRP. The H_2 and CO components of syngas appear to behave as inert with respect to sulfur formed at the SSRP conditions. One problem in the SSRP process that needs to be eliminated or minimized is COS formation that may occur due to reaction of CO with sulfur formed from the Claus reaction.

The objectives of this research are to formulate monolithic catalysts for removal of H_2S from coal gases and minimum formation of COS with monolithic catalyst supports, γ -alumina wash or carbon coats, and catalytic metals, to develop a catalytic regeneration method for a deactivated monolithic catalyst, to measure kinetics of both direct oxidation of H_2S to elemental sulfur with SO_2 as an oxidizer and formation of COS in the presence of a simulated coal gas mixture containing H_2 , CO, CO_2 , and moisture, using a monolithic catalyst reactor, and to develop kinetic rate equations and model the direct oxidation process to assist in the design of large-scale plants. This heterogeneous catalytic reaction has gaseous reactants such as H_2S and SO_2 . However, this heterogeneous catalytic reaction has heterogeneous products such as liquid elemental sulfur and steam.

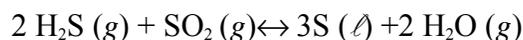
Experiments on conversion of hydrogen sulfide into elemental sulfur and formation of COS were carried out for the space time range of 130 – 156 seconds at 120 – 140°C to formulate catalysts suitable for the removal of H_2S and COS from coal gases, evaluate removal capabilities of hydrogen sulfide and COS from coal gases with formulated catalysts, and develop an

economic regeneration method of deactivated catalysts. Simulated coal gas mixtures consist of 3,300 – 3,800-ppmv hydrogen sulfide, 1,600 – 1,900 ppmv sulfur dioxide, 18 – 21 v% hydrogen, 29 – 34 v% CO, 8 – 10 v% CO₂, 5 – 18 vol % moisture, and nitrogen as remainder. Volumetric feed rates of a simulated coal gas mixture to the reactor are 114 – 132 SCCM. The temperature of the reactor is controlled in an oven at 120 – 140°C. The pressure of the reactor is maintained at 116 – 129 psia. The molar ratio of H₂S to SO₂ in the monolithic catalyst reactor is maintained approximately at 2 for all the reaction experiment runs

INTRODUCTION

Coal is our most abundant energy resource. It is strategically important to our nation to increase coal use as an energy source in an environmentally acceptable manner. Coal gasification, a primary step in advanced coal utilization processes, produces a coal gas containing hydrogen (H₂) and carbon monoxide (CO) as the fuel components. Raw coal gas, however, also contains a number of major and trace contaminants including hydrogen sulfide (H₂S), carbonyl sulfide (COS), ammonia (NH₃), hydrogen chloride (HCl), alkali, heavy metals, and particulate. Thus, this gas must be cleaned before further use. H₂S is a major coal gas contaminant that can range from 1000 to 10,000 ppmv, depending on the sulfur content of the coal. Removal of H₂S from coal gas and sulfur recovery are key steps in the development of Department of Energy's (DOE's) advanced Vision 21 plants combining a power plant and a refinery based on coal and natural gas to co-produce electricity and clean transportation-grade liquid fuels. These Vision 21 plants will require highly clean coal gas with H₂S below 1 ppmv and negligible amounts of other contaminants such as COS, HCl, NH₃, alkali, heavy metals, and particulate.

The conventional method of removing H₂S and sulfur recovery involves a number of steps including amine scrubbing at low temperature followed by amine regeneration using steam to produce a concentrated H₂S-containing gas. This concentrated H₂S-containing gas is then combusted to produce a gas with a H₂S to sulfur dioxide (SO₂) ratio of 2 to 1 in a Claus furnace. This is followed by up to three (3) stages of Claus reaction at temperatures of around 250-280°C over an alumina catalyst to recover elemental sulfur:



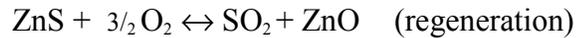
The Claus reaction is exothermic and equilibrium limited. To circumvent equilibrium limitations, the reaction is conducted in up to three (3) reaction stages with interstage cooling/sulfur condensation followed by interstage re-heating. However, even with three (3) stages, the reaction is not complete due to thermodynamic limitations at 250°C. The Claus tail gas contains sulfur that must be further treated in an expensive tail gas treatment plant (e.g., SCOT) before discharge. Thus, overall H₂S removal and sulfur recovery using this conventional sequence is extremely cumbersome, equipment intensive, and expensive.

A second generation approach for sulfur removal/recovery developed under DOE's sponsorship involves three steps:

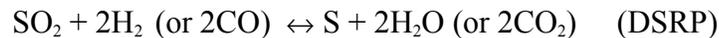
- (i) hot-gas desulfurization (HGD) using regenerable zinc oxide-based sorbents



- (ii) sorbent regeneration using air to produce SO_2



- (iii) catalytic reduction of SO_2 to elemental sulfur with a small portion of the coal gas in the Direct Sulfur Recovery Process (DSRP):



This approach integrates well with a coal gasifier in an integrated gasification (IGCC) system because the raw coal gas does not have to be cooled all the way down to near room temperature as is the case with the conventional amine/Claus/tail-gas treatment method. However, the overall process scheme requires solid sorbent handling/circulation, and three separate reactors. Also, there is a small energy penalty associated with the use of coal gas to reduce SO_2 by DSRP. Furthermore, since trace contaminants e.g. NH_3 and HCl are not removed by the zinc-based sorbents. This approach is primarily targeted towards the development of advanced IGCC plants that produce electricity only (but do not co-produce both electricity and clean transportation grade fuels).

There is an immediate as well as long-term need for the development of clean processes that produce highly clean coal gas for next generation Vision 21 plants producing both electricity and transportation-grade liquid fuels. To this end, several research organizations are developing a novel process in which the H_2S in coal gas is directly oxidized to elemental sulfur over a selective catalyst using sulfur dioxide (SO_2) produced by burning a portion of the sulfur produced.

The direct oxidation process is ideally suited for coal gas from a commercial gasifier with a quench system. During quench, the trace contaminants (except sulfur) are essentially completely removed and H_2S (with some COS) remains as the only contaminant. The gas contains all of the major coal gas components including H_2 , CO , CO_2 and H_2O . Its typical pressure and temperature conditions are 40 to 220 psia and 125 to 155°C. In the direct oxidation process, the Claus reaction is carried out over a selective monolithic catalyst in the presence of the major gas components at around 125 to 155°C to yield liquid sulfur. The low-temperature phase change allows the H_2S - SO_2 reaction to proceed selectively over a catalyst and removes equilibrium limitation. Due to low reactant concentrations, the reaction proceeds nearly isothermally and has the potential to proceed to completion in a single reactor. Burning a required portion of the liquid sulfur in a sulfur burner produces the SO_2 for the process. The process has the potential to produce a super clean coal gas much more economically than both conventional amine-based processes and HGD/DSRP.

The Single-Step Sulfur Recovery Process (SSRP) consists of injecting sulfur dioxide (SO_2) directly into the quenched syngas in the presence of a monolithic catalyst at 125 to 160°C (257 to 320°F) to oxidize H_2S and recover elemental sulfur in a single step via the Claus reaction

($2 \text{H}_2\text{S} + \text{SO}_2 \rightarrow 3/n \text{S}_n + 2\text{H}_2\text{O}$). The SO_2 needed is obtained by burning a portion of the produced sulfur in an external sulfur burner. The key differences between the above-mentioned SSRP process and the traditional Claus process are: (a) in the proposed SSRP process, the Claus reaction occurs in a highly reducing syngas atmosphere containing hydrogen (H_2) and carbon monoxide (CO) and (b) the reaction is carried out at the pressure of the syngas (40-1200 psia). Furthermore, in conventional low-temperature fixed-bed Claus processes e.g. SuperClaus, the catalyst is poisoned by sulfur plugging and must be regenerated by heating externally. In the proposed SSRP process, the liquid elemental sulfur formed from the H_2S removal reaction (Claus reaction) can be detached from the monolithic catalyst surface with the aid of the slip velocity (special flow pattern) of the gaseous reaction mixture at the interface between the thin liquid sulfur layer and the gaseous reaction mixture. The slip velocity, developed from a special flow pattern in monolithic catalyst support channels, induces the pressure difference between the solid catalyst surface and the liquid-sulfur interface by the venturi effect, thereby facilitating catalyst regeneration, sulfur recovery, and favorable shift in thermodynamic limitation on sulfur formation.

Work to date at DOE/NETL, Tuskegee University and RTI has shown the potential of SSRP to convert 99 + % of the H_2S at 40 – 220 psia to elemental sulfur with less than 40 ppmv COS slip. Differential kinetic experiments at Tuskegee University have shown significant increases in rate with pressure increase from 40 to 170 psia. Considering that the commercial SSRP plant will operate at up to 1200 psia, there is potential for complete sulfur removal and recovery. One problem in SSRP that needs to be eliminated or minimized is COS formation that may occur due to reaction of CO with sulfur formed from the Claus reaction.

The objectives of this research are to formulate monolithic catalysts for removal of H_2S from coal gases and minimum formation of COS with monolithic catalyst supports, γ -alumina wash coats, and catalytic metals, to develop a catalytic regeneration method for a deactivated monolithic catalyst, to measure kinetics of both direct oxidation of H_2S to elemental sulfur with SO_2 as an oxidizer and formation of COS in the presence of a simulated coal gas mixture containing, H_2 , CO , CO_2 , and moisture, using a monolithic catalyst reactor, and to develop kinetic rate equations and model the direct oxidation process to assist in the design of large-scale plants. This heterogeneous catalytic reaction has gaseous reactants such as H_2S and SO_2 . However, this heterogeneous catalytic reaction has heterogeneous products such as liquid elemental sulfur and steam.

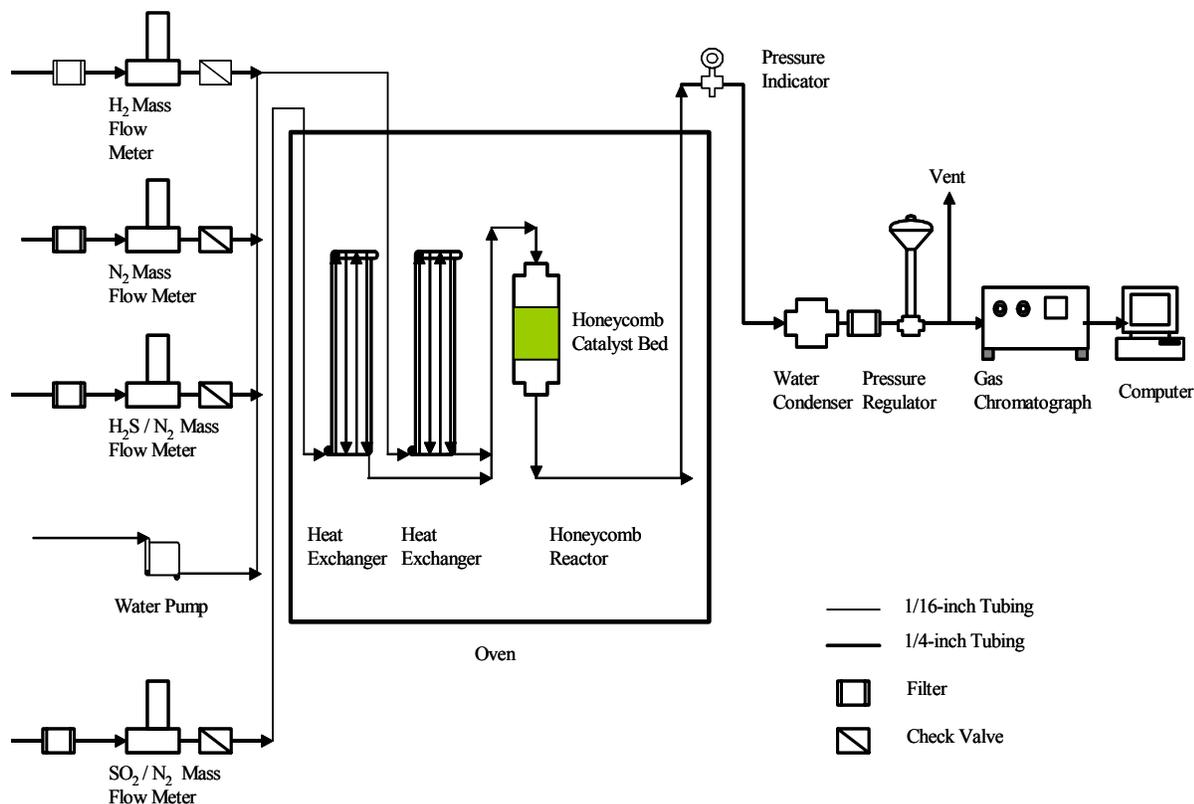
Experiments on conversion of hydrogen sulfide to elemental sulfur and formation of COS using a monolithic catalyst reactor were carried out for the space time range of 130 – 156 seconds at 120 – 140°C and 116 – 129 psia to formulate catalysts suitable for the removal of H_2S and COS from coal gases, evaluate removal capabilities of hydrogen sulfide and COS from coal gases with formulated catalysts, and develop an economic regeneration method of deactivated catalysts. Simulated coal gas mixtures consist of 3,300 – 3,800-ppmv hydrogen sulfide, 1,600 – 1,900 ppmv sulfur dioxide, 18 – 21 v% hydrogen, 29 – 34 v% CO , 8 – 10 v% CO_2 , 5 – 18 vol % moisture, and nitrogen as remainder. Volumetric feed rates of a simulated coal gas mixture to the monolithic catalyst reactor are 114 -132 SCCM. The molar ratio of H_2S to SO_2 in the monolithic catalyst reactor is maintained approximately at 2 for all the reaction experiment runs.

EXPERIMENTAL SETUPS

A monolithic catalyst reactor was fabricated with a 2.2-cm inside diameter and 15-cm long 316-stainless steel HPLC column. A γ -alumina wash-coated monolithic catalyst support, 2-cm in the diameter and 15-cm long, has 200 square cells and 1040 cm² flat surface area. The cell density and the wall thickness of the cordierite monolithic catalyst support are 400 square cells/inch² and 0.02 cm, respectively. A simulated coal gas mixture containing H₂S and SO₂ was reacted with the aid of the catalyst in the monolithic catalyst reactor at 120 – 140°C. Conversion of hydrogen sulfide to elemental sulfur was analyzed with the flame photometric detector (FPD) and the thermal conductivity detector (TCD) of a gas chromatograph. The range of space (residence) time of the reaction gas mixture in the reactor was 130 – 156 seconds under the reaction conditions. Space times are obtained by dividing the bulk volume of the monolithic catalyst in the reactor with the volumetric flow rate of a feed gaseous mixture at reaction conditions.

A reactor assembly mainly consists of four mass flow meters for gases, one reactor, two preheaters, one high pressure liquid pump for water, one four-way switch valve, one oven, five filters for gases, four check valves, and one water collection bottle, as shown in Figure 1. The preheaters are made of 20-ft-long 1/16-inch Teflon tubing.

Figure 1. Schematic Diagram on a monolithic catalyst reactor assembly



The reaction gas mixtures are fed downward to a vertical monolithic catalyst reactor, as shown in Figure 1. The reactor was loaded with a γ -alumina-wash-coated monolithic catalyst in the vertical reactor. The vertical reactor, loaded with the monolithic catalyst, was placed inside the oven to be heated at a desired temperature. Nitrogen was introduced into the catalyst-loaded reactor during preheating the reactor. When the temperature of the reactor was raised at the desired temperature, one simulated coal gas mixture stream containing H₂S and another feed stream containing SO₂ were introduced into the reactor, by switching nitrogen with the simulated coal gas mixture. The reaction conditions are shown in Table 1. The properties of the monolithic catalyst support are shown in Table 2. The experimental data, shown in Tables 3 through 14, were used for drawing the Figures 2 through 13.

Table 1. Experimental conditions for the reaction of hydrogen sulfide with sulfur dioxide as an oxidant using a monolithic catalyst reactor.

Bulk Volume of the honeycomb catalyst bed, cm ³ :	47
Temperature, °C:	120 -140
Reaction Pressure, psia	116 – 129
New Space Time under the reaction conditions, s:	130 – 156
Total Feed Rate, SCCM	114 – 132
Concentration of H ₂ S, ppmv	3,300 – 3,800
Concentration of SO ₂ , ppmv	1,600 – 1,900
Carbon Monoxide, v%	29 – 34
Hydrogen, vol %	18 – 21
Carbon Dioxide, vol %	8 – 10
Moisture, vol %:	5 – 18
Nitrogen, vol %	Remainder

Table 2. Dimensions and properties of the monolithic catalyst support

Diameter, cm	2
Length, cm	15
Flat Surface Area, cm ²	1,040
Wash Coat	γ -Al ₂ O ₃
Cell Shape	square
Cells/inch ² (CPSI)	400
Wall Thickness, cm	0.02
Flat Area/Length/Cell, cm ² /cm-length/cell	0.345
Chemical Composition	Cordierite (2MgO-2Al ₂ O ₃ -5SiO ₂)
Oxide Additives	Na, K, Mg, Zn, Fe (III)

Table 3. Conversion of H₂S to elemental sulfur and formation of COS with 114 – 132 SCCM feed streams containing 3,300 – 3,800 ppmv H₂S, 1,600 – 1,900 ppmv SO₂ as an oxidant, 29 – 34 v% CO, 18 – 21 v% H₂, 8 – 10 v% CO₂ and 5 – 18-v% moisture at 120 – 140°C, 116 – 129 psia, and 130 – 156 s space time, regenerating the monolithic catalyst with N₂ at 140 - 270°C overnight.

Run #	Temp. °C	Press. psia	Total Flow Rate, SCCM	Space Time, s	Feed Composition, v%							conversion H ₂ S	COS, ppm		
					H ₂ S	SO ₂	CO	H ₂	H ₂ O	CO ₂	N ₂		Cylinder Feed	Blank Product Mixture	Reaction Product Mixture
283	130	118.7	120	141	0.36	0.18	32.02	20.26	10.01	9.07	28.11	-0.0400	10	75	88
284	130	118.7	120	141	0.36	0.18	32.02	20.26	10.00	9.07	28.11	0.1223	22	68	103
285	130	120.7	120	143	0.36	0.18	32.02	20.26	10.00	9.07	28.11	0.8095	13	76	47
286	130	120.7	120	143	0.36	0.18	32.02	20.26	10.00	9.07	28.11	0.8066	8	69	108
287	130	117.7	120	140	0.36	0.18	32.02	20.26	10.00	9.07	28.11	0.8103	11	89	105
288	130	120.7	120	143	0.36	0.18	32.02	20.26	10.00	9.07	28.11	0.8599	9	94	105
289	130	122.7	120	145	0.36	0.18	32.02	20.26	10.00	9.07	28.11	0.7929	9	112	116
290	130	121.7	120	144	0.36	0.18	32.02	20.26	10.00	9.07	28.11	0.8034	10	110	108
291	130	120.7	120	143	0.36	0.18	32.02	20.26	10.00	9.07	28.11	0.8168	10	104	130
292	125	119.7	120	144	0.36	0.18	32.02	20.26	10.00	9.07	28.11	0.7797	11	98	94
293	125	120.7	120	145	0.36	0.18	32.02	20.26	10.00	9.07	28.11	0.7635	10	106	104
294	125	121.7	120	146	0.36	0.18	32.02	20.26	10.00	9.07	28.11	0.7152	10	108	112
295	125	118.7	120	142	0.36	0.18	32.02	20.26	10.00	9.07	28.11	0.7455	10	108	107
296	125	120.7	120	145	0.36	0.18	32.02	20.26	10.00	9.07	28.11	0.7171	10	107	111
297	125	120.7	120	145	0.36	0.18	32.02	20.26	10.00	9.07	28.11	0.7171	11	120	117
298	120	120.7	120	147	0.36	0.18	32.02	20.26	10.00	9.07	28.11	0.6390	10	115	125
299	120	118.7	120	144	0.36	0.18	32.02	20.26	10.00	9.07	28.11	0.5667	11	101	107
300	120	120.7	120	147	0.36	0.18	32.02	20.26	10.00	9.07	28.11	0.4911	11	26	63
301	120	119.7	120	146	0.36	0.18	32.02	20.26	10.00	9.07	28.11	0.4098	11	29	68
302	120	118.7	120	144	0.36	0.18	32.02	20.26	10.00	9.07	28.11	0.5135	11	43	89
303	120	120.7	120	147	0.36	0.18	32.02	20.26	10.00	9.07	28.11	0.3223	12	86	93
304	120	120.7	120	147	0.36	0.18	32.02	20.26	10.00	9.07	28.11	0.1760	12	93	106
305	120	122.7	120	149	0.36	0.18	32.02	20.26	10.00	9.07	28.11	0.2094	11	86	114
306	125	122.7	120	147	0.36	0.18	32.02	20.26	10.00	9.07	28.11	0.1639	12	133	121
307	130	121.7	120	144	0.36	0.18	32.02	20.26	10.00	9.07	28.11	0.1398	12	124	129
308	140	120.7	120	140	0.36	0.18	32.02	20.26	10.00	9.07	28.11	0.1607	13	119	130
309	140	118.7	120	137	0.36	0.18	32.02	20.26	10.00	9.07	28.11	0.8925	12	125	119
310	140	119.7	120	138	0.36	0.18	32.02	20.26	10.00	9.07	28.11	0.8552	12	122	109
311	140	118.7	120	137	0.36	0.18	32.02	20.26	10.00	9.07	28.11	0.8332	12	118	112
312	140	120.7	120	140	0.36	0.18	32.02	20.26	10.00	9.07	28.11	0.8075	13	115	111
313	140	117.7	120	136	0.36	0.18	32.02	20.26	10.00	9.07	28.11	0.4480	12	115	108
314	120	117.7	120	143	0.36	0.18	32.02	20.26	10.00	9.07	28.11	0.7617	12	74	88
315	120	120.7	120	147	0.36	0.18	32.02	20.26	10.00	9.07	28.11	0.6981	13	61	99
316	120	119.7	120	146	0.36	0.18	32.02	20.26	10.00	9.07	28.11	0.5888	13	77	101
317	120	118.7	120	144	0.36	0.18	32.02	20.26	10.00	9.07	28.11	0.5506	13	96	5
318	120	119.7	120	146	0.36	0.18	32.02	20.26	10.00	9.07	28.11	0.4650	13	75	113
319	120	117.7	120	143	0.36	0.18	32.02	20.26	10.00	9.07	28.11	0.6981	13	65	104
320	140	116.7	120	135	0.36	0.18	32.02	20.26	10.00	9.07	28.11	0.4799	14	128	118
321	140	118.7	120	137	0.36	0.18	32.02	20.26	10.00	9.07	28.11	0.4297	14	138	130
322	140	118.7	120	137	0.36	0.18	32.02	20.26	10.00	9.07	28.11	0.3554	13	120	103

Table 3. Continued – 1

Run #	Temp. °C	Press. psia	Total Flow Rate, SCCM	Space Time, s	Feed Composition, v%							conversion H ₂ S	COS, ppm		
					H ₂ S	SO ₂	CO	H ₂	H ₂ O	CO ₂	N ₂		Cylinder Feed	Blank Product Mixture	Reaction Product Mixture
323	140	118.7	120	137	0.36	0.18	32.02	20.26	10.00	9.07	28.11	0.3777	13	121	106
324	140	119.7	120	138	0.36	0.18	32.02	20.26	10.00	9.07	28.11	0.2955	13	110	110
325	140	119.7	120	138	0.36	0.18	32.02	20.26	10.00	9.07	28.11	0.3816	15	109	90
326	140	121.7	120	141	0.36	0.18	32.02	20.26	10.00	9.07	28.11	0.3009	14	96	91
327	140	120.7	120	140	0.36	0.18	32.02	20.26	10.00	9.07	28.11	0.3179	14	101	103
328	140	123.7	120	143	0.36	0.18	32.02	20.26	10.00	9.07	28.11	0.2225	15	97	94
329	140	118.7	120	137	0.36	0.18	32.02	20.26	10.00	9.07	28.11	0.2230	15	118	119
330	140	117.7	120	136	0.36	0.18	32.02	20.26	10.00	9.07	28.11	0.3355	15	114	103
331	140	119.7	120	138	0.36	0.18	32.02	20.26	10.00	9.07	28.11	0.2711	15	99	88
332	140	118.7	120	137	0.36	0.18	32.02	20.26	10.00	9.07	28.11	0.9760	15	94	149
333	140	118.7	120	137	0.36	0.18	32.02	20.26	10.00	9.07	28.11	0.9331	16	102	286
334	140	119.7	120	138	0.36	0.18	32.02	20.26	10.00	9.07	28.11	0.4850	16	102	235
335	140	118.7	120	137	0.36	0.18	32.02	20.26	10.00	9.07	28.11	0.3630	18	101	218
336	125	117.7	120	141	0.36	0.18	32.02	20.26	10.00	9.07	28.11	0.4461	16	64	200
337	125	121.7	120	146	0.36	0.18	32.02	20.26	10.00	9.07	28.11	0.9584	17	81	44
338	125	119.7	120	144	0.36	0.18	32.02	20.26	10.00	9.07	28.11	0.8188	18	87	120
339	125	120.7	120	145	0.36	0.18	32.02	20.26	10.00	9.07	28.11	0.6118	17	81	99
340	125	120.7	120	145	0.36	0.18	32.02	20.26	10.00	9.07	28.11	0.4529	17	76	100
341	125	118.7	120	142	0.36	0.18	32.02	20.26	10.00	9.07	28.11	0.4419	19	94	116
342	125	119.7	120	144	0.36	0.18	32.02	20.26	10.00	9.07	28.11	0.4014	18	105	96
343	125	117.7	120	141	0.36	0.18	32.02	20.26	10.00	9.07	28.11	0.3348	17	100	89
344	140	121.7	120	141	0.36	0.18	32.02	20.26	10.00	9.07	28.11	0.3155	18	124	120
345	125	121.7	120	146	0.36	0.18	32.02	20.26	10.00	9.07	28.11	na	18	100	135
346	125	120.7	120	145	0.36	0.18	32.02	20.26	10.00	9.07	28.11	0.9649	18	100	171
347	125	120.7	120	145	0.36	0.18	32.02	20.26	10.00	9.07	28.11	0.7282	18	124	196
348	125	116.7	120	140	0.36	0.18	32.02	20.26	10.00	9.07	28.11	-0.0440	18	126	221
349	125	121.7	120	146	0.36	0.18	32.02	20.26	10.00	9.07	28.11	-0.8358	19	29	184
350	125	122.7	120	147	0.36	0.18	32.02	20.26	10.00	9.07	28.11	-0.3571	18	26	161
351	125	116.7	120	140	0.36	0.18	32.02	20.26	10.00	9.07	28.11	0.1906	19	34	75
352	125	121.7	120	146	0.36	0.18	32.02	20.26	10.00	9.07	28.11	0.9057	18	49	74
353	125	119.7	120	144	0.36	0.18	32.02	20.26	10.00	9.07	28.11	0.9479	19	52	134
354	125	117.7	120	141	0.36	0.18	32.02	20.26	10.00	9.07	28.11	0.8795	19	48	157
355	125	117.7	120	141	0.36	0.18	32.02	20.26	10.00	9.07	28.11	0.8676	19	43	121
356	125	123.7	120	148	0.36	0.18	32.02	20.26	10.00	9.07	28.11	0.8974	18	38	107
357	125	116.7	120	140	0.36	0.18	32.02	20.26	10.00	9.07	28.11	0.9005	19	58	130
358	125	118.7	120	142	0.36	0.18	32.02	20.26	10.00	9.07	28.11	0.9034	19	58	125
359	125	119.7	120	144	0.36	0.18	32.02	20.26	10.00	9.07	28.11	0.8823	19	58	123
360	125	120.7	120	145	0.36	0.18	32.02	20.26	10.00	9.07	28.11	0.8568	19	47	119
361	125	118.7	120	142	0.36	0.18	32.02	20.26	10.00	9.07	28.11	0.8965	19	65	123
362	125	121.7	120	146	0.36	0.18	32.02	20.26	10.00	9.07	28.11	0.8760	19	53	25
363	125	117.7	120	141	0.36	0.18	32.02	20.26	10.00	9.07	28.11	0.9529	19	67	117
364	125	120.7	120	145	0.36	0.18	32.02	20.26	10.00	9.07	28.11	0.9231	20	58	128
365	125	121.7	120	146	0.36	0.18	32.02	20.26	10.00	9.07	28.11	0.9331	20	49	128
366	125	121.7	120	146	0.36	0.18	32.02	20.26	10.00	9.07	28.11	0.9326	19	56	114
367	125	115.7	120	139	0.36	0.18	32.02	20.26	10.00	9.07	28.11	0.9285	20	56	122
368	125	118.7	120	142	0.36	0.18	32.02	20.26	10.00	9.07	28.11	0.8644	20	71	133

Table 3. Continued – 2

Run #	Temp. °C	Press. psia	Total Flow Rate, SCCM	Space Time, s	Feed Composition, v%							conversion H ₂ S	COS, ppm		
					H ₂ S	SO ₂	CO	H ₂	H ₂ O	CO ₂	N ₂		Cylinder Feed	Blank Product Mixture	Reaction Product Mixture
369	125	118.7	120	142	0.36	0.18	32.02	20.26	10.00	9.07	28.11	0.8942	20	62	135
370	125	118.7	120	142	0.36	0.18	32.02	20.26	10.00	9.07	28.11	0.7891	21	92	135
371	125	119.7	120	144	0.36	0.18	32.02	20.26	10.00	9.07	28.11	0.7402	21	89	193
372	125	117.7	120	141	0.36	0.18	32.02	20.26	10.00	9.07	28.11	0.7520	21	109	204
373	125	118.7	132	130	0.33	0.16	29.11	18.42	18.18	8.25	25.55	0.6703	20	169	336
374	125	121.7	132	133	0.33	0.16	29.11	18.42	18.18	8.25	25.55	0.6499	25	152	302
375	125	118.7	132	130	0.33	0.16	29.11	18.42	18.18	8.25	25.55	0.582	24	154	320
376	125	118.7	114	150	0.38	0.19	33.71	21.32	5.26	9.55	29.59	0.7115	24	152	237
377	125	121.7	114	154	0.38	0.19	33.61	21.45	5.26	9.54	29.57	0.6578	10	64	183
378	125	121.7	114	154	0.38	0.19	33.61	21.45	5.26	9.54	29.57	0.6821	7	61	216
379	125	118.7	114	150	0.38	0.19	33.61	21.45	5.26	9.54	29.57	0.6316	7	75	330
380	125	119.7	114	151	0.38	0.19	33.61	21.45	5.26	9.54	29.57	0.6298	6	74	193
381	125	119.7	114	151	0.38	0.19	33.61	21.45	5.26	9.54	29.57	0.3957	6	89	187
382	125	120.7	114	152	0.38	0.19	33.61	21.45	5.26	9.54	29.57	0.4566	6	94	147
383	125	120.7	114	152	0.38	0.19	33.61	21.45	5.26	9.54	29.57	0.3991	6	99	124
384	125	120.7	114	152	0.38	0.19	33.61	21.45	5.26	9.54	29.57	0.5082	6	62	253
385	125	123.7	114	156	0.38	0.19	33.61	21.45	5.26	9.54	29.57	0.3885	5	76	231
386	125	121.7	114	154	0.38	0.19	33.61	21.45	5.26	9.54	29.57	0.2779	5	52	221
387	125	121.7	120	146	0.36	0.18	31.93	20.38	10.00	9.07	28.09	0.9044	4	62	141
388	125	122.7	114	155	0.38	0.19	33.61	21.45	5.26	9.54	29.57	0.8395	3	85	128
389	125	120.7	120	145	0.36	0.18	31.93	20.38	10.00	9.07	28.09	0.8731	5	57	220
390	125	118.7	120	142	0.36	0.18	31.93	20.38	10.00	9.07	28.09	0.9287	5	71	141
391	125	118.7	120	142	0.36	0.18	31.93	20.38	10.00	9.07	28.09	0.6987	4	52	248
392	125	122.7	120	147	0.36	0.18	31.93	20.38	10.00	9.07	28.09	0.3410	5	51	184
393	125	120.7	120	145	0.36	0.18	31.93	20.38	10.00	9.07	28.09	0.7553	6	63	139
394	125	121.7	120	146	0.36	0.18	31.93	20.38	10.00	9.07	28.09	0.5210	5	123	133
395	125	119.7	120	144	0.36	0.18	31.93	20.38	10.00	9.07	28.09	0.5254	5	142	179
396	125	120.7	120	145	0.36	0.18	31.93	20.38	10.00	9.07	28.09	0.3428	6	53	99
397	125	120.7	120	145	0.36	0.18	31.93	20.38	10.00	9.07	28.09	0.2062	6	89	121
398	125	117.7	120	141	0.36	0.18	31.93	20.38	10.00	9.07	28.09	0.8108	5	79	207
399	125	119.7	120	144	0.36	0.18	31.93	20.38	10.00	9.07	28.09	0.7348	5	59	224
400	125	120.7	120	145	0.36	0.18	31.93	20.38	10.00	9.07	28.09	0.7744	5	72	163
401	125	119.7	120	144	0.36	0.18	31.93	20.38	10.00	9.07	28.09	0.8154	5	53	161
402	125	121.7	120	146	0.36	0.18	31.93	20.38	10.00	9.07	28.09	0.1779	5	62	193
403	125	119.7	120	144	0.36	0.18	31.93	20.38	10.00	9.07	28.09	0.7339	5	45	138
404	125	121.7	120	146	0.36	0.18	31.93	20.38	10.00	9.07	28.09	0.8201	5	48	119
405	125	123.7	120	148	0.36	0.18	31.93	20.38	10.00	9.07	28.09	0.6095	4	68	153
406	125	119.7	120	144	0.36	0.18	31.93	20.38	10.00	9.07	28.09	0.3270	5	70	137
407	125	120.7	120	145	0.36	0.18	31.93	20.38	10.00	9.07	28.09	0.2864	6	80	121
408	125	118.7	120	142	0.36	0.18	31.93	20.38	10.00	9.07	28.09	0.8602	7	69	106
409	125	118.7	120	142	0.36	0.18	31.93	20.38	10.00	9.07	28.09	0.9269	5	60	121
410	125	120.7	120	145	0.36	0.18	31.93	20.38	10.00	9.07	28.09	0.9309	4	59	145
411	125	122.7	120	147	0.36	0.18	31.93	20.38	10.00	9.07	28.09	0.9027	4	148	178
412	125	122.7	120	147	0.36	0.18	31.93	20.38	10.00	9.07	28.09	0.8547	5	125	161
413	125	119.7	120	144	0.36	0.18	31.93	20.38	10.00	9.07	28.09	0.8410	4	177	188
414	125	120.7	120	145	0.36	0.18	31.93	20.38	10.00	9.07	28.09	0.7072	4	116	190

Table 3. Continued – 3

Run #	Temp. °C	Press. psia	Total Flow Rate, SCCM	Space Time, s	Feed Composition, v%							conversion H ₂ S	COS, ppm		
					H ₂ S	SO ₂	CO	H ₂	H ₂ O	CO ₂	N ₂		Cylinder Feed	Blank Product Mixture	Reaction Product Mixture
415	125	119.7	120	144	0.36	0.18	31.93	20.38	10.00	9.07	28.09	0.6785	4	97	165
416	125	122.7	120	147	0.36	0.18	31.93	20.38	10.00	9.07	28.09	0.8935	4	110	191
417	125	122.7	120	147	0.36	0.18	31.93	20.38	10.00	9.07	28.09	0.7925	4	121	216
418	125	121.7	120	146	0.36	0.18	31.93	20.38	10.00	9.07	28.09	0.7027	4	122	248
419	125	119.7	120	144	0.36	0.18	31.93	20.38	10.00	9.07	28.09	0.6082	5	157	231
420	125	121.7	120	146	0.36	0.18	31.93	20.38	10.00	9.07	28.09	0.5535	5	116	215
421	125	119.7	120	144	0.36	0.18	31.93	20.38	10.00	9.07	28.09	0.6156	4	116	209
422	125	119.7	120	144	0.36	0.18	31.93	20.38	10.00	9.07	28.09	0.7023	4	101	187
423	125	116.7	120	140	0.36	0.18	31.93	20.38	10.00	9.07	28.09	0.7857	4	110	202
424	125	119.7	120	144	0.36	0.18	31.93	20.38	10.00	9.07	28.09	0.7343	4	111	223
425	125	121.7	120	146	0.36	0.18	31.93	20.38	10.00	9.07	28.09	0.6678	4	142	243
426	125	120.7	120	145	0.36	0.18	31.93	20.38	10.00	9.07	28.09	0.6056	5	129	218
427	125	115.7	120	139	0.36	0.18	31.93	20.38	10.00	9.07	28.09	0.7794	4	129	402
428	125	118.7	120	142	0.36	0.18	31.93	20.38	10.00	9.07	28.09	0.8661	5	131	148
429	125	121.7	120	146	0.36	0.18	31.93	20.38	10.00	9.07	28.09	0.9073	5	98	115
430	125	117.7	120	141	0.36	0.18	31.93	20.38	10.00	9.07	28.09	0.7673	5	99	142
431	125	120.7	120	145	0.36	0.18	31.93	20.38	10.00	9.07	28.09	0.7929	5	120	128
432	125	128.7	120	154	0.36	0.18	31.93	20.38	10.00	9.07	28.09	1.0000	5	119	103
433	125	121.7	120	146	0.36	0.18	31.93	20.38	10.00	9.07	28.09	0.1718	5	108	200
434	125	115.7	120	139	0.36	0.18	31.93	20.38	10.00	9.07	28.09	0.6977	4	142	2
435	125	119.7	120	144	0.36	0.18	31.93	20.38	10.00	9.07	28.09	0.7108	4	118	64
436	125	117.7	120	141	0.36	0.18	31.93	20.38	10.00	9.07	28.09	1.0000	4	121	2
437	125	118.7	120	142	0.36	0.18	31.93	20.38	10.00	9.07	28.09	0.8961	4	126	140
438	125	120.7	120	145	0.36	0.18	31.93	20.38	10.00	9.07	28.09	0.2990	4	18	182
439	125	120.7	120	145	0.36	0.18	31.93	20.38	10.00	9.07	28.09	0.2383	5	37	147
440	125	119.7	120	144	0.36	0.18	31.93	20.38	10.00	9.07	28.09	0.5517	4	20	90
441	125	119.7	120	144	0.36	0.18	31.93	20.38	10.00	9.07	28.09	0.7503	4	14	100
442	125	119.7	120	144	0.36	0.18	31.93	20.38	10.00	9.07	28.09	0.8165	4	48	103
443	125	121.7	120	146	0.36	0.18	31.93	20.38	10.00	9.07	28.09	0.8213	4	30	114
444	125	120.7	120	145	0.36	0.18	31.93	20.38	10.00	9.07	28.09	0.8004	4	21	39
445	125	120.7	120	145	0.36	0.18	31.93	20.38	10.00	9.07	28.09	0.7956	4	26	66
446	125	123.7	120	148	0.36	0.18	31.93	20.38	10.00	9.07	28.09	0.2445	5	58	138
447	125	119.7	120	144	0.36	0.18	31.93	20.38	10.00	9.07	28.09	0.3075	5	31	137
448	125	118.7	120	142	0.36	0.18	31.93	20.38	10.00	9.07	28.09	0.8316	5	41	51
449	125	118.7	120	142	0.36	0.18	31.93	20.38	10.00	9.07	28.09	0.8884	4	32	67
450	125	116.7	120	140	0.36	0.18	31.93	20.38	10.00	9.07	28.09	0.8906	4	29	62
451	125	121.7	120	146	0.36	0.18	31.93	20.38	10.00	9.07	28.09	0.8764	5	72	79
452	125	119.7	120	144	0.36	0.18	31.93	20.38	10.00	9.07	28.09	0.8779	4	57	84
453	125	119.7	120	144	0.36	0.18	31.93	20.38	10.00	9.07	28.09	0.8677	3	70	88
454	125	119.7	120	144	0.36	0.18	31.93	20.38	10.00	9.07	28.09	0.8517	4	75	131
455	125	119.7	120	144	0.36	0.18	31.93	20.38	10.00	9.07	28.09	0.6470	4	79	104
456	125	119.7	120	144	0.36	0.18	31.93	20.38	10.00	9.07	28.09	0.6484	4	166	128
457	125	116.7	120	140	0.36	0.18	31.93	20.38	10.00	9.07	28.09	0.8283	5	93	92
458	125	118.7	120	142	0.36	0.18	31.93	20.38	10.00	9.07	28.09	0.8370	5	63	96
459	125	121.7	120	146	0.36	0.18	31.93	20.38	10.00	9.07	28.09	0.8139	5	77	96
460	125	118.7	120	142	0.36	0.18	31.93	20.38	10.00	9.07	28.09	0.8213	5	83	92

Table 3. Continued – 4

Run #	Temp. °C	Press. psia	Total Flow Rate, SCCM	Space Time, s	Feed Composition, v%							conversion H ₂ S	COS, ppm		
					H ₂ S	SO ₂	CO	H ₂	H ₂ O	CO ₂	N ₂		Cylinder Feed	Blank Product Mixture	Reaction Product Mixture
461	125	120.7	120	145	0.36	0.18	31.93	20.38	10.00	9.07	28.09	0.7894	5	74	102
462	125	122.7	120	147	0.36	0.18	31.93	20.38	10.00	9.07	28.09	0.7943	5	90	121
463	125	121.7	120	146	0.36	0.18	31.93	20.38	10.00	9.07	28.09	0.8040	6	69	97
464	125	119.7	120	144	0.36	0.18	31.93	20.38	10.00	9.07	28.09	0.7853	5	84	107
465	125	121.7	120	146	0.36	0.18	31.93	20.38	10.00	9.07	28.09	0.7803	18	77	127
466	125	121.7	120	146	0.36	0.18	31.93	20.38	10.00	9.07	28.09	0.7700	5	91	151
467	125	119.7	120	144	0.36	0.18	31.93	20.38	10.00	9.07	28.09	0.7879	12	75	118
468	125	118.7	120	142	0.36	0.18	31.93	20.38	10.00	9.07	28.09	0.8565	5	68	107
469	125	119.7	120	144	0.36	0.18	31.93	20.38	10.00	9.07	28.09	0.9181	5	112	129
470	125	118.7	120	142	0.36	0.18	31.93	20.38	10.00	9.07	28.09	0.8565	5	80	207
471	125	119.7	120	144	0.36	0.18	31.93	20.38	10.00	9.07	28.09	0.9087	5	84	460
472	125	118.7	120	142	0.36	0.18	31.93	20.38	10.00	9.07	28.09	0.9584	5	54	199
473	125	117.7	120	141	0.36	0.18	31.93	20.38	10.00	9.07	28.09	0.7669	5	58	196
474	125	119.7	120	144	0.36	0.18	31.93	20.38	10.00	9.07	28.09	0.8941	4	53	164
475	125	120.7	120	145	0.36	0.18	31.93	20.38	10.00	9.07	28.09	0.9626	6	73	159

*SCCM: standard cubic centimeters per minute, volumetric flow rates of gases measured at 1 atm and 25°C

Table 4. Effects of temperature on conversion of H₂S to elemental sulfur and formation of COS with a 120-SCCM feed stream containing 3,600-ppmv H₂S, 1,800-ppmv SO₂, 32-v% CO, 20-v% H₂, 9-v% CO₂ and 10-v% moisture at 120 – 140°C, 117- 124 psia and 135 - 149 s space time, removing elemental sulfur from a γ -alumina wash-coated monolithic catalyst support with N₂ overnight.

Run #	Temp. °C	Press. psia	Total Flow Rate, SCCM	Space Time, s	Feed Composition, v%							Catalyst Aging min	conversion H ₂ S	COS, ppm				Remarks
					H ₂ S	SO ₂	CO	H ₂	H ₂ O	CO ₂	N ₂			Formation	Cylinder Feed	Blank Product Mixture	Reaction Product Mixture	
285	130	120.7	120	143	0.36	0.18	32.02	20.26	10.00	9.07	28.11	197	0.8095	-29	13	76	47	removing elemental sulfur from the catalyst with N ₂ at 140°C overnight
286	130	120.7	120	143	0.36	0.18	32.02	20.26	10.00	9.07	28.11	323	0.8066	38	8	69	108	
287	130	117.7	120	140	0.36	0.18	32.02	20.26	10.00	9.07	28.11	484	0.8103	17	11	89	105	
288	130	120.7	120	143	0.36	0.18	32.02	20.26	10.00	9.07	28.11	682	0.8599	11	9	94	105	
289	130	122.7	120	145	0.36	0.18	32.02	20.26	10.00	9.07	28.11	810	0.7929	4	9	112	116	
290	130	121.7	120	144	0.36	0.18	32.02	20.26	10.00	9.07	28.11	986	0.8034	-3	10	110	108	
291	130	120.7	120	143	0.36	0.18	32.02	20.26	10.00	9.07	28.11	1118	0.8168	26	10	104	130	
292	125	119.7	120	144	0.36	0.18	32.02	20.26	10.00	9.07	28.11	1299	0.7797	-4	11	98	94	
293	125	120.7	120	145	0.36	0.18	32.02	20.26	10.00	9.07	28.11	1547	0.7635	-2	10	106	104	
294	125	121.7	120	146	0.36	0.18	32.02	20.26	10.00	9.07	28.11	1687	0.7152	4	10	108	112	
295	125	118.7	120	142	0.36	0.18	32.02	20.26	10.00	9.07	28.11	1838	0.7455	-1	10	108	107	
296	125	120.7	120	145	0.36	0.18	32.02	20.26	10.00	9.07	28.11	1976	0.7171	4	10	107	111	
297	125	120.7	120	145	0.36	0.18	32.02	20.26	10.00	9.07	28.11	2166	0.7171	-3	11	120	117	
298	120	120.7	120	147	0.36	0.18	32.02	20.26	10.00	9.07	28.11	2387	0.6390	10	10	115	125	
299	120	118.7	120	144	0.36	0.18	32.02	20.26	10.00	9.07	28.11	2587	0.5667	5	11	101	107	
300	120	120.7	120	147	0.36	0.18	32.02	20.26	10.00	9.07	28.11	2718	0.4911	37	11	26	63	
301	120	119.7	120	146	0.36	0.18	32.02	20.26	10.00	9.07	28.11	2980	0.4098	39	11	29	68	
302	120	118.7	120	144	0.36	0.18	32.02	20.26	10.00	9.07	28.11	3142	0.5135	47	11	43	89	
303	120	120.7	120	147	0.36	0.18	32.02	20.26	10.00	9.07	28.11	3299	0.3223	7	12	86	93	
304	120	120.7	120	147	0.36	0.18	32.02	20.26	10.00	9.07	28.11	3549	0.1760	12	12	93	106	
305	120	122.7	120	149	0.36	0.18	32.02	20.26	10.00	9.07	28.11	3673	0.2094	28	11	86	114	removing elemental sulfur from the catalyst with N ₂ at 270°C overnight
306	125	122.7	120	147	0.36	0.18	32.02	20.26	10.00	9.07	28.11	3823	0.1639	-12	12	133	121	
307	130	121.7	120	144	0.36	0.18	32.02	20.26	10.00	9.07	28.11	3948	0.1398	5	12	124	129	
308	140	120.7	120	140	0.36	0.18	32.02	20.26	10.00	9.07	28.11	4073	0.1607	11	13	119	130	
309	140	118.7	120	137	0.36	0.18	32.02	20.26	10.00	9.07	28.11	165	0.8925	-6	12	125	119	
310	140	119.7	120	138	0.36	0.18	32.02	20.26	10.00	9.07	28.11	371	0.8552	-12	12	122	109	
311	140	118.7	120	137	0.36	0.18	32.02	20.26	10.00	9.07	28.11	526	0.8332	-6	12	118	112	
312	140	120.7	120	140	0.36	0.18	32.02	20.26	10.00	9.07	28.11	648	0.8075	-4	13	115	111	

Table 4. Continued – 1

Run #	Temp. °C	Press. psia	Total Flow Rate, SCCM	Space Time, s	Feed Composition, v%							Catalyst Aging min	conversion H ₂ S	COS, ppm				Remarks
					H ₂ S	SO ₂	CO	H ₂	H ₂ O	CO ₂	N ₂			Formation	Cylinder Feed	Blank Product Mixture	Reaction Product Mixture	
313	140	117.7	120	136	0.36	0.18	32.02	20.26	10.00	9.07	28.11	773	0.4480	-7	12	115	108	
314	120	117.7	120	143	0.36	0.18	32.02	20.26	10.00	9.07	28.11	932	0.7617	14	12	74	88	
315	120	120.7	120	147	0.36	0.18	32.02	20.26	10.00	9.07	28.11	1125	0.6981	37	13	61	99	
316	120	119.7	120	146	0.36	0.18	32.02	20.26	10.00	9.07	28.11	1253	0.5888	25	13	77	101	
317	120	118.7	120	144	0.36	0.18	32.02	20.26	10.00	9.07	28.11	1444	0.5506	9	13	96	5	
318	120	119.7	120	146	0.36	0.18	32.02	20.26	10.00	9.07	28.11	1543	0.4650	38	13	75	113	
319	120	117.7	120	143	0.36	0.18	32.02	20.26	10.00	9.07	28.11	1672	0.6981	40	13	65	104	
320	140	116.7	120	135	0.36	0.18	32.02	20.26	10.00	9.07	28.11	1895	0.4799	-11	14	128	118	
321	140	118.7	120	137	0.36	0.18	32.02	20.26	10.00	9.07	28.11	2085	0.4297	-8	14	138	130	
322	140	118.7	120	137	0.36	0.18	32.02	20.26	10.00	9.07	28.11	2250	0.3554	-16	13	120	103	
323	140	118.7	120	137	0.36	0.18	32.02	20.26	10.00	9.07	28.11	2348	0.3777	-16	13	121	106	
324	140	119.7	120	138	0.36	0.18	32.02	20.26	10.00	9.07	28.11	2476	0.2955	0	13	110	110	
325	140	119.7	120	138	0.36	0.18	32.02	20.26	10.00	9.07	28.11	2603	0.3816	-19	15	109	90	
326	140	121.7	120	141	0.36	0.18	32.02	20.26	10.00	9.07	28.11	2824	0.3009	-5	14	96	91	
327	140	120.7	120	140	0.36	0.18	32.02	20.26	10.00	9.07	28.11	2923	0.3179	2	14	101	103	
328	140	123.7	120	143	0.36	0.18	32.02	20.26	10.00	9.07	28.11	3055	0.2225	-3	15	97	94	
329	140	118.7	120	137	0.36	0.18	32.02	20.26	10.00	9.07	28.11	3168	0.2230	1	15	118	119	New GC Column
330	140	117.7	120	136	0.36	0.18	32.02	20.26	10.00	9.07	28.11	3359	0.3355	-11	15	114	103	
331	140	119.7	120	138	0.36	0.18	32.02	20.26	10.00	9.07	28.11	3607	0.2711	-11	15	99	88	

*SCCM: standard cubic centimeters per minute, volumetric flow rates of gases measured at 1 atm and 25°C

Table 5. Effects of catalyst aging on conversion of H₂S and formation of COS with a γ -alumina wash-coated monolithic catalyst support soaked in 1-w% Zn aqueous solution and heated for 4 hours at 450°C, removing elemental sulfur from the catalyst with N₂ overnight at 140°C.

Run #	Temp. °C	Press. psia	Total Flow Rate, SCCM	Space Time, s	Feed Composition, v%							Catalyst Aging min	conversion H ₂ S	COS, ppm				Remarks
					H ₂ S	SO ₂	CO	H ₂	H ₂ O	CO ₂	N ₂			Formation	Cylinder Feed	Blank Product Mixture	Reaction Product Mixture	
362	125	121.7	120	146	0.36	0.18	32.02	20.26	10.00	9.07	28.11	157	0.8760	-23	19	53	25	soaked in 1-w% Zn aqueous solution and heated for 4 hours at 450°C, removing elemental sulfur from the catalyst with N ₂ at 140°C overnight
363	125	117.7	120	141	0.36	0.18	32.02	20.26	10.00	9.07	28.11	317	0.9529	50	19	67	117	
364	125	120.7	120	145	0.36	0.18	32.02	20.26	10.00	9.07	28.11	494	0.9231	71	20	58	128	

Table 5. Continued – 1

Run #	Temp. °C	Press. psia	Total Flow Rate, SCCM	Space Time, s	Feed Composition, v%							Catalyst Aging , min	conversion H ₂ S	COS, ppm				Remarks
					H ₂ S	SO ₂	CO	H ₂	H ₂ O	CO ₂	N ₂			Formation	Cylinder Feed	Blank Product Mixture	Reaction Product Mixture	
365	125	121.7	120	146	0.36	0.18	32.02	20.26	10.00	9.07	28.11	623	0.9331	79	20	49	128	
366	125	121.7	120	146	0.36	0.18	32.02	20.26	10.00	9.07	28.11	782	0.9326	58	19	56	114	
367	125	115.7	120	139	0.36	0.18	32.02	20.26	10.00	9.07	28.11	967	0.9285	67	20	56	122	
368	125	118.7	120	142	0.36	0.18	32.02	20.26	10.00	9.07	28.11	1206	0.8644	61	20	71	133	
369	125	118.7	120	142	0.36	0.18	32.02	20.26	10.00	9.07	28.11	1337	0.8942	73	20	62	135	
370	125	118.7	120	142	0.36	0.18	32.02	20.26	10.00	9.07	28.11	1495	0.7891	43	21	92	135	
371	125	119.7	120	144	0.36	0.18	32.02	20.26	10.00	9.07	28.11	1654	0.7402	104	21	89	193	
372	125	117.7	120	141	0.36	0.18	32.02	20.26	10.00	9.07	28.11	1812	0.7520	95	21	109	204	
373	125	118.7	132	130	0.33	0.16	29.11	18.42	18.18	8.25	25.55	1915	0.6703	167	20	169	336	
374	125	121.7	132	133	0.33	0.16	29.11	18.42	18.18	8.25	25.55	2042	0.6499	150	25	152	302	
375	125	118.7	132	130	0.33	0.16	29.11	18.42	18.18	8.25	25.55	2149	0.582	166	24	154	320	
376	125	118.7	114	150	0.38	0.19	33.71	21.32	5.26	9.55	29.59	2280	0.7115	85	24	152	237	
377	125	121.7	114	154	0.38	0.19	33.61	21.45	5.26	9.54	29.57	2409	0.6578	118	10	64	183	
378	125	121.7	114	154	0.38	0.19	33.61	21.45	5.26	9.54	29.57	2511	0.6821	154	7	61	216	
379	125	118.7	114	150	0.38	0.19	33.61	21.45	5.26	9.54	29.57	2639	0.6316	255	7	75	330	

*SCCM: standard cubic centimeters per minute, volumetric flow rates of gases measured at 1 atm and 25°C

Table 6. Effects of removal temperature of elemental sulfur attached to a catalyst on conversion of H₂S and formation of COS with the γ -alumina wash-coated monolithic catalyst support soaked in 1-w% Zn aqueous solution followed by heating it for 4 hours at 450°C, removing elemental sulfur from the catalyst with N₂ overnight.

Run #	Temp. °C	Press. psia	Total Flow Rate, SCCM	Space Time, s	Feed Composition, v%							Catalyst Aging , min	conversion H ₂ S	COS, ppm				Remarks
					H ₂ S	SO ₂	CO	H ₂	H ₂ O	CO ₂	N ₂			Formation	Cylinder Feed	Blank Product Mixture	Reaction Product Mixture	
377	125	121.7	114	154	0.38	0.19	33.61	21.45	5.26	9.54	29.57	2409	0.6578	118	10	64	183	sulfur removed from the catalyst with N ₂ at 140°C overnight
378	125	121.7	114	154	0.38	0.19	33.61	21.45	5.26	9.54	29.57	2511	0.6821	154	7	61	216	
379	125	118.7	114	150	0.38	0.19	33.61	21.45	5.26	9.54	29.57	2639	0.6316	255	7	75	330	
380	125	119.7	114	151	0.38	0.19	33.61	21.45	5.26	9.54	29.57	2767	0.6298	118	6	74	193	sulfur removed from the catalyst with N ₂ at 200°C overnight
381	125	119.7	114	151	0.38	0.19	33.61	21.45	5.26	9.54	29.57	2869	0.3957	98	6	89	187	

Table 7. Effects of elemental sulfur removed from a monolithic catalyst on conversion of H₂S and formation of COS with the γ -alumina wash-coated catalyst support soaked in 1-w% Zn aqueous solution followed by heating it for 4 hours at 450°C, removing elemental sulfur from the catalyst with N₂ at 200°C overnight.

Run #	Temp. °C	Press. psia	Total Flow Rate, SCCM	Space Time, s	Feed Composition, v%							Catalyst Aging, min	conversion H ₂ S	COS, ppm				Remarks
					H ₂ S	SO ₂	CO	H ₂	H ₂ O	CO ₂	N ₂			Formation	Cylinder Feed	Blank Product Mixture	Reaction Product Mixture	
380	125	119.7	114	151	0.38	0.19	33.61	21.45	5.26	9.54	29.57	2767	0.6298	118	6	74	193	removing elemental sulfur from the catalyst with N ₂ at 200°C overnight.
381	125	119.7	114	151	0.38	0.19	33.61	21.45	5.26	9.54	29.57	2869	0.3957	98	6	89	187	
382	125	120.7	114	152	0.38	0.19	33.61	21.45	5.26	9.54	29.57	3021	0.4566	54	6	94	147	no sulfur removed
383	125	120.7	114	152	0.38	0.19	33.61	21.45	5.26	9.54	29.57	3178	0.3991	25	6	99	124	
384	125	120.7	114	152	0.38	0.19	33.61	21.45	5.26	9.54	29.57	3415	0.5082	191	6	62	253	
385	125	123.7	114	156	0.38	0.19	33.61	21.45	5.26	9.54	29.57	3521	0.3885	155	5	76	231	
386	125	121.7	114	154	0.38	0.19	33.61	21.45	5.26	9.54	29.57	3649	0.2779	169	5	52	221	

*SCCM: standard cubic centimeters per minute, volumetric flow rates of gases measured at 1 atm and 25°C

Table 8. Effects of washing a γ -alumina wash-coated monolithic catalyst in NaOH aqueous solution on conversion of H₂S and formation of COS with the catalyst support soaked in 1-w% Zn aqueous solution followed by heating it for 4 hrs at 450°C

Run #	Temp. °C	Press. psia	Total Flow Rate, SCCM	Space Time, s	Feed Composition, v%							Catalyst Aging, min	conversion H ₂ S	COS, ppm				Remarks
					H ₂ S	SO ₂	CO	H ₂	H ₂ O	CO ₂	N ₂			Formation	Cylinder Feed	Blank Product Mixture	Reaction Product Mixture	
362	125	121.7	120	146	0.36	0.18	32.02	20.26	10.00	9.07	28.11	157	0.8760	-23	19	53	25	sulfur removed from the catalyst with N ₂ at 140°C overnight
363	125	117.7	120	141	0.36	0.18	32.02	20.26	10.00	9.07	28.11	317	0.9529	50	19	67	117	
364	125	120.7	120	145	0.36	0.18	32.02	20.26	10.00	9.07	28.11	494	0.9231	71	20	58	128	
365	125	121.7	120	146	0.36	0.18	32.02	20.26	10.00	9.07	28.11	623	0.9331	79	20	49	128	
366	125	121.7	120	146	0.36	0.18	32.02	20.26	10.00	9.07	28.11	782	0.9326	58	19	56	114	
367	125	115.7	120	139	0.36	0.18	32.02	20.26	10.00	9.07	28.11	967	0.9285	67	20	56	122	
368	125	118.7	120	142	0.36	0.18	32.02	20.26	10.00	9.07	28.11	1206	0.8644	61	20	71	133	
369	125	118.7	120	142	0.36	0.18	32.02	20.26	10.00	9.07	28.11	1337	0.8942	73	20	62	135	
370	125	118.7	120	142	0.36	0.18	32.02	20.26	10.00	9.07	28.11	1495	0.7891	43	21	92	135	
371	125	119.7	120	144	0.36	0.18	32.02	20.26	10.00	9.07	28.11	1654	0.7402	104	21	89	193	

Table 8. Continued – 1

Run #	Temp. °C	Press. psia	Total Flow Rate, SCCM	Space Time, s	Feed Composition, v%							Catalyst Aging, min	conversi on H ₂ S	COS, ppm				Remarks
					H ₂ S	SO ₂	CO	H ₂	H ₂ O	CO ₂	N ₂			Format ion	Cylinde r Feed	Blank Product Mixture	Reaction Product Mixture	
372	125	117.7	120	141	0.36	0.18	32.02	20.26	10.00	9.07	28.11	1812	0.7520	95	21	109	204	
373	125	118.7	132	130	0.33	0.16	29.11	18.42	18.18	8.25	25.55	1915	0.6703	167	20	169	336	
374	125	121.7	132	133	0.33	0.16	29.11	18.42	18.18	8.25	25.55	2042	0.6499	150	25	152	302	
375	125	118.7	132	130	0.33	0.16	29.11	18.42	18.18	8.25	25.55	2149	0.5820	166	24	154	320	
376	125	118.7	114	150	0.38	0.19	33.71	21.32	5.26	9.55	29.59	2280	0.7115	85	24	152	237	
377	125	121.7	114	154	0.38	0.19	33.61	21.45	5.26	9.54	29.57	2409	0.6578	118	10	64	183	
378	125	121.7	114	154	0.38	0.19	33.61	21.45	5.26	9.54	29.57	2511	0.6821	154	7	61	216	
379	125	118.7	114	150	0.38	0.19	33.61	21.45	5.26	9.54	29.57	2639	0.6316	255	7	75	330	
380	125	119.7	114	151	0.38	0.19	33.61	21.45	5.26	9.54	29.57	2767	0.6298	118	6	74	193	sulfur removed from the catalyst with N ₂ at 200°C overnight
381	125	119.7	114	151	0.38	0.19	33.61	21.45	5.26	9.54	29.57	2869	0.3957	98	6	89	187	
382	125	120.7	114	152	0.38	0.19	33.61	21.45	5.26	9.54	29.57	3021	0.4566	54	6	94	147	no sulfur removed from the catalyst with N ₂ overnight
383	125	120.7	114	152	0.38	0.19	33.61	21.45	5.26	9.54	29.57	3178	0.3991	25	6	99	124	
384	125	120.7	114	152	0.38	0.19	33.61	21.45	5.26	9.54	29.57	3415	0.5082	191	6	62	253	
385	125	123.7	114	156	0.38	0.19	33.61	21.45	5.26	9.54	29.57	3521	0.3885	155	5	76	231	
386	125	121.7	114	154	0.38	0.19	33.61	21.45	5.26	9.54	29.57	3649	0.2779	169	5	52	221	
389	125	120.7	120	145	0.36	0.18	31.93	20.38	10.00	9.07	28.09	3827	0.8731	163	5	57	220	catalyst washed in 0.1 M NaOH aqueous solution overnight
391	125	118.7	120	142	0.36	0.18	31.93	20.38	10.00	9.07	28.09	3974	0.6987	196	4	52	248	
392	125	122.7	120	147	0.36	0.18	31.93	20.38	10.00	9.07	28.09	4141	0.3410	133	5	51	184	catalyst not washed in NaOH aqueous solution overnight
398	125	117.7	120	141	0.36	0.18	31.93	20.38	10.00	9.07	28.09	4303	0.8108	128	5	79	207	catalyst washed in 0.1 M NaOH aqueous solution overnight, and heated for 4 hrs at 450°C
399	125	119.7	120	144	0.36	0.18	31.93	20.38	10.00	9.07	28.09	4467	0.7348	165	5	59	224	
400	125	120.7	120	145	0.36	0.18	31.93	20.38	10.00	9.07	28.09	4617	0.7744	91	5	72	163	
403	125	119.7	120	144	0.36	0.18	31.93	20.38	10.00	9.07	28.09	4758	0.7339	93	5	45	138	
408	125	118.7	120	142	0.36	0.18	31.93	20.38	10.00	9.07	28.09	4940	0.8602	38	7	69	106	0.3 M NaOH washed overnight, heated for 4 hrs at 900°C, no sulfur removed
409	125	118.7	120	142	0.36	0.18	31.93	20.38	10.00	9.07	28.09	5114	0.9269	61	5	60	121	
410	125	120.7	120	145	0.36	0.18	31.93	20.38	10.00	9.07	28.09	5325	0.9309	86	4	59	145	
411	125	122.7	120	147	0.36	0.18	31.93	20.38	10.00	9.07	28.09	5441	0.9027	29	4	148	178	
412	125	122.7	120	147	0.36	0.18	31.93	20.38	10.00	9.07	28.09	5530	0.8547	36	5	125	161	
413	125	119.7	120	144	0.36	0.18	31.93	20.38	10.00	9.07	28.09	5710	0.8410	11	4	177	188	
414	125	120.7	120	145	0.36	0.18	31.93	20.38	10.00	9.07	28.09	5957	0.7072	74	4	116	190	

Table 8. Continued – 2

Run #	Temp. °C	Press. psia	Total Flow Rate, SCCM	Space Time, s	Feed Composition, v%							Catalyst Aging, min	conversion H ₂ S	COS, ppm				Remarks
					H ₂ S	SO ₂	CO	H ₂	H ₂ O	CO ₂	N ₂			Format ion	Cylind er Feed	Blank Product Mixture	Reaction Product Mixture	
415	125	119.7	120	144	0.36	0.18	31.93	20.38	10.00	9.07	28.09	6109	0.6785	68	4	97	165	
416	125	122.7	120	147	0.36	0.18	31.93	20.38	10.00	9.07	28.09	6282	0.8935	81	4	110	191	
417	125	122.7	120	147	0.36	0.18	31.93	20.38	10.00	9.07	28.09	6531	0.7925	94	4	121	216	
418	125	121.7	120	146	0.36	0.18	31.93	20.38	10.00	9.07	28.09	6683	0.7027	126	4	122	248	
419	125	119.7	120	144	0.36	0.18	31.93	20.38	10.00	9.07	28.09	6814	0.6082	74	5	157	231	
420	125	121.7	120	146	0.36	0.18	31.93	20.38	10.00	9.07	28.09	7020	0.5535	100	5	116	215	
421	125	119.7	120	144	0.36	0.18	31.93	20.38	10.00	9.07	28.09	7242	0.6156	93	4	116	209	
422	125	119.7	120	144	0.36	0.18	31.93	20.38	10.00	9.07	28.09	7379	0.7023	86	4	101	187	
423	125	116.7	120	140	0.36	0.18	31.93	20.38	10.00	9.07	28.09	7536	0.7857	91	4	110	202	
424	125	119.7	120	144	0.36	0.18	31.93	20.38	10.00	9.07	28.09	7640	0.7343	112	4	111	223	
425	125	121.7	120	146	0.36	0.18	31.93	20.38	10.00	9.07	28.09	7765	0.6678	101	4	142	243	
426	125	120.7	120	145	0.36	0.18	31.93	20.38	10.00	9.07	28.09	7902	0.6056	89	5	129	218	
427	125	115.7	120	139	0.36	0.18	31.93	20.38	10.00	9.07	28.09	8003	0.7794	273	4	129	402	
433	125	121.7	120	146	0.36	0.18	31.93	20.38	10.00	9.07	28.09	8100	0.1718	92	5	108	200	sulfur removed at 200°C for several days washed in 0.3 M NaOH aqueous solution overnight, and heated for 4hrs at 900°C
438	125	120.7	120	145	0.36	0.18	31.93	20.38	10.00	9.07	28.09	8228	0.2990	164	4	18	182	no sulfur removed
439	125	120.7	120	145	0.36	0.18	31.93	20.38	10.00	9.07	28.09	8350	0.2383	110	5	37	147	
446	125	123.7	120	148	0.36	0.18	31.93	20.38	10.00	9.07	28.09	8516	0.2445	80	5	58	138	
447	125	119.7	120	144	0.36	0.18	31.93	20.38	10.00	9.07	28.09	8685	0.3075	106	5	31	137	

*SCCM: standard cubic centimeters per minute, volumetric flow rates of gases measured at 1 atm and 25°C

Table 9. Effects of elemental sulfur removed from a γ -alumina wash-coated catalyst on conversion of H₂S and formation of COS with the catalyst support soaked in 1-w% Zn aqueous solution followed by heating it for 4 hours at 450°C, and then washed in 0.3 M NaOH aqueous solution followed by heating it for 4 hrs at 900°C, removing elemental sulfur from the catalyst with N₂ at 200°C

Run #	Temp. °C	Press. psia	Total Flow Rate, SCCM	Space Time, s	Feed Composition, v%							Catalyst Aging, min	conversi on H ₂ S	COS, ppm				Remarks
					H ₂ S	SO ₂	CO	H ₂	H ₂ O	CO ₂	N ₂			Form ation	Cylinder Feed	Blank Product Mixture	Reaction Product Mixture	
408	125	118.7	120	142	0.36	0.18	31.93	20.38	10.00	9.07	28.09	4940	0.8602	38	7	69	106	washed in 0.3 M NaOH aqueous solution and heated for 4 hrs at 900°C, no sulfur removed
409	125	118.7	120	142	0.36	0.18	31.93	20.38	10.00	9.07	28.09	5114	0.9269	61	5	60	121	
410	125	120.7	120	145	0.36	0.18	31.93	20.38	10.00	9.07	28.09	5325	0.9309	86	4	59	145	
411	125	122.7	120	147	0.36	0.18	31.93	20.38	10.00	9.07	28.09	5441	0.9027	29	4	148	178	
412	125	122.7	120	147	0.36	0.18	31.93	20.38	10.00	9.07	28.09	5530	0.8547	36	5	125	161	
413	125	119.7	120	144	0.36	0.18	31.93	20.38	10.00	9.07	28.09	5710	0.841	11	4	177	188	
414	125	120.7	120	145	0.36	0.18	31.93	20.38	10.00	9.07	28.09	5957	0.7072	74	4	116	190	
415	125	119.7	120	144	0.36	0.18	31.93	20.38	10.00	9.07	28.09	6109	0.6785	68	4	97	165	
416	125	122.7	120	147	0.36	0.18	31.93	20.38	10.00	9.07	28.09	6282	0.8935	81	4	110	191	
417	125	122.7	120	147	0.36	0.18	31.93	20.38	10.00	9.07	28.09	6531	0.7925	94	4	121	216	
418	125	121.7	120	146	0.36	0.18	31.93	20.38	10.00	9.07	28.09	6683	0.7027	126	4	122	248	
419	125	119.7	120	144	0.36	0.18	31.93	20.38	10.00	9.07	28.09	6814	0.6082	74	5	157	231	
420	125	121.7	120	146	0.36	0.18	31.93	20.38	10.00	9.07	28.09	7020	0.5535	100	5	116	215	
421	125	119.7	120	144	0.36	0.18	31.93	20.38	10.00	9.07	28.09	7242	0.6156	93	4	116	209	
422	125	119.7	120	144	0.36	0.18	31.93	20.38	10.00	9.07	28.09	7379	0.7023	86	4	101	187	
423	125	116.7	120	140	0.36	0.18	31.93	20.38	10.00	9.07	28.09	7536	0.7857	91	4	110	202	
424	125	119.7	120	144	0.36	0.18	31.93	20.38	10.00	9.07	28.09	7640	0.7343	112	4	111	223	
425	125	121.7	120	146	0.36	0.18	31.93	20.38	10.00	9.07	28.09	7765	0.6678	101	4	142	243	
426	125	120.7	120	145	0.36	0.18	31.93	20.38	10.00	9.07	28.09	7902	0.6056	89	5	129	218	
427	125	115.7	120	139	0.36	0.18	31.93	20.38	10.00	9.07	28.09	8003	0.7794	273	4	129	402	
433	125	121.7	120	146	0.36	0.18	31.93	20.38	10.00	9.07	28.09	8100	0.1718	92	5	108	200	removing sulfur from the catalyst with N ₂ for several days at 200°C
438	125	120.7	120	145	0.36	0.18	31.93	20.38	10.00	9.07	28.09	8228	0.299	164	4	18	182	washed in 0.3 M NaOH overnight, heated for 4 hrs at 900°C
439	125	120.7	120	145	0.36	0.18	31.93	20.38	10.00	9.07	28.09	8350	0.2383	110	5	37	147	no sulfur removed
446	125	123.7	120	148	0.36	0.18	31.93	20.38	10.00	9.07	28.09	8516	0.2445	80	5	58	138	no sulfur removed
447	125	119.7	120	144	0.36	0.18	31.93	20.38	10.00	9.07	28.09	8685	0.3075	106	5	31	137	no sulfur removed

*SCCM: standard cubic centimeters per minute, volumetric flow rates of gases measured at 1 atm and 25°C

Table 10. Effects of washing a γ -alumina wash-coated monolithic catalyst support in NaOH aqueous solution on conversion of H₂S and formation of COS.

Run #	Temp. °C	Press. psia	Total Flow Rate, SCCM	Space Time, s	Feed Composition, v%							Catalyst Aging, min	conversi on H ₂ S	COS, ppm				Remarks
					H ₂ S	SO ₂	CO	H ₂	H ₂ O	CO ₂	N ₂			Forma tion	Cylinder Feed	Blank Product Mixture	Reaction Product Mixture	
352	125	121.7	120	146	0.36	0.18	32.02	20.26	10.00	9.07	28.11	147	0.9057	25	18	49	74	removing sulfur from the catalyst with N ₂ at 140°C overnight
353	125	119.7	120	144	0.36	0.18	32.02	20.26	10.00	9.07	28.11	254	0.9479	82	19	52	134	
354	125	117.7	120	141	0.36	0.18	32.02	20.26	10.00	9.07	28.11	358	0.8795	109	19	48	157	
355	125	117.7	120	141	0.36	0.18	32.02	20.26	10.00	9.07	28.11	516	0.8676	79	19	43	121	
356	125	123.7	120	148	0.36	0.18	32.02	20.26	10.00	9.07	28.11	679	0.8974	68	18	38	107	
357	125	116.7	120	140	0.36	0.18	32.02	20.26	10.00	9.07	28.11	810	0.9005	72	19	58	130	
358	125	118.7	120	142	0.36	0.18	32.02	20.26	10.00	9.07	28.11	939	0.9034	67	19	58	125	
359	125	119.7	120	144	0.36	0.18	32.02	20.26	10.00	9.07	28.11	1076	0.8823	65	19	58	123	
360	125	120.7	120	145	0.36	0.18	32.02	20.26	10.00	9.07	28.11	1248	0.8568	72	19	47	119	
361	125	118.7	120	142	0.36	0.18	32.02	20.26	10.00	9.07	28.11	1434	0.8965	58	19	65	123	
387	125	121.7	120	146	0.36	0.18	31.93	20.38	10.00	9.07	28.09	1641	0.9044	78	4	62	141	removing sulfur from the catalyst with N ₂ at 200°C overnight
388	125	122.7	114	155	0.38	0.19	33.61	21.45	5.26	9.54	29.57	1763	0.8395	43	3	85	128	
390	125	118.7	120	142	0.36	0.18	31.93	20.38	10.00	9.07	28.09	1946	0.9287	70	5	71	141	washed in 0.1 M NaOH overnight
393	125	120.7	120	145	0.36	0.18	31.93	20.38	10.00	9.07	28.09	2159	0.7553	77	6	63	139	
394	125	121.7	120	146	0.36	0.18	31.93	20.38	10.00	9.07	28.09	2330	0.5210	10	5	123	133	washed in 0.1 M NaOH aqueous solution overnight, and heated for 4 hrs at 450°C, removed sulfur from the catalyst with N ₂ at 200°C
395	125	119.7	120	144	0.36	0.18	31.93	20.38	10.00	9.07	28.09	2429	0.5254	37	5	142	179	
396	125	120.7	120	145	0.36	0.18	31.93	20.38	10.00	9.07	28.09	2559	0.3428	46	6	53	99	
397	125	120.7	120	145	0.36	0.18	31.93	20.38	10.00	9.07	28.09	2680	0.2062	31	6	89	121	washed in 0.2 M NaOH aqueous solution overnight, and heated for 4 hrs at 450°C, removed sulfur from the catalyst with N ₂ at 200°C
401	125	119.7	120	144	0.36	0.18	31.93	20.38	10.00	9.07	28.09	2893	0.8154	108	5	53	161	
402	125	121.7	120	146	0.36	0.18	31.93	20.38	10.00	9.07	28.09	3094	0.1779	131	5	62	193	washed in 0.3 M NaOH aqueous solution overnight, and heated for 1.5 hrs at 900°C, removed sulfur from the catalyst with N ₂ at 200°C
404	125	121.7	120	146	0.36	0.18	31.93	20.38	10.00	9.07	28.09	3249	0.8201	70	5	48	119	
405	125	123.7	120	148	0.36	0.18	31.93	20.38	10.00	9.07	28.09	3484	0.6095	85	4	68	153	
406	125	119.7	120	144	0.36	0.18	31.93	20.38	10.00	9.07	28.09	3613	0.3270	67	5	70	137	

Table 10. Continued - 1

Run #	Temp. °C	Press. psia	Total Flow Rate, SCCM	Space Time, s	Feed Composition, v%							Catalyst Aging, min	conversi on H ₂ S	COS, ppm				Remarks
					H ₂ S	SO ₂	CO	H ₂	H ₂ O	CO ₂	N ₂			Forma tion	Cylinder Feed	Blank Product Mixture	Reaction Product Mixture	
407	125	120.7	120	145	0.36	0.18	31.93	20.38	10.00	9.07	28.09	3745	0.2864	42	6	80	121	washed in 0.4 M NaOH aqueous solution overnight, and heated for 4 hrs at 900°C, removed sulfur from the catalyst with N ₂ at 200°C no sulfur removed
428	125	118.7	120	142	0.36	0.18	31.93	20.38	10.00	9.07	28.09	3884	0.8661	17	5	131	148	
429	125	121.7	120	146	0.36	0.18	31.93	20.38	10.00	9.07	28.09	4061	0.9073	18	5	98	115	
430	125	117.7	120	141	0.36	0.18	31.93	20.38	10.00	9.07	28.09	4186	0.7673	42	5	99	142	
431	125	120.7	120	145	0.36	0.18	31.93	20.38	10.00	9.07	28.09	4385	0.7929	8	5	120	128	
444	125	120.7	120	145	0.36	0.18	31.93	20.38	10.00	9.07	28.09	4590	0.8004	18	4	21	39	
445	125	120.7	120	145	0.36	0.18	31.93	20.38	10.00	9.07	28.09		0.7956	40	4	26	66	

*SCCM: standard cubic centimeters per minute, volumetric flow rates of gases measured at 1 atm and 25°C

Table 11. Conversion of H₂S and formation of COS with a γ -alumina wash-coated monolithic catalyst support, soaked in 4-w% Zn aqueous solution followed by heating it for 4 hrs at 600°C, and soaked in 4-w% KOH aqueous solution followed by heating it for 4 hrs at 550°C.

Run #	Temp. °C	Press. psia	Total Flow Rate, SCCM	Space Time, s	Feed Composition, v%							Catalyst Aging, min	conversi on H ₂ S	COS, ppm				Remarks
					H ₂ S	SO ₂	CO	H ₂	H ₂ O	CO ₂	N ₂			Forma tion	Cylinder Feed	Blank Product Mixture	Reaction Product Mixture	
432	125	128.7	120	154	0.36	0.18	31.93	20.38	10.00	9.07	28.09	136	1.0000	-16	5	119	103	soaked with 4-w% Zn aqueous solution and heated for 4 hrs at 600°C soaked with 4-w% KOH aqueous solution and heated for 4 hrs at 550°C. no sulfur removed
436	125	117.7	120	141	0.36	0.18	31.93	20.38	10.00	9.07	28.09	232	1.0000	-118	4	121	2	
437	125	118.7	120	142	0.36	0.18	31.93	20.38	10.00	9.07	28.09	469	0.8961	14	4	126	140	
468	125	118.7	120	142	0.36	0.18	31.93	20.38	10.00	9.07	28.09	719	0.8565	39	5	68	107	
469	125	119.7	120	144	0.36	0.18	31.93	20.38	10.00	9.07	28.09	893	0.9181	16	5	112	129	
470	125	118.7	120	142	0.36	0.18	31.93	20.38	10.00	9.07	28.09	1112	0.8565	127	5	80	207	
471	125	119.7	120	144	0.36	0.18	31.93	20.38	10.00	9.07	28.09	1432	0.9087	376	5	84	460	
472	125	118.7	120	142	0.36	0.18	31.93	20.38	10.00	9.07	28.09	1579	0.9584	145	5	54	199	
473	125	117.7	120	141	0.36	0.18	31.93	20.38	10.00	9.07	28.09	1748	0.7669	138	5	58	196	
474	125	119.7	120	144	0.36	0.18	31.93	20.38	10.00	9.07	28.09	1920	0.8941	111	4	53	164	
475	125	120.7	120	145	0.36	0.18	31.93	20.38	10.00	9.07	28.09	2061	0.9626	86	6	73	159	

Table 12. Conversion of H₂S and formation of COS with a γ -alumina wash-coated monolithic catalyst support soaked in 4-w% KOH aqueous solution followed by heating it for 4 hrs at 550°C.

Run #	Temp. °C	Press. psia	Total Flow Rate, SCCM	Space Time, s	Feed Composition, v%							Catalyst Aging, min	conversi on H ₂ S	COS, ppm				Remarks
					H ₂ S	SO ₂	CO	H ₂	H ₂ O	CO ₂	N ₂			Forma tion	Cylinder Feed	Blank Product Mixture	Reaction Product Mixture	
434	125	115.7	120	139	0.36	0.18	31.93	20.38	10.00	9.07	28.09	209	0.6977	-140	4	142	2	soaked with 4-w% KOH aqueous solution and heated for 4 hrs at 550°C
435	125	119.7	120	144	0.36	0.18	31.93	20.38	10.00	9.07	28.09	365	0.7108	-54	4	118	64	no sulfur removed
440	125	119.7	120	144	0.36	0.18	31.93	20.38	10.00	9.07	28.09	574	0.5517	70	4	20	90	
441	125	119.7	120	144	0.36	0.18	31.93	20.38	10.00	9.07	28.09	718	0.7503	86	4	14	100	
442	125	119.7	120	144	0.36	0.18	31.93	20.38	10.00	9.07	28.09	912	0.8165	54	4	48	103	
443	125	121.7	120	146	0.36	0.18	31.93	20.38	10.00	9.07	28.09	1049	0.8213	85	4	30	114	

*SCCM: standard cubic centimeters per minute, volumetric flow rates of gases measured at 1 atm and 25°C

Table 13. Conversion of H₂S and formation of COS with a γ -alumina wash-coated monolithic catalyst support soaked in 2-w% Fe³⁺ aqueous solution followed by heating it for 4 hrs at 450°C, removing sulfur from the catalyst with N₂ overnight.

Run #	Temp. °C	Press. psia	Total Flow Rate, SCCM	Space Time, s	Feed Composition, v%							Catalyst Aging, min	conversi on H ₂ S	COS, ppm				Remarks
					H ₂ S	SO ₂	CO	H ₂	H ₂ O	CO ₂	N ₂			Forma tion	Cylinder Feed	Blank Product Mixture	Reaction Product Mixture	
332	140	118.7	120	137	0.36	0.18	32.02	20.26	10.00	9.07	28.11	194	0.9760	54	15	94	149	soaked with 2-w% Fe ³⁺ aqueous solution and heated for 4 hrs at 450°C. removing sulfur from the catalyst with N at 270°C
333	140	118.7	120	137	0.36	0.18	32.02	20.26	10.00	9.07	28.11	385	0.9331	184	16	102	286	
334	140	119.7	120	138	0.36	0.18	32.02	20.26	10.00	9.07	28.11	530	0.4850	133	16	102	235	
335	140	118.7	120	137	0.36	0.18	32.02	20.26	10.00	9.07	28.11	640	0.3630	117	18	101	218	
336	125	117.7	120	141	0.36	0.18	32.02	20.26	10.00	9.07	28.11	726	0.4461	136	16	64	200	
345	125	121.7	120	146	0.36	0.18	32.02	20.26	10.00	9.07	28.11	214	na	34	18	100	135	removing sulfur from the catalyst with N ₂ at 200°C overnight
346	125	120.7	120	145	0.36	0.18	32.02	20.26	10.00	9.07	28.11	450	0.9649	71	18	100	171	
347	125	120.7	120	145	0.36	0.18	32.02	20.26	10.00	9.07	28.11	648	0.7282	71	18	124	196	
348	125	116.7	120	140	0.36	0.18	32.02	20.26	10.00	9.07	28.11	807	-0.0440	95	18	126	221	
349	125	121.7	120	146	0.36	0.18	32.02	20.26	10.00	9.07	28.11	943	-0.8358	155	19	29	184	
350	125	122.7	120	147	0.36	0.18	32.02	20.26	10.00	9.07	28.11	1081	-0.3571	135	18	26	161	

Table 14. Conversion of H₂S and formation of COS with a γ -alumina wash-coated monolithic catalyst support, soaked in 0.6-M NaOH aqueous solution followed by heating it for 4 hrs at 950°C, soaked in 4-w% KOH aqueous solution followed by heating it for 2 h at 550°C, and soaked in 0.5-w% MgCl₂ aqueous solution followed by heating it for 2 hrs at 550°C, removing no sulfur.

Run #	Temp. °C	Press. psia	Total Flow Rate, SCCM	Space Time, s	Feed Composition, v%							Catalyst Aging, min	conversi on H ₂ S	COS, ppm				Remarks
					H ₂ S	SO ₂	CO	H ₂	H ₂ O	CO ₂	N ₂			Forma tion	Cylinder Feed	Blank Product Mixture	Reaction Product Mixture	
448	125	118.7	120	142	0.36	0.18	31.93	20.38	10.00	9.07	28.09	204	0.8316	10	5	41	51	soaked in 0.6-M NaOH aqueous solution followed by heating it for 4 hrs at 950°C, soaked in 4-w% KOH followed by heating it for 2 h at 550°C, and soaked in 0.5-w% MgCl ₂ aqueous solution followed by heating it for 2 hrs at 550°C removing no sulfur
449	125	118.7	120	142	0.36	0.18	31.93	20.38	10.00	9.07	28.09	401	0.8884	35	4	32	67	
450	125	116.7	120	140	0.36	0.18	31.93	20.38	10.00	9.07	28.09	600	0.8906	33	4	29	62	
451	125	121.7	120	146	0.36	0.18	31.93	20.38	10.00	9.07	28.09	772	0.8764	7	5	72	79	
452	125	119.7	120	144	0.36	0.18	31.93	20.38	10.00	9.07	28.09	962	0.8779	27	4	57	84	
453	125	119.7	120	144	0.36	0.18	31.93	20.38	10.00	9.07	28.09	1132	0.8677	19	3	70	88	
454	125	119.7	120	144	0.36	0.18	31.93	20.38	10.00	9.07	28.09	1330	0.8517	56	4	75	131	
457	125	116.7	120	140	0.36	0.18	31.93	20.38	10.00	9.07	28.09	1585	0.8283	-1	5	93	92	
458	125	118.7	120	142	0.36	0.18	31.93	20.38	10.00	9.07	28.09	1750	0.8370	33	5	63	96	
459	125	121.7	120	146	0.36	0.18	31.93	20.38	10.00	9.07	28.09	1939	0.8139	19	5	77	96	
460	125	118.7	120	142	0.36	0.18	31.93	20.38	10.00	9.07	28.09	2103	0.8213	8	5	83	92	
461	125	120.7	120	145	0.36	0.18	31.93	20.38	10.00	9.07	28.09	2284	0.7894	28	5	74	102	
462	125	122.7	120	147	0.36	0.18	31.93	20.38	10.00	9.07	28.09	2460	0.7943	31	5	90	121	
463	125	121.7	120	146	0.36	0.18	31.93	20.38	10.00	9.07	28.09	2598	0.8040	28	6	69	97	
464	125	119.7	120	144	0.36	0.18	31.93	20.38	10.00	9.07	28.09	2770	0.7853	23	5	84	107	
465	125	121.7	120	146	0.36	0.18	31.93	20.38	10.00	9.07	28.09	2932	0.7803	50	18	77	127	
466	125	121.7	120	146	0.36	0.18	31.93	20.38	10.00	9.07	28.09	3097	0.7700	60	5	91	151	
467	125	119.7	120	144	0.36	0.18	31.93	20.38	10.00	9.07	28.09	3264	0.7879	43	12	75	118	

CALCULATIONS

Concentrations of H₂S and COS in the outlet stream from a monolithic catalyst reactor are analyzed by using a gas chromatograph equipped with a flame photometric detector (FPD) and a thermal conductivity detector (TCD), and a calibration curve. A calibration curve for H₂S is developed with three H₂S samples in different concentrations such as 4,980 ppmv, 996 ppmv, and 249 ppmv, whereas a calibration curve for COS is developed with three COS samples in different concentrations such as 45 ppmv, 30 ppmv, and 15 ppmv.

Each experimental reaction run proceeds after a blank run, which is carried out in the absence of moisture and monolithic catalyst in a reactor. Conversions of H₂S are obtained with concentrations of H₂S from a reaction run and those from its blank run, as shown in the following equation.

$$x = \frac{(C_B - C_R)}{C_B} \quad (1)$$

where x : conversion of H₂S.

C_B : concentration of H₂S in the outlet stream for a blank run.

C_R : concentration of H₂S in the outlet stream for a reaction run

Elemental sulfur is formed with the following reversible stoichiometric reaction formula, as shown in Equation (2). COS is formed in the presence of moisture and catalyst according to the reversible stoichiometric reaction formula, as shown in Equation (3) and Equation (4), which is obtained by adding Equation (2) to Equation (3) multiplied by 3, whereas COS is formed in the absence of moisture and catalyst according to the reversible stoichiometric reaction formula, as shown in Equation (5).



RESULTS AND DISCUSSION

Experiments on conversion of hydrogen sulfide into element sulfur were carried out over the space time range of 130 – 156 seconds at 120 - 140°C (see Table 3) to formulate catalysts suitable for the removal of H₂S and COS from coal gases, evaluate removal capabilities of hydrogen sulfide and COS from coal gases with formulated catalysts, and develop an economic regeneration method of deactivated catalysts. Catalysts were formulated by soaking γ -alumina wash-coated monolithic catalyst supports in catalytically active additive aqueous solutions followed by heating them under air environment at elevated temperatures. Simulated coal gas mixtures consist of 3,300 - 3,800 ppmv hydrogen sulfide, 1,600 - 1,900 ppmv sulfur dioxide, 29 – 34 v% CO, 18 – 21 v% hydrogen, 5 – 18 vol % moisture, 8 – 10 v% CO₂, and nitrogen as remainder. Volumetric feed rates of a simulated coal gas mixture to a monolithic catalyst reactor are 130 - 156 cm³/min at room temperature and atmospheric pressure (SCCM). The temperature

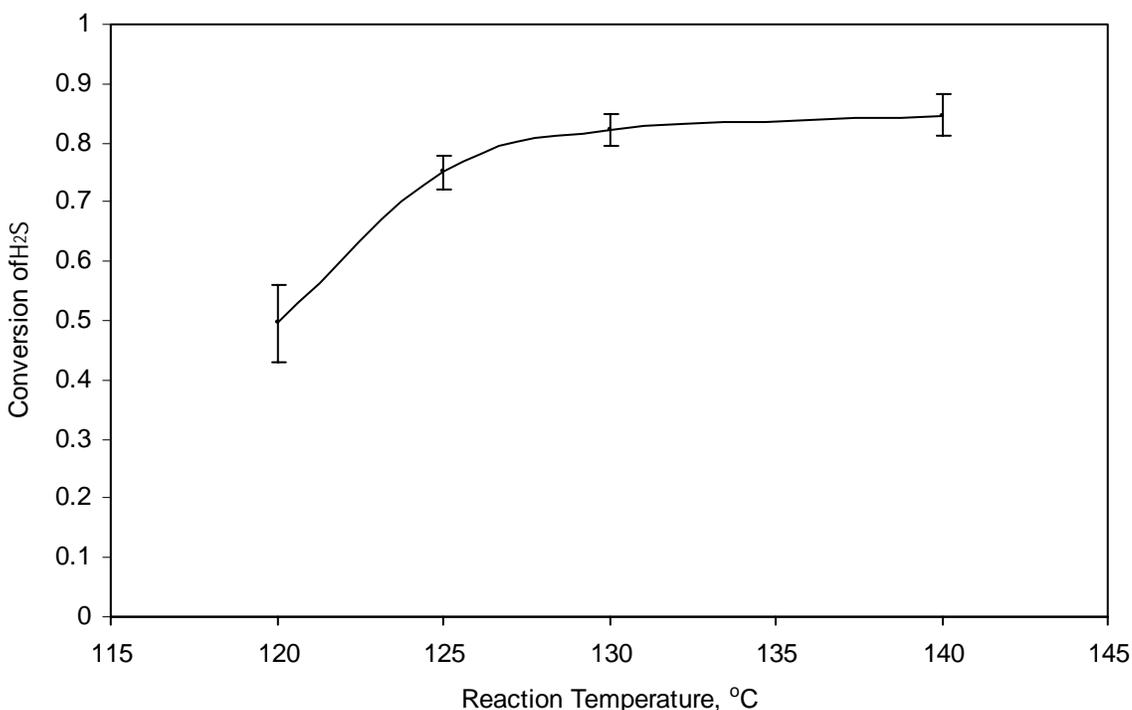
of the reactor is controlled in an oven at 120 - 140°C. The pressure of the reactor is maintained at 116 - 129 psia. Elemental sulfur deposited on a monolithic catalyst is removed with nitrogen at 140 - 270°C overnight.

Effects of Temperature on Conversion of H₂S into Elemental Sulfur and formation of COS

Experiments on conversion of hydrogen sulfide to elemental sulfur and formation of COS with a 2-cm-diameter 15-cm-long γ -alumina wash-coated 400-cells/inch² monolithic catalyst were carried out over the space time range of 135 - 149 s to evaluate effects of reaction temperature on conversion of hydrogen sulfide to elemental sulfur and formation of COS at 120 - 140°C and 117 - 124 psia, using quadruple experimental data. Gas mixtures are fed to a monolithic catalyst reactor containing 3,600-ppmv H₂S, 1,800 ppmv SO₂, 32-v% CO, 20-v% hydrogen, 10-v% moisture, 9-v% CO₂, and nitrogen as remainder. Volumetric feed rates of gas mixtures to the monolithic catalyst reactor are 120 SCCM. Conversion of H₂S to elemental sulfur is 0.50 - 0.82.

Conversion of H₂S to elemental sulfur does not follow the Arrhenius' equation, although conversion of H₂S to elemental sulfur increases with increased reaction temperature over the temperature range of 120 -140°C (see Figure 2).

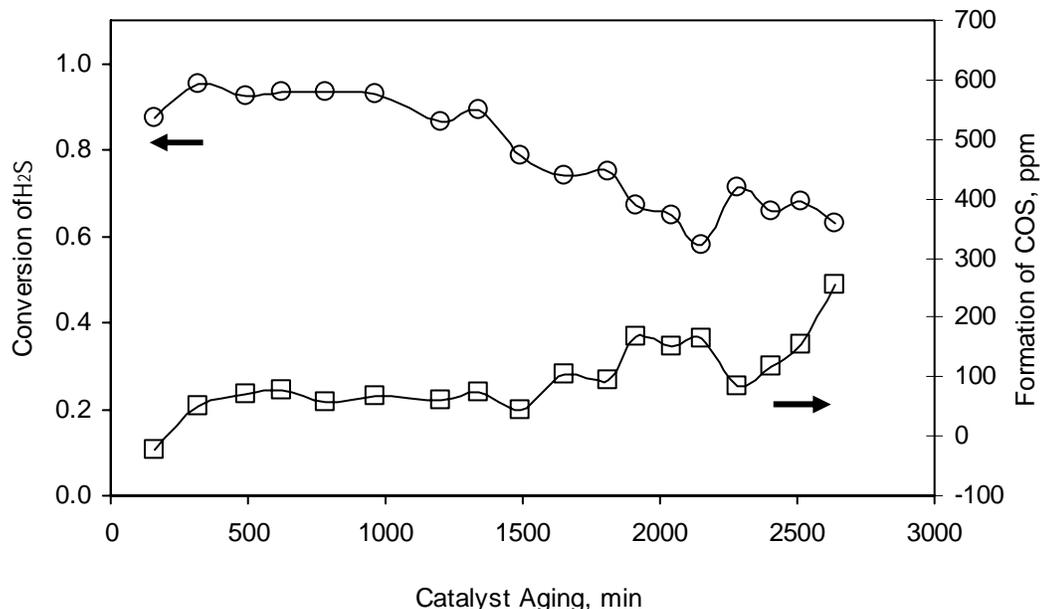
Figure 2. Effects of temperature on conversion of H₂S to elemental sulfur and formation of COS with a 120-SCCM feed stream containing 3,600-ppmv H₂S, 1,800-ppmv SO₂, 32-v% CO, 20-v% H₂, 9-v% CO₂ and 10-v% moisture at 120 - 140°C, 117- 124 psia and 135 - 149 s space time, removing elemental sulfur from a γ -alumina wash-coated monolithic catalyst with N₂ overnight.



Effects of Catalyst Aging on Conversion of H₂S into Elemental Sulfur and formation of COS

Experiments on conversion of hydrogen sulfide to elemental sulfur and formation of COS with a 2-cm-diameter 15-cm-long γ -alumina wash-coated 400-cells/inch² monolithic catalyst were carried out over the space time range of 130 - 154 s to evaluate effects of catalyst aging on conversion of hydrogen sulfide to elemental sulfur and formation of COS at 125°C and 116 - 122 psia. Gas mixtures are fed to a monolithic catalyst reactor containing 3,300 - 3,800-ppmv H₂S, 1,600 - 1,900 ppmv SO₂, 29 - 34-v% CO, 18 - 21-v% hydrogen, 5 -18-v% moisture, 8 - 10-v% CO₂, and nitrogen as remainder. Volumetric feed rates of gas mixtures to the monolithic catalyst reactor are 114 - 132 SCCM. A γ -alumina wash-coated 400-cells/inch² monolithic catalyst support is soaked in 1-w% Zn aqueous solution and heated for 4 hours at 450°C. Elemental sulfur was removed from the catalyst with N₂ at 140°C overnight. Conversion of H₂S to elemental sulfur is 0.58 - 0.95.

Figure 3. Effects of catalyst aging on conversion of H₂S and formation of COS with a γ -alumina wash-coated catalyst support soaked in 1-w% Zn aqueous solution followed by heating it for 4 hours at 450°C, removing elemental sulfur from the catalyst with N₂ overnight at 140°C.

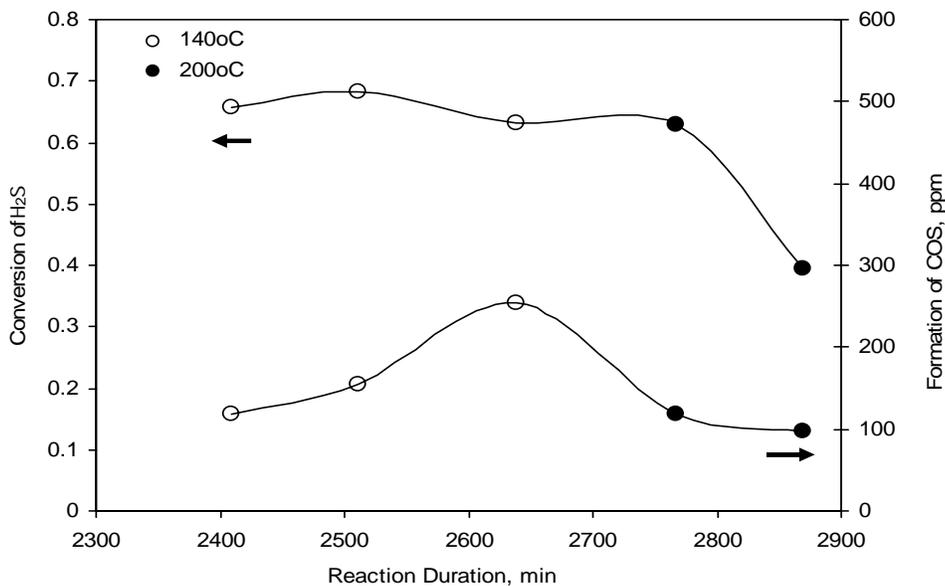


Conversion of H₂S into elemental sulfur and formation of COS are constant up to 1,400-min catalyst aging. Thereafter, conversion of H₂S into elemental sulfur decreases with increased catalyst aging, while formation of COS increases with increased catalyst aging, as shown in Figure 3.

Temperature Effects of Removing Elemental Sulfur from a Catalyst on Conversion of H₂S and formation of COS.

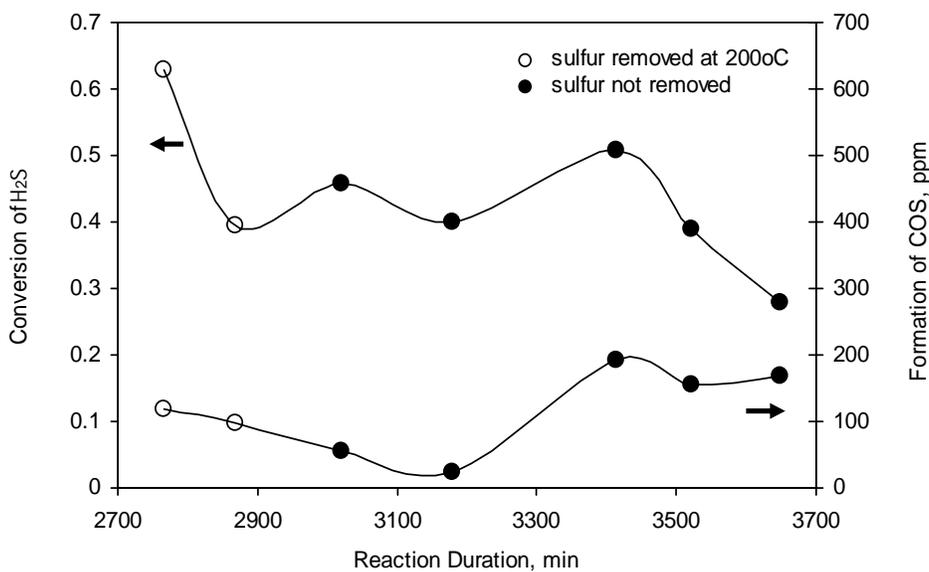
Conversion of H₂S into elemental sulfur and formation of COS decrease with increased temperature at which elemental sulfur is removed from the catalyst soaked with 1-w% Zn aqueous solution followed by heating it for 4 hours at 450°C (see Figure 4).

Figure 4. Effects of removal temperature of elemental sulfur attached to a γ -alumina wash-coated catalyst on conversion of H_2S and formation of COS with the monolithic catalyst support soaked in 1-w% Zn aqueous solution followed by heating it for 4 hours at $450^\circ C$, removing elemental sulfur from the catalyst with N_2 overnight.



Effects of Sulfur Removal from a Zn-treated Monolithic Catalyst on Conversion of H_2S and Formation of COS

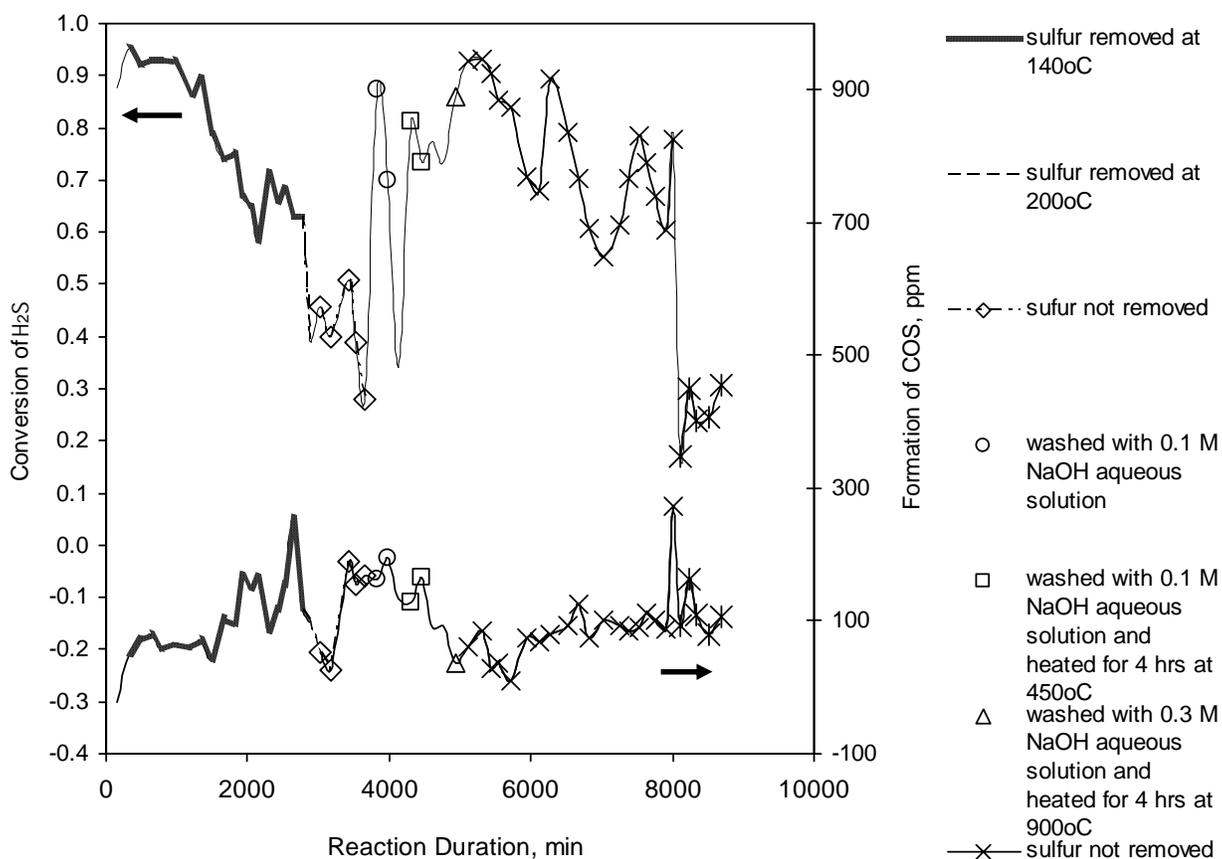
Figure 5. Effects of sulfur removal from a γ -alumina wash-coated monolithic catalyst on conversion of H_2S and formation of COS with the catalyst support soaked with 1-w% Zn aqueous solution followed by heating it for 4 hours at $450^\circ C$, removing elemental sulfur from the catalyst with N_2 at $200^\circ C$ overnight.



A γ -alumina wash-coated catalyst support was soaked in 1-w% Zn aqueous solution followed by heating it for 4 hours at 450°C to increase conversion of H₂S into elemental sulfur and decrease formation of COS. Elemental sulfur was removed from the catalyst by heating the catalyst with N₂ at 200°C overnight. Conversion of H₂S into elemental sulfur seems to be higher on removing elemental sulfur from the catalyst than leaving elemental sulfur on the catalyst. Formation of COS seems to be lower on removing elemental sulfur from the catalyst than leaving elemental sulfur on the catalyst.

Effects of Soaking a Zn-Treated Catalyst in NaOH Aqueous Solution on Conversion of H₂S and Formation of COS

Figure 6. Effects of soaking a catalyst in NaOH aqueous solution on conversion of H₂S and formation of COS with the γ -alumina wash-coated monolithic catalyst support soaked in 1-w% Zn aqueous solution followed by heating it for 4 hrs at 450°C



A γ -alumina wash-coated catalyst support was soaked with 1-w% Zn aqueous solution followed by heating it for 4 hours at 450°C to increase conversion of H₂S into elemental sulfur and decrease formation of COS. Conversion of H₂S into elemental sulfur decreases and formation of COS increases with increased catalyst aging, although elemental sulfur was removed from the catalyst by heating the catalyst with N₂ at either 140 or 200°C overnight.

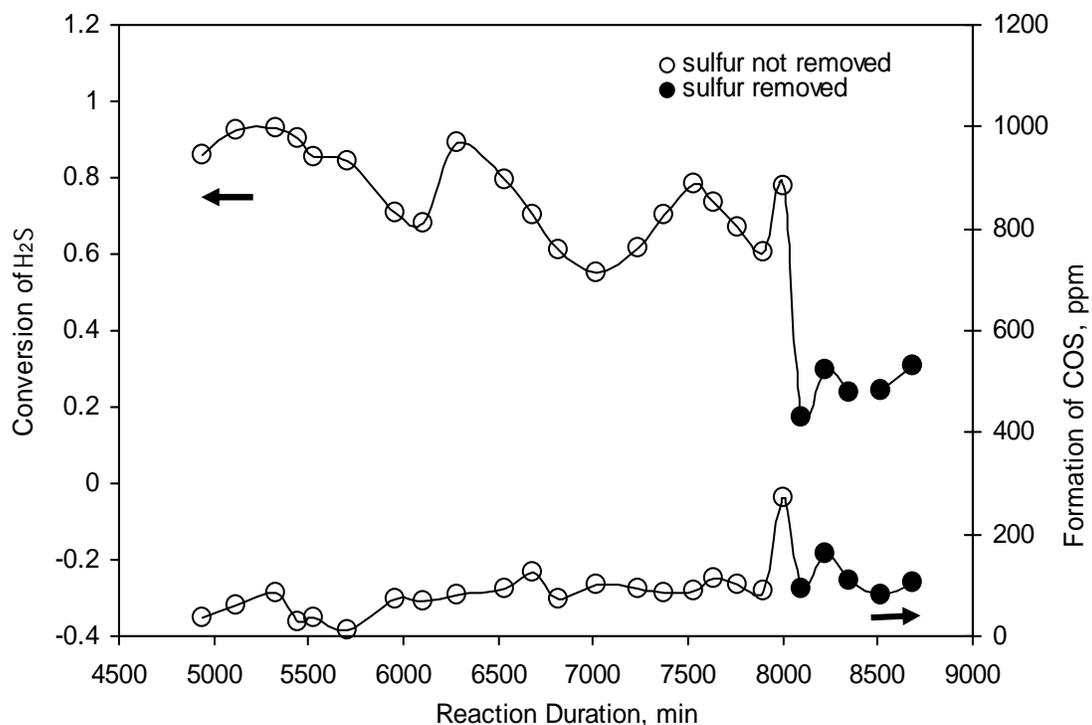
The catalyst was washed in 0.1-M NaOH aqueous solution overnight followed by heating it for 4 hrs at 450°C and then washed in 0.3-M NaOH aqueous solution overnight followed by heating it for 4 hrs at 900°C for the regeneration of the deactivated catalyst. Effects of washing

the catalyst in NaOH aqueous solution overnight followed by heating it for 4 hrs at 450°C and then for 4 hrs at 900°C on conversion of H₂S into elemental sulfur are pronounced and long-lived, although elemental sulfur was not removed from the catalyst by heating it overnight, as shown in Figure 6.

Effects of Removing Elemental Sulfur from a Zn-Treated and NaOH-Regenerated Catalyst on Conversion of H₂S and Formation of COS.

A catalyst washed in 0.1-M NaOH aqueous solution overnight followed by heating it for 4 hrs at 450°C and then washed in 0.3-M NaOH aqueous solution overnight followed by heating it for 4 hrs at 900°C for the regeneration of the catalyst was used for the removal of H₂S without removing elemental sulfur from the catalyst overnight by heating it for the 3,000 min reaction duration. Thereafter, elemental sulfur was removed from the catalyst by heating it overnight at 200°C. Conversion of H₂S into elemental sulfur decreases drastically upon removing elemental sulfur from the catalyst, as shown in Figure 7. This observation may suggest that the elemental sulfur deposited on the catalyst play a catalytic role in removing H₂S from the catalyst.

Figure 7. Effects of removing elemental sulfur from a catalyst on conversion of H₂S and formation of COS with the γ -alumina wash-coated catalyst support soaked in 1-w% Zn aqueous solution followed by heating it for 4 hours at 450°C, and washed in 0.3 M NaOH aqueous solution followed by heating it for 4 hrs at 900°C, removing sulfur from the catalyst with N₂ at 200°C overnight.

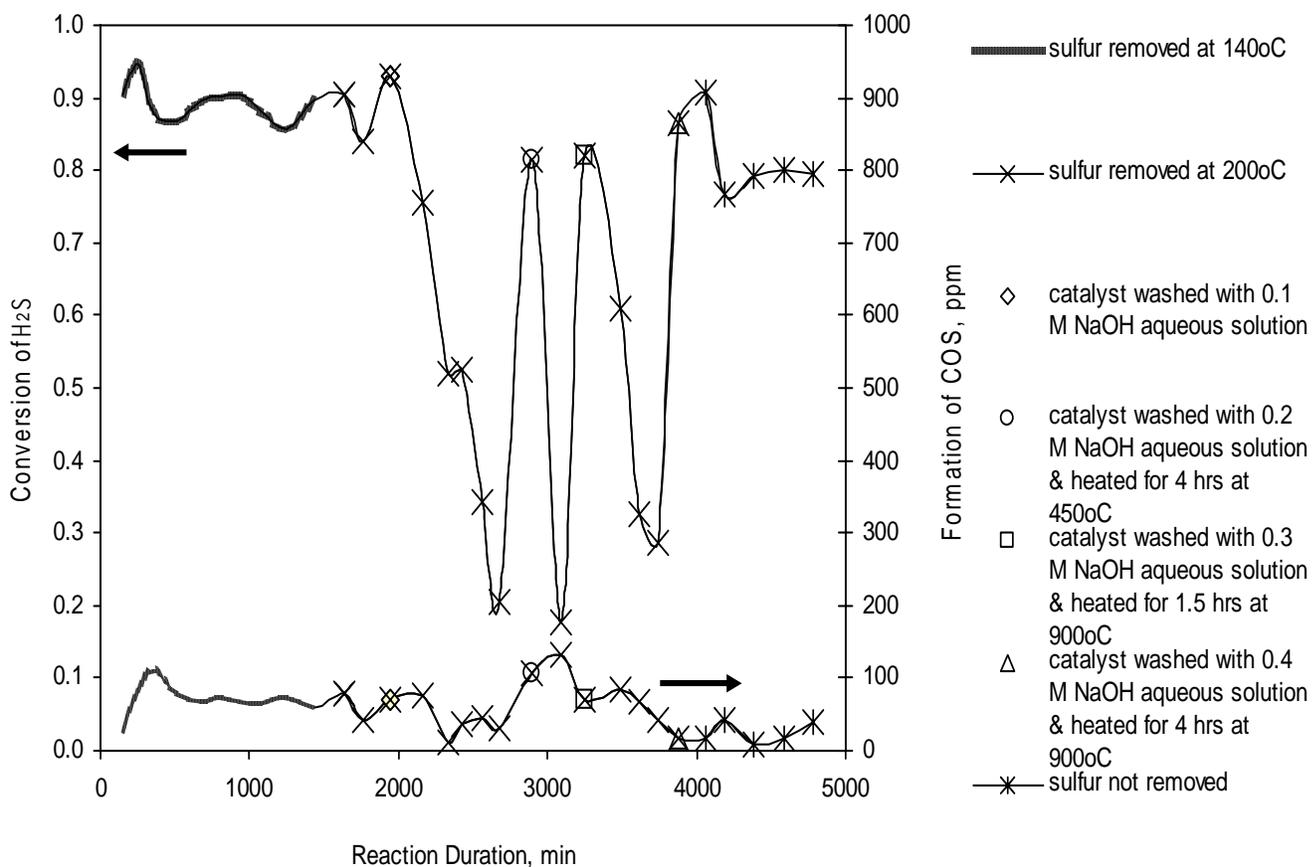


Effects of Washing a Catalyst in NaOH Aqueous Solution on Conversion of H₂S and Formation of COS

Catalysts are mainly deactivated by liquid elemental sulfur deposition below the dew temperature of elemental sulfur, carbon deposition, aluminum sulfate formation, and catalyst aging. Catalysts are washed in NaOH aqueous solutions to dissolve alumina sulfate or other water-soluble substances on catalyst surfaces. Catalysts are heated at elevated temperatures to remove elemental sulfur from catalysts by vaporizing it.

Effects of washing a γ -alumina wash-coated catalyst support in 0.1-M NaOH aqueous solution, washing the catalyst support in 0.2-M NaOH aqueous solution followed by heating it for 4 hrs at 450°C, and washing the catalyst in 0.3-M NaOH aqueous solution followed by heating it for 1.5 hrs at 900°C on conversion of H₂S into elemental sulfur are short-lived. However, effects of washing the catalyst in 0.4-M NaOH aqueous solution followed by heating it for 4 hrs at 900°C on conversion of H₂S into elemental sulfur is long-lived, as shown in Figure 8.

Figure 8. Effects of washing a γ -alumina wash-coated monolithic catalyst support in NaOH aqueous solution on conversion of H₂S and formation of COS.



Effects of Soaking a Catalyst in Zn Aqueous Solution and then KOH Aqueous Solution on Conversion of H₂S and Formation of COS

A γ -alumina catalyst support was soaked in 4-w% Zn aqueous solution followed by heating it for 4 hrs at 600°C, and then soaked in 4-w% KOH aqueous solution followed by heating it for 4 hrs at 550°C to increase conversion of H₂S and reduce formation of COS. Elemental sulfur deposited on the catalyst is not removed. Effects of soaking the catalyst with Zn and KOH aqueous solutions on conversion of H₂S seem to be good initially. However, effects of soaking the catalyst in Zn and KOH aqueous solutions on formation of COS seem to be short-lived by changing formation of COS from negative to positive, as shown in Figure 9.

Figure 9. Conversion of H₂S and formation of COS with a γ -alumina wash-coated monolithic catalyst support, soaked in 4-w% Zn aqueous solution followed by heating it for 4 hrs at 600°C, and then soaked in 4-w% KOH aqueous solution followed by heating it for 4 hrs at 550°C.

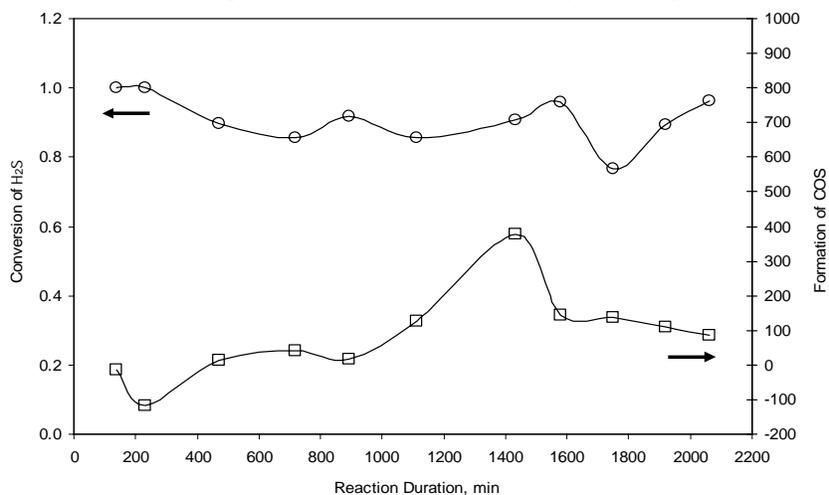
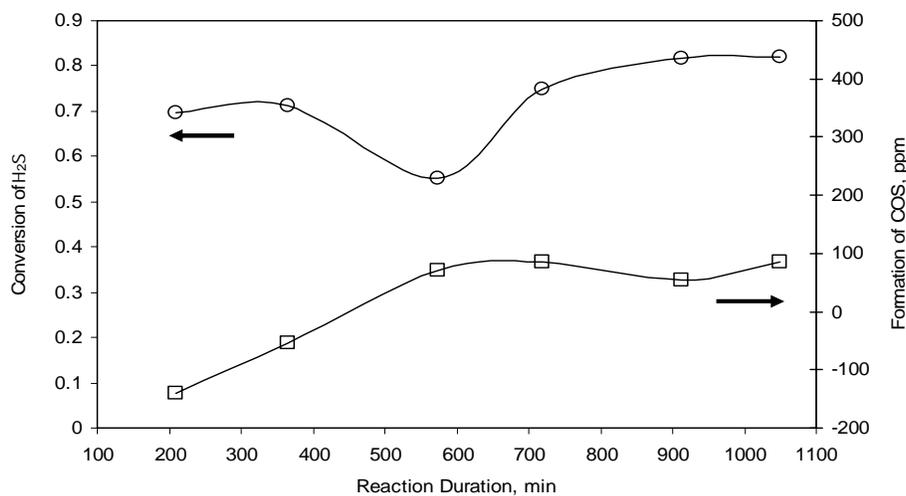


Figure 10. Conversion of H₂S and formation of COS with a γ -alumina wash-coated monolithic catalyst support soaked with 4-w% KOH aqueous solution followed by heating it for 4 hrs at 550°C

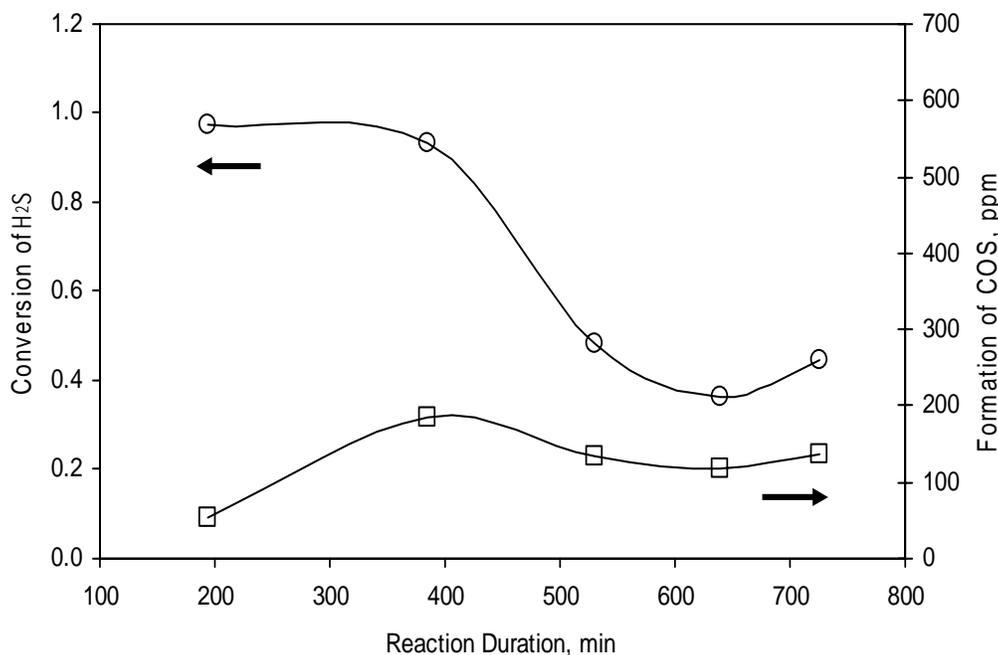


A catalyst support was soaked in 4-w% KOH aqueous solution followed by heating it for 4 hrs at 550°C. Effects of soaking the catalyst in KOH aqueous solutions on conversion of H₂S are good initially. However, favorable effects of soaking the catalyst in KOH aqueous solution on formation of COS seem to be short-lived, as shown in Figure 10. Conversion of H₂S into elemental sulfur is much higher with the catalyst soaked in Zn and KOH aqueous solutions than that in KOH aqueous solution only (see Figures 9 and 10).

Effects of Soaking a Catalyst in Fe³⁺ Aqueous Solution on Conversion of H₂S and Formation of COS

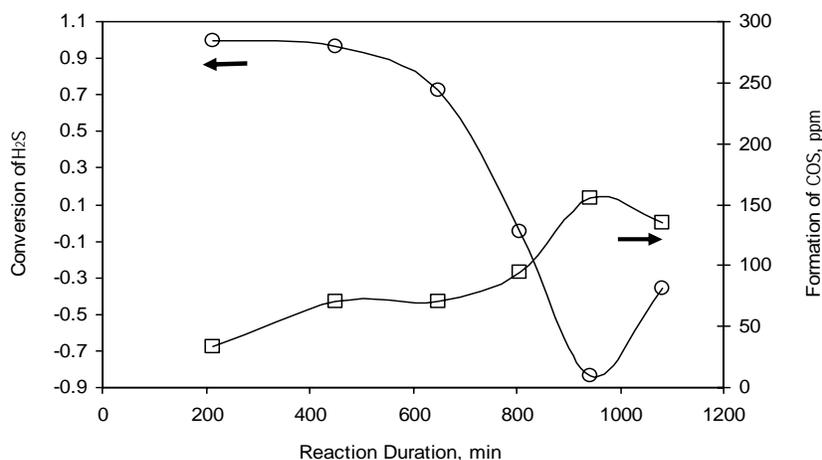
A γ -alumina wash-coated catalyst support was soaked in 2-w% Fe³⁺ aqueous solution followed by heating it for 4 hrs at 550°C. Conversion of H₂S drastically decreases with increased reaction duration with removing sulfur from the catalyst with N₂ at 270°C, as shown in Figure 11.

Figure 11. Conversion of H₂S and formation of COS with a γ -alumina wash-coated monolithic catalyst support soaked in 2-w% Fe³⁺ aqueous solution followed by heating it for 4 hrs at 450°C, removing elemental sulfur from the catalyst with N₂ at 270°C.



Conversion of H₂S drastically decreases and becomes negative with increased reaction duration with removing sulfur from the 2-w% Fe³⁺ treated catalyst with N₂ at 200°C, as shown in Figure 12. This fact may suggest that H₂S be produced rather than removed from the simulated coal gas. Formation of COS is very high with the catalyst soaked in 2-w% Fe³⁺ aqueous solution followed by heating it for 4 hrs at 550°C.

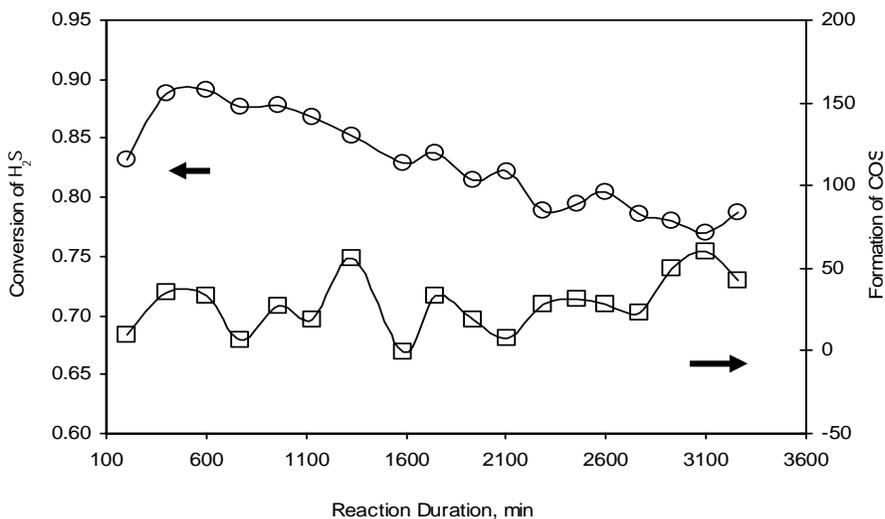
Figure 12. Conversion of H₂S and formation of COS with a γ -alumina wash-coated monolithic catalyst support soaked in 2-w% Fe³⁺ aqueous solution followed by heating it for 4 hrs at 450°C, removing sulfur from the catalyst with N₂ at 200°C overnight.



Effects of Soaking a Catalyst in NaOH, KOH, and MgCl₂ Aqueous Solutions on Conversion of H₂S and Formation of COS

A γ -alumina wash-coated monolithic catalyst support was soaked in 0.6-M NaOH aqueous solution followed by heating it for 4 hrs at 950°C, soaked in 4-w% KOH followed by heating it for 2 hrs at 550°C, and soaked in 0.5-w% MgCl₂ aqueous solution followed by heating it for 2 hrs at 550°C. Conversion of H₂S decreases and formation of COS increases with increased reaction duration, although elemental sulfur is removed from the catalyst throughout experiments.

Figure 13. Conversion of H₂S and formation of COS with a γ -alumina wash-coated monolithic catalyst support, soaked in 0.6-M NaOH aqueous solution followed by heating it for 4 hrs at 950°C, soaked in 4-w% KOH followed by heating it for 2 h at 550°C, and soaked in 0.5-w% MgCl₂ aqueous solution by heating it for 2 hrs at 550°C, removing no sulfur.



CONCLUSIONS

The following conclusions were drawn based on experimental data generated from the monolithic catalyst reactor system, and their interpretations. Each reaction experimental run proceeds after a blank experimental run, which is carried out in the absence of moisture and a monolithic catalyst.

Conversion of H₂S to elemental sulfur does not follow the Arrhenius' equation, although conversion of H₂S to elemental sulfur increases with increased reaction temperature over the temperature range of 120 -140°C. Conversion of H₂S into elemental sulfur and formation of COS decrease with increased temperature at which elemental sulfur is removed from the catalyst soaked with 1-w% Zn aqueous solution followed by heating it for 4 hours at 450°C.

Conversion of H₂S into elemental sulfur and formation of COS are constant up to 1,400-min aging of the 1-w% Zn-treated γ -alumina wash-coated catalyst. Thereafter, conversion of H₂S into elemental sulfur decreases with increased catalyst aging, while formation of COS increases with increased catalyst aging. However, conversion of H₂S into elemental sulfur decreases and formation of COS increases with increased aging of the other 1-w% Zn-treated catalyst, although elemental sulfur was removed from the catalyst by heating the catalyst with N₂ at either 140 or 200°C overnight.

Effects of washing the deactivated Zn-treated catalyst in NaOH aqueous solution overnight followed by heating it for 4 hrs at 900°C on conversion of H₂S into elemental sulfur are pronounced and long-lived, although elemental sulfur was not removed from the catalyst by heating it overnight. Effects of washing the deactivated γ -alumina wash-coated support itself in 0.4-M NaOH aqueous solution followed by heating it for 4 hrs at 900°C on conversion of H₂S into elemental sulfur also is long-lived.

Conversion of H₂S into elemental sulfur decreases drastically upon removing elemental sulfur from the catalyst treated with NaOH and Zn aqueous solutions. This observation may suggest that the elemental sulfur deposited on the catalyst play a catalytic role in removing H₂S from the catalyst.

Effects of soaking the catalyst with Zn and KOH aqueous solutions on conversion of H₂S seem to be good initially. However, effects of soaking the catalyst with Zn and KOH aqueous solutions on formation of COS seem to be short-lived by changing formation of COS from negative to positive. Effects of soaking the catalyst in KOH aqueous solution only on conversion of H₂S are good initially. However, favorable effects of soaking the catalyst in KOH aqueous solution on formation of COS seem to be short-lived. Conversion of H₂S into elemental sulfur is much higher with the catalyst soaked in Zn and KOH aqueous solutions than that in KOH aqueous solution only. Conversion of H₂S decreases and formation of COS increases with increased reaction duration with the catalyst treated with NaOH, KOH, and MgCl₂, although Elemental sulfur deposited on the catalyst is not removed throughout experiments.

Conversion of H₂S drastically decreases with increased reaction duration with removing a sulfur from the 2-w% Fe³⁺ treated catalyst with N₂ at 270°C. Conversion of H₂S drastically

decreases and becomes negative with increased reaction duration with removing elemental sulfur from the 2-w% Fe³⁺ treated catalyst with N₂ at 200°C. This fact may suggest that H₂S be produced rather than removed from the simulated coal gas. Formation of COS is very high with the catalyst soaked in 2-w% Fe³⁺ aqueous solution followed by heating it for 4 hrs at 550°C

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