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REGENERATIVE PROCESS FOR DESULFURIZATION OF HIGH TEMPERATURE COMBUSTION AND FUEL GASES

QUARTERLY PROGRESS REPORT NO. 4
JANUARY 1 - MARCH 31, 1977

PROCESS TECHNOLOGY DIVISION
DEPARTMENT OF APPLIED SCIENCE

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REGENERATIVE PROCESS FOR DESULFURIZATION OF HIGH TEMPERATURE COMBUSTION AND FUEL GASES

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Contributors:

A.S. Albanese	M-S. Shen
G. Farber	R. Smol
F.B. Kainz	M. Steinberg
J. Pruzansky	R.T. Yang

M. STEINBERG, Head
R.T. YANG, Project Leader

PROCESS TECHNOLOGY DIVISION

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DEPARTMENT OF APPLIED SCIENCE

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BROOKHAVEN NATIONAL LABORATORY
UPTON, NEW YORK 11973

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Abstract

Processes for regeneration of lime and lime-based sorbents to be used in fluidized-bed combustion (FBC) are being developed. Carbon, silica, and coal ash (which contains significant amounts of carbon and silica) are being investigated as the regeneration agents. Kiln-type regenerators are being considered for the apparent solid-solid reactions involved in these processes.

Introduction

The purpose of the Brookhaven program is to provide basic process chemistry information required for the development of processes for the utilization and regeneration of lime-based sorbents used in desulfurization of combustion and fuel gases for power production cycles.

Two basic processes for regeneration are currently under development. One is based on the reaction between CaSO_4 and carbon for the regeneration of CaO . Another is being designed for regeneration and recycling of the calcium silicates as sorbents, with lime and siliceous matters as the starting materials. The basic reactions involved in the latter process are the formation of silicates from CaSO_4 and SiO_2 in the regeneration and the sulfation of the silicates in the combustor.

The two basic processes can be ideally combined in a third system by utilizing the fly ash. Fly ash from the FB combustor contains significant amounts of carbon; about 5-40% from the ANL and the Exxon fluidized bed pilot combustors. By feeding fly ash and sulfated limestone to a kiln-type regenerator, calcium oxide and silicates are formed and are to be recycled to the combustor.

Kinetics and other relevant studies such as particle strength for fluidization and chemical analyses of the products for the three processes are being undertaken in parallel. TGA static systems as well as a micro-pilot system are being used for the kinetic studies. Process and cost analyses are also being made. These include material and energy balances and cost analysis with special attention to the regenerative processes being developed. Results of the studies will serve to guide future experimental work.

In the course of a continuing search for catalytic effects in these processes, we found that sodium chloride showed significant positive effect. However, materials, environmental and corrosion problems from the chlorine compounds are also being considered.

Experimental

In this report, the rates of regeneration and sulfation were obtained with TGA reactors. A Mettler TA-1, a DuPont 951 and a Cahn R100 were installed with new Tylan mass flowmeters for the measurements. The reactor systems and the experimental and calculation procedures have been described elsewhere.¹⁻⁴ Chlorine content in the off-gas was analyzed by scrubbing in a caustic solution and the solution was subsequently analyzed colorimetrically with a Technicon Auto Analyzer. Surface area was measured by a Micromeritics 2200 High Speed Surface Area Analyzer. Attrition was tested in a quartz tube fluidized with air for a certain period of time. A micro-pilot unit is under construction, which consists of a micro-rotary kiln as the regenerator (a screw feeder type reactor is also being considered) and a small (about 3-inch diameter) fluidized-bed combustor. Kinetics from this unit would provide a more realistic basis for designing the scale-up systems.

The sulfated limestones were either a 30% sulfated Greer limestone from a FBC at Argonne National Laboratory or the Greer stone which was calcined at 900°C in dry N₂ and subsequently sulfated at 900°C with a gas containing 5% SO₂, 10% O₂ in dry N₂. The calcination and sulfation were both carried out in static beds and the sulfation was 65% or 80% complete. Coal ash, silicates and carbon will be described in the respective sections. The grades of the gases were the same as those used previously.

Results and Discussion

A. Regeneration of CaO with carbon

The calcium sulfate is reduced to SO_2 by carbon:

which is a two-step reaction:

Reaction 3 has also been discussed by Hubble et al⁵ as a possible means for lime regeneration.

(1) Temperature Effect

It has been shown that reaction 2 is much faster than reaction 3 and that the amount of carbon is the controlling factor for determining the reaction product, i.e., CaO vs. CaS. The rate of reaction 3 controls the rate of regeneration of CaO. The temperature dependence is presented in Arrhenius fashion in Fig. 1. It is recalled that a surface layer on the CaSO_4 is first reduced rapidly by carbon via reaction 2. The reduced layer then reacts with the remaining inner CaSO_4 to form CaO via reaction 3. Two distinct slopes on the weight-time curves were obtained in the $\text{CaSO}_4 + 1/2 \text{ C}$ reaction. The second slope was used to calculate the rates in Fig. 1. The rates here were based on the area of reacting interface, assuming the sulfated Greer limestone particles were perfect spheres. The temperature dependence shown in Fig. 1 is, however, accurate regardless whether this assumption was made, because the same amount of the same materials were used at each temperature.

The activation energy of reaction 3 is 62.7 kcal/mole CaO which indicates a solid-phase diffusion and/or chemical reaction rate-limiting mechanism.

This overall temperature dependence also means that the rate of regeneration of CaO is increased by a factor of three per 50°C rise in temperature in this temperature range.

(2) Effect of NaCl on Regeneration

The effects are demonstrated in Figs. 2 and 3. Figure 2 shows that 3% NaCl (of CaSO_4 , by wt) catalyzes both reactions 2 and 3, at 900°C. Figure 3 shows that at 900°C, NaCl first catalyzes reaction 3 but very intriguingly, retards the reaction after about 35% regeneration. However, the results in Fig. 3 were with analytical reagent grade chemicals. As will be shown later, the retarding effect does not take place in the systems containing coal ash and limestone. Also in Fig. 3, the sizes were not specified. The samples were of A.R. grades powder. Figs. 4 and 5 show NaCl effect on regeneration at 850°C using the analytical reagent CaSO_4 and Drierite (99.6% CaSO_4) respectively.

(3) Effect of the Size of CaSO_4

In the regeneration scheme, the size of the sulfated stone has to be suitable for fluidized-bed operation while the size of carbon can be small. Figure 6 shows the integrated rates of the two stages (reactions 2 and 3) of the reactions between a partially sulfated Greer lime and coconut charcoal. The integrated rate was based on the total weight loss divided by the total time for each reaction. As shown in this figure, reaction 2 depends strongly on the size of the sulfated stone while reaction 3 has only a very slight dependence on the size. This is understandable because reaction 2 requires close contact between CaSO_4 and C whereas reaction 3 does not, and the finer sizes of CaSO_4 provide greater contacting areas.

B. Sulfation and Regeneration of Calcium Silicates

The sulfation rates for CaO and CaSiO₃ are compared in Figs. 7 to 11 as percent of completion for sulfation versus time (hours).

Figures 12 and 13 show that in all cases an increase in temperature increases the rate of sulfation. Also the extent of completion for calcined limestone CaO is higher in all cases, yet the initial chemical rates for CaO are in fact lower than CaSiO₃.

Steam is shown in Figures 14 and 15 to be a catalyst in the rate of sulfation for both CaO and CaSiO₃, as also found in the calculated rates for the initial chemical rates in Tables A and C.

For calculations of the initial slopes (linear regression program) utilizing a Texas Instrument computing calculator Model SR-60, the initial chemical rates of SO₃ uptake for both CaO and CaSiO₃ were calculated. The results are found in Table A.

From the results in Table A, the initial chemical rate for calcium silicates reactivity to SO₃ in flue gas conditions is greater in each case for temperatures 800°-950°C and also in the case of steam addition. This increase is substantial (15-25%) for the sulfation rate, based solely on mass and size for both CaO and CaSiO₃ systems.

In Table B, the results for surface area measurements for 16/20 mesh CaO and CaSiO₃ systems are given. The results are given as the average of two readings for each sample.

Based on the surface area measurements in Table B, the rates can thus be expressed as the amount of SO₃ uptake for the total surface area available for both CaO and CaSiO₃. The results in Table C for the rates are given as mole SO₃/cm² min. Here the difference in rate based on

available surface area is greatest. Calcium silicate sulfates at a rate of four times greater; still higher at higher temperatures.

C. Regeneration with coal ash containing unburnt carbon

This scheme represents the most practical and attractive process. Numerous experiments have been performed on this system, using partially sulfated Greer limestones from static beds and from Argonne's fluid bed, and coal ash containing carbon that we generated at Brookhaven using small fluidized tubes and the fly ash from Exxon's Miniplant. Argonne's flyash will also be used shortly.

(1) Rate of Regeneration

Figure 16 shows the rate of regeneration of CaO from a 30% sulfated Greer limestone from Argonne's FBC and a coal ash (Ill. No. 6) containing 7% carbon, at 1000°C. It is seen that more than 90% of the sulfated stone was regenerated within 20 minutes, and about 70% was regenerated in 7 min. On the other hand, using the 65% sulfated Greer limestone and the same ash under identical conditions, it took about 3 hours for 30% regeneration at 900°C. It appeared that the impurities in the FBC sample catalyzed the reaction greatly.

(2) Reactivity of Regenerated Stone

Figure 17 shows the sulfation rates of the first cycle and the second cycle after regeneration with coal ash. Preliminary results indicate that there is no tendency for the reactivity of the regenerated stone to decay. Work in progress are physical and chemical properties of the regenerated stone.

(3) NaCl Effect

Rates of regeneration with and without 3% NaCl are shown in Fig. 18. Sodium chloride does catalyze the regeneration; more so in the initial

stage of reaction 3. It does not retard the reaction up to about 60% CaO.

(4) Effect of the Size of Coal Ash

Figure 19 shows the effect of the size of ash on rates of reactions 2 and 3. Both reactions are affected strongly by the size. It is not yet understood why reaction 3 has a stronger dependence on the size. The effect of the carbon content in ash will be investigated.

(5) Reaction Product Analyses

Reactions were carried out between 850 and 1000°C. The amount of ash (carbon content known) was controlled according to the stoichiometry of reaction 1. After each reaction, the ash was sieved out and the stone was analyzed by x-ray diffraction.

The x-ray diffraction analyses to date show that CaO is the pre-dominant product. Some CaS was detected. A trace of CaSO_4 was also found. Some weak-intensity lines indicated the possibility of the existence of the calcium silicates. Our efforts now in this respect are to identify the silicates and to quantify them.

The x-ray results are consistent with the fact that the rates of reaction 1 are higher than the rates of the reaction $\text{CaSO}_4 + \text{SiO}_4 \rightarrow \text{CaO} \cdot \text{SiO}_2 + \text{SO}_2 + 1/2\text{O}_2$. However, at the steady state in a continuous recycling process, the amounts of the silicates would be much higher because for each particle, as it is being recycled, contents of silicates would increase with the number of cycle. This is due to the fact that the silicates stay in the structure once formed.

D. Catalytic Effect of Sulfation and Calcination

(1) NaCl Effect on Sulfation

With 3% NaCl mixed in analytic reagent CaO, sulfated with 0.25% SO₂, 5% O₂ and balance of N₂ at different temperatures are shown in Figs. 20-23 and with 3% NaCl mixed in Greer CaO shown in Fig. 24. The sulfation rate is increased by more than 100% below about 850°C and has an adverse effect above 900°C.

(2) Steam Effect on Sulfation

The comparison of sulfation with and without 5% steam are shown in Fig. 21 (analytical reagent CaO), and Fig. 25 (Greer CaO). The combined effects of 5% steam and 3% NaCl are also shown in the figures. Steam increases the sulfation rate, however, it is not clear why the combined effects of steam and NaCl are not additive.

(3) Fe₂O₃ Effect on Sulfation

Fe₂O₃ catalyzes sulfation. Figure 26 shows that 4% Fe₂O₃ (of CaO, by wt) catalyzes sulfation at 850°C. The size of Fe₂O₃ was not specified. Work is presently being done on the size and concentration effects of Fe₂O₃ on sulfation.

(4) NaCl Effect on Calcination

NaCl catalyzes the calcination of limestone which is shown in Fig. 27.

E. Materials Properties and Considerations

(1) Attrition Test.

The tests were designed for minute quantities of sample. The fluidizing material is a coarse sea sand. The sample which has a smaller size is sieved out after the test and its size analyzed. Table C shows the results for Greer limestone (starting material), 65% sulfated Greer limestone and first cycle regenerated stone. Preliminary results show

that the strength of the regenerated sample depends on the amount of CaSO_4 remaining. The residual CaSO_4 as well as other impurities seem to strengthen the sample.

(2) Surface Area

Table D shows the surface areas of several different materials. Before measuring the surface area, the materials were heated at 850°C for 2 hours in N_2 flow. In calcining the Greer CaCO_3 at 850°C , 3% NaCl decreases the surface area of the CaO. In sulfation, 3% NaCl mixed in the CaO also decreases the surface area. In regeneration (the decomposition of CaSO_4), 3% NaCl decreases the surface area of the CaSO_4 too. However, the calcination, sulfation and regeneration rates are increased with 3% NaCl addition. This rules out the proposition that the effect of NaCl increased the surface area and hence increased the rate. It is possible that the sodium ion serves as a fluxing material thereby decreases the surface areas.

(3) Mechanism and Fate of NaCl in Sulfation and Regeneration

The fate of NaCl in FBC is being studied under simulated combustion conditions in static beds. With 3% NaCl mixed in CaO, sulfated with 0.25% SO_2 , 5% O_2 , 5% steam and the balance of N_2 , the total chlorine was collected by bubbling the off-gas through NH_4OH or NaOH solution for a certain period of time. The chlorine was converted into chloride. The chloride is determined via formation of the ferric-thiocyanate complex. It reacts with undissociated mercuric thiocyanate to release an equivalent amount of thiocyanate ion. This immediately reacts with the ferric ion present to form the red-brown complex, which is measured at 480 m μ . Preliminary results show that high percentages of the chlorine in NaCl

were collected and that the higher the temperature, the higher percentage collected. More careful work is progressing in analyzing and quantifying the chlorine compounds under various conditions.

In the pilot-scale studies at PER, it has been indicated⁶ that no additional amount of HCl was detected in the FBC off-gas with NaCl in bed (the normal level being 40 ppm). In light of our observations, it is suggested that the additional chlorine compounds from the added NaCl may react with and deposit on the walls in FBC which are primarily metals and metal oxides.

E. Process Design and Evaluation

Two process flow diagrams were prepared based on the best available data on FBC's, one for a once through sorbent, carbon burn-off cell system (System I); the other, for a regenerative sorbent system based on BNL's carbon reduction of CaSO_4 process (System II). The feed to both systems was assumed to be Illinois No. 6 coal with a sulfur content of 3 weight percent and both systems were assumed to operate at atmospheric pressure.

Based on mass and energy balance calculations, it appears that the net energy output of System I (once through) is equal to that of System II (regenerative). However, the quantity of limestone feed required to satisfy the material balance of System I is appreciably greater than that required by System II. For a 200 MW(e) power plant operating at a cycle efficiency of 40%, these quantities are 18.752 tons/hr versus 1.312 tons/hr, respectively. At \$12/ton of limestone (including the cost of calcium sulfate disposal) this amounts to \$1,971,000/year for the once through system, and \$138,000/year for the regenerative system (assuming that total system attrition losses are equal to 7% of the

total calcium feed to the FBC at 2.5 moles Ca/mole S). Furthermore, it does not appear that the costs of the additional equipment items required by the regenerative system will offset this savings in operating costs. Thus, we anticipate that the regenerative system will be economically more attractive than the once through system. A more definitive economic analysis will be made during the next several months which will include an analysis of means of converting the SO_2 contained in the regenerator gaseous effluent to sulfuric acid and to elemental sulfur.

From an operating standpoint, the regenerative system also appears more attractive than the once through system. Some of the advantages are as follows:

- 1) Limestone feed to the FBC (makeup in the case of the regenerative system) would not have to be controlled as carefully (in proportion to coal feed) as in the once through system because most of the calcium sorbent is recycled at an essentially constant rate. Maintaining an acceptable SO_2 emission level would thus be facilitated.
- 2) The regenerative system is not as cost sensitive to calcium to sulfur ratio as is the once through system.
- 3) For the same calcium to sulfur ratio and assuming that 80% of the feed CaCO_3 is calcined to CaO in the FBC, a greater portion of the calcium would be present as CaO (less as CaCO_3) which is the reaction with SO_2 . Reductions in Ca/S may be realizable.

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Table A

Rates of Sulfation of Greer Limestone and
Calcium Silicate in Simulated Flue Gas Conditions

Temp., °C	(0.25% SO ₂ , 5% O ₂ , 94.75% N ₂) (%/min)	
	CaO	CaSiO ₃
800	0.25 ± 0.02	0.30 ± 0.02
850	0.25 ± 0.02	0.31 ± 0.02
900	0.26 ± 0.03	0.32 ± 0.01
900	0.27 ± 0.01 ^a	0.35 ± 0.03 ^b
950	0.27 ± 0.01	0.36 ± 0.02

^a4.5 percent steam

^b3.5 percent steam

Table B

Surface Area Measurements (m²/g)
of Calcined Greer Limestone and Calcium Silicate

Temp., °C	CaO	CaSiO ₃
800	2.68 ± 0.01	0.49 ± 0.01
850	2.56 ± 0.06	0.31 ± 0.02
900	2.18 ± 0.04	0.29 ± 0.02
950	1.36 ± 0.05	0.27 ± 0.06

Table C

Rates of Sulfation of Greer Limestone and
Calcium Silicate in Flue Gas Conditions
(0.25% SO₂, 5% O₂, 94.75% N₂) (mole/cm² min.)

Temp., °C	CaO	CaSiO ₃
800	1.2 ± 0.1 × 10 ⁻⁹	4.8 ± 0.4 × 10 ⁻⁹
850	1.2 ± 0.1	8.7 ± 0.8
900	1.5 ± 0.1	9 ± 1
900	1.6 ± 0.1 ^a	9.9 ^b
950	2.5 ± 0.2	10* ± 2

^a4.5 percent steam

^b3.5 percent steam

* error large due to large error for small surface area measurement

Table D

Attrition Test

One gram sample (16/20 mesh) and 200 g sea sand (4/8 mesh) in a 3 in. diameter quartz tube fluidized with 18.5 cu ft/min air flow at room temperature for 18 hours. The air distributor was a fritted quartz plate.

Sample/size (mesh)	16/20	20/24	> 24	Blown away as dust
Greer limestone	4.5%	77.1%	0.2%	18.2%
Greer CaSO ₄ (65%)	64.4	19.7	1.7	14.2
1st cycle regenerated Greer limestone	43	10.2	1.8	45

Table E
Surface Area

Material (16/20 mesh)	Treatment	Surface Area (m ² /g)
Greer CaO	Calcined at 850°C	2.31
Greer CaO	Calcined with 3% NaCl at 850°C; Heated at 850°C 2 hr in 500 cc/min N ₂	0.69
Greer CaO + 3% NaCl	Heated at 850°C 2 hrs in 500 cc/min N ₂	1.50
Drierite CaSO ₄	"	1.39
Drierite CaSO ₄ + 3% NaCl	"	0.00
Greer 65% CaSO ₄	"	0.31
Greer 65% CaSO ₄ + 3% NaCl	"	0.11

Figure 1. Rate of the reaction $3\text{CaSO}_4 + \text{CaS} \rightarrow 4\text{CaO} + 4\text{SO}_2$. 80% sulfated Greer lime (16/20 mesh) and coconut charcoal (200/250 mesh) were the starting reactants.

Figure 2. Rate of regeneration $\text{CaSO}_4 + 1/2\text{C} \rightarrow \text{CaO} + 1/2\text{CO}_2 + \text{SO}_2$ at 900°C , with 100 mg 65% sulfated Greer lime (16/20 mesh) and 3.55 mg coconut charcoal (200/250 mesh).

Figure 3. Rate of reaction $3\text{CaSO}_4 + \text{CaS} \rightarrow 4\text{SO}_2$ at 900°C , with powdered reagent grade samples.

Figure 4. Rate of regeneration of 850°C, with 100 mg powdered reagent CaSO₄ and 4.4 mg coconut charcoal (200/250 mesh).

Figure 5. Rate of regeneration at 850°C, with 100 mg Drierite (99.6% CaSO₄, 16/20 mesh) and 4.4 mg coconut charcoal (200/250 mesh).

Figure 6. Effect of size of CaSO_4 on regeneration at 900°C . 100 mg sulfated Greer lime and 3.55 mg coconut charcoal (200/250 mesh). I: $\text{CaSO}_4 + 2\text{C} \rightarrow \text{CaS} + 2\text{CO}_2$; II: $\text{CaS} + 3\text{CaSO}_4 \rightarrow 4\text{CaO} + 4\text{SO}_2$.

Figure 7. Comparison of rate of sulfation at 800°C . between 16/20 mesh Greer CaO (calcined at 800°C) and 16/20 mesh reagent grade (99.75%) CaSiO_3 in 0.25% SO_2 , 5% O_2 , and a balance of N_2 with a total flow of 925 cm^3/min at 1 atmosphere (STP).

Figure 8. Comparison of rate of sulfation at 850°C between 16/20 mesh Greer CaO (calcined at 850°C) and 16/20 mesh reagent grade (99.75%) CaSiO_3 , in 0.25% SO_2 , 5% O_2 , and a balance of N_2 with a total flow of 925 cm^3/min at 1 atmosphere (STP).

Figure 9. Comparison of rate of sulfation at 900°C between 16/20 mesh Greer CaO (calcined at 900°C) and 16/20 mesh reagent grade (99.75%) CaSiO_3 in 0.25% SO_2 , 5% O_2 , and a balance of N_2 with a total flow of 925 cm^3/min at 1 atmosphere (STP).

Figure 10. Comparison of rate of sulfation at 900°C between 16/20 mesh Greer CaO (calcined at 900°C) and 16/20 mesh reagent grade (99.75%) CaSiO_3 in 0.25% SO_2 , 5% O_2 and balance of N_2 with $(\text{N}_2 + \text{O}_2)$ carrying a steam calcination of 3.5% for CaSiO_3 and 4.5% for CaO. Total flow was 925 cm^3/min at 1 atmosphere (STP).

Figure 11. Comparison of rate of sulfation at 950°C between 16/20 mesh Greer CaO (calcined at 950°C) and 16/20 mesh reagent grade (99.75%) CaSiO_3 in 0.25% SO_2 , 5% O_2 and a balance of N_2 for a total flow of 925 cm^3/min at 1 atmosphere (STP).

Figure 12. Comparison of rates of sulfation of 16/20 mesh reagent grade (99.75%) CaSiO_3 at temperatures of 800°C, 850°C, 900°C, and 950°C in 0.25% SO_2 and 5% O_2 and a balance of N_2 in a total flow of 925 cm^3/min at 1 atmosphere (STP).

Figure 13. Comparison of rates of sulfation of 16/20 mesh Greer CaO (calcined temperatures 800-950°C) at temperatures of 800°C, 850°C, 900°C, and 950°C in 0.25% SO_2 , 5% O_2 and a balance of N_2 for a total flow of 925 cm^3/min at 1 atmosphere (STP).

Figure 14. Comparison of rate of sulfation between 16/20 mesh reagent grade (99.75%) CaSiO_3 with 3.5% steam and without steam at 900°C in 0.25% SO_2 , 5% O_2 and a balance flow of N_2 for a total flow of 925 cm^3/min at 1 atmosphere (STP) (steam carried by O_2 and N_2 flow).

Figure 15. Comparison rate of sulfation between 16/20 mesh Greer CaO (calcined at 900°C) with 4.5% steam and without steam at 900°C in 0.25% SO_2 , 5% O_2 and a balance of N_2 for a total flow of 925 cm^3/min at 1 atmosphere (STP) (steam carried by O_2 and N_2 flow).

Figure 16. Rate of regeneration with coal ash at 1000°C. 100 mg 30% sulfated Greer stone from Argonne FBC (Sample J-11202) and 18.9 mg Illinois No. 6 coal ash with 7% carbon (200/270 mesh).

Figure 17. Sulfation rates of 95 mg Greer CaO at 850°C (0.25% SO₂ and 5% O₂) between 1st cycle and the 2nd cycle after regeneration at 950°C with 30.4 mg Illinois No. 6 coal ash (7% carbon, 200/270 mesh).

Figure 18. Rate of regeneration with coal ash at 900°C. 100 mg 65% sulfated (in TGA) Greer stone (16/20 mesh) and 41 mg Illinois No. 6 coal ash with 7% carbon (200/270 mesh).

Figure 19. Effect of size of ash on regeneration at 900°C. 100 mg 65% sulfated Greer lime (16/20 mesh) and 50.7 mg Illinois No. 6 coal ash with 7% carbon. I: $\text{CaSO}_4 + 2\text{C} \rightarrow \text{CaS} + 2\text{CO}_2$; II: $\text{CaS} + 3\text{CaSO}_4 \rightarrow 4\text{CaO} + 4\text{SO}_2$.

Figure 20. Sulfation rate at 800°C, with 20 mg powdered reagent CaO, 0.25% SO_2 and 5% O_2 .

Figure 21. Sulfation rate of powdered reagent CaO at 850°C, with NaCl and steam.

Figure 22. Sulfation rate of powdered reagent CaO at 900°C.

Figure 23. Sulfation rate of powdered reagent CaO at 950°C.

Figure 24. Sulfation rate of Greer CaO (16/20 mesh) at 850°C.

Figure 25. Sulfation rates of Greer Cao at 850°C, with NaCl and steam.

Figure 26. Sulfation rate at 900°C, with powdered reagent grade samples.

Figure 27. Calcination rate of Greer limestone at 850°C.

Distribution: A. Macek, FE/ERDA (25)
W. E. Winsche, BNL
J. M. Hendrie, BNL
B. Manowitz, BNL
M. Steinberg, BNL
R. T. Yang, BNL (5)
N. Abuaf, BNL
A. S. Albanese, BNL
G. Farber, BNL
F. B. Kainz, BNL
C. R. Krishna, BNL
M-S. Shen, BNL
R. Smol, BNL
D. Schweller, ERDA (BNL)
D. B. Henschel, EPA
J. W. Jones, EPA
F. Princiotta, EPA
H. B. Levine, Jaycor