

# MASTER

THE USE OF OIL SHALE FOR SO<sub>2</sub> EMISSION CONTROL IN  
ATMOSPHERIC-PRESSURE FLUIDIZED-BED COAL COMBUSTORS

by

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# The Use of Oil Shale for SO<sub>2</sub> Emission Control in Atmospheric-Pressure Fluidized-Bed Coal Combustors

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## Abstract

Oil shale-SO<sub>2</sub> reactivity, determined with a thermogravimetric analyzer, was used to estimate the quantity of oil shale required to reduce SO<sub>2</sub> concentration in the effluent gas sufficiently to meet the SO<sub>2</sub> emission standard in atmospheric-pressure fluidized-bed coal combustion (AFBC). It was calculated that the oil shale could reduce the SO<sub>2</sub> concentration in the effluent gas from FBC units below the SO<sub>2</sub> emission limit. In evaluating virgin oil shale and spent oil shale for SO<sub>2</sub> emission control, we compared them with (1) Germany Valley limestone, (2) Greer limestone, and (3) Tymochtee dolomite. The results indicate that, due to the low calcium content of the shale, less dolomite or limestone than oil shale, may be required to meet the SO<sub>2</sub> emission standard.

The attrition rate of Green River oil shale was found to be similar to attrition rates of limestones and dolomites.

## Introduction

Atmospheric-pressure fluidized-bed combustion (FBC) is a new method being considered for producing power from high-sulfur coal while meeting EPA SO<sub>2</sub> emission standards. In this process, coal is burned at 850-950°C in a bed consisting of fluidized solid particles. These particles have two functions: (1) to increase the heat transfer rate to boiler tubes

immersed in the bed, and (2) to reduce  $\text{SO}_2$  emissions from the boiler by reacting with the  $\text{SO}_2$ . Limestones or dolomites are the usual bed materials of choice due to (1) their high calcium content and thus usually high reactivity with  $\text{SO}_2$ , (2) their low cost, and (3) their wide availability.

An oil shale was investigated as a possible alternative bed material to limestones in fluidized-bed coal combustors. Virgin Green River oil shales tested contained approximately 30 wt %  $\text{CaCO}_3$ ; spent Green River oil shale (kerogen removed) contained about 35 wt %  $\text{CaCO}_3$ . These materials and other shales may be acceptable  $\text{SO}_2$  sorbents in FBC units.

Oil shale is plentiful. The oil shale used here is from the Green River formation located in northwest Colorado, reported to contain total reserves equivalent to 644 billion  $\text{m}^3$  of oil (4050 billion barrels). Of this total, the equivalent of 99 million  $\text{m}^3$  oil (620 billion barrels) at concentrations ranging from 0.1 to 0.27  $\text{m}^3/\text{t}$  (25 to 65 gal/ton), is considered to be economically recoverable (Hendrickson, 1975). The processing of this vast energy resource by retorting would yield a substantial quantity of spent oil shale.

An experimental study of Green River oil shale was initiated to determine the quantity of oil shale necessary to reduce the  $\text{SO}_2$  concentration in the effluent gas sufficiently to meet the  $\text{SO}_2$  emission standard. In this work,  $\text{SO}_2$  removal by virgin oil shale and spent oil shale also was compared with two limestones and one dolomite.

The attrition rate of the oil shale was determined. Attrition rate had been found to be important in previous work showing that some limestones have high attrition rates, making it difficult to maintain a fluidized bed of solid particles.

## Materials

The compositions of the virgin and spent oil shales studied are given in Table I. Spent oil shale was prepared by heating virgin oil shale at 400°C in air for 3 h to remove the organic material (kerogen). The chemical compositions of Germany Valley limestone, Greer limestone, and Tymochtee dolomite also are given in Table I.

## Experimental

A thermogravimetric analyzer (TGA) was used for these kinetic studies. The TGA apparatus has been described in detail in a previous publication (Snyder *et al.*, 1977a). A 0.3% SO<sub>2</sub> - 5% O<sub>2</sub> - 20% CO<sub>2</sub> in N<sub>2</sub> synthetic combustion gas was used for all reactions. The oil shale-SO<sub>2</sub> reactions were performed at temperatures of 700 to 1050°C. The weight change of a 150-mg sample which was continuously recorded, was used as a measure of the conversion of CaO to CaSO<sub>4</sub> within the shale. X-ray diffraction and wet chemical analyses of the samples at the beginning and the end of each TGA run were utilized to help determine and quantify chemical changes which occurred.

Attrition tests were performed in a 5.08-cm-ID 61-cm-long quartz vessel with a fluidized-bed height of 6.4 cm (L/D = 1.25). Additional freeboard height was provided by a 7.62-cm-ID 46-cm-long disengaging section above the fluidized bed. This disengaging section eliminated elutriation of the starting bed material (-14 +30 mesh material). All overhead material was smaller than 70 mesh particle size and was produced by attrition. A glass frit was used as the grid plate. The fluidized bed was heated by an external electrical furnace. The attrition tests were performed for 2 h at 870°C, using a fluidizing gas consisting of 0.3%

$\text{SO}_2$ -5%  $\text{O}_2$  and the balance  $\text{N}_2$ . The superficial gas velocity for all tests was 1.45 m/s.

### Sulfation Results

Spent oil shale was precalcined at  $900^\circ\text{C}$  in 29%  $\text{CO}_2$ - $\text{N}_2$  and then was reacted with  $\text{SO}_2$  and  $\text{O}_2$  for 3 h. In Fig. 1, the conversion of  $\text{CaO}$  to  $\text{CaSO}_4$  in spent calcined oil shale at various temperatures ( $700$ - $1050^\circ\text{C}$ ) is given as a function of time. The reaction rates obtained in experiments performed at  $700$ - $900^\circ\text{C}$  were the same during the first hour. The reaction rate, for all experiments except those at  $700$  and  $750^\circ\text{C}$  differed significantly with temperature during the remaining two hours. The reaction rate was much lower at  $1000$  and  $1050^\circ\text{C}$  than at the lower temperatures. This is due to the competing reaction of  $\text{CaSO}_4$  with  $\text{SiO}_2$ , releasing  $\text{SO}_2$  and forming the products  $(\text{Ca}, \text{Fe}, \text{Mg})\text{SiO}_3$  and  $\text{Ca}(\text{Fe}, \text{Mg})\text{SiO}_2$ .

Table II lists the chemical compounds formed when the oil shale was subjected to various conditions. Oil shale and spent oil shale contain mainly dolomite, calcium carbonate, silica, and sodium aluminum silicates. The shale sulfated at  $750^\circ\text{C}$  contained  $\text{CaSO}_4$ , the double salt  $3\text{MgSO}_4 \cdot \text{CaSO}_4$ , silica, and the silicates. However, when the shale was sulfated at  $900$ ,  $1000$ , and  $1100^\circ\text{C}$ , the products include  $\text{CaSO}_4$  and  $\text{Ca}(\text{Fe}, \text{Mg})$  silicates, with the  $\text{CaSO}_4$  concentration decreasing and the calcium silicates concentrations increasing with temperature. The formation of calcium silicates instead of  $\text{CaSO}_4$  in oil shales at high temperatures is similar to the results obtained by Morgantown Energy Research Center for partially sulfated coal ash (Mazza, 1978).

At the lower temperatures,  $700$  to  $800^\circ\text{C}$ , the weight gain obtained from the TGA was larger than would be obtained if 100% of the  $\text{CaO}$  converted to

$\text{CaSO}_4$  (Fig. 1). Results from X-ray diffraction and wet chemical analyses indicated that at these temperatures,  $3\text{MgSO}_4 \cdot \text{CaSO}_4$  forms, as mentioned above. This double salt was previously found to form in oil shales (Fuchs *et al.* 1977). Fuchs found that either low temperature (lower than  $800^\circ\text{C}$ ) or high  $\text{SO}_2$  concentration in the gas phase produced the double salt product. This  $3\text{MgSO}_4 \cdot \text{CaSO}_4$  product forms more readily in oil shales than in limestones.

Spent oil shale was simultaneously calcined and sulfated at  $900^\circ\text{C}$ , using a 0.3%  $\text{SO}_2$ -20%  $\text{CO}_2$ -5%  $\text{O}_2$  balance  $\text{N}_2$  synthetic combustion gas. The reaction rate was the same as for the precalcined material. Also, virgin oil shale was sulfated at these conditions. Conversion of calcium to  $\text{CaSO}_4$  for the virgin oil shale was slightly lower, 73%, than for the spent oil shale, 86%. Both reactions were essentially complete in 1 h.

Figure 2 compares the reaction rate of spent oil shale with those of Tymochtee dolomite, Greer limestone, and Germany Valley limestone (Snyder *et al.*, 1977b). During the first hours, the percent of calcium changed to  $\text{CaSO}_4$  for the oil shale is higher than for Tymochtee dolomite (which is a highly reactive dolomite). Nevertheless, by the end of the 3-h run, 98% of the  $\text{CaO}$  in the Tymochtee was utilized to capture  $\text{SO}_2$ , compared with 83.5% for the spent oil shale. The reaction rates of Greer limestone and Germany Valley limestone are much lower than those of spent shale and Tymochtee dolomite.

#### Prediction of $\text{SO}_2$ Retention for Oil Shales

The reactivities of oil shale with  $\text{SO}_2$  determined on the TGA were used to predict pilot plant calcium utilization in the sorbent and  $\text{SO}_2$  retention in a FBC.

The TGA experimental data obtained at  $800^\circ\text{C}$  and below was not used because  $\text{MgSO}_4$  forms a double salt with  $\text{CaSO}_4$  at these temperatures. The

formation of  $MgSO_4$  may be undesirable due to its high solubility in  $H_2O$  making for a possible waste disposal problem. The experimental kinetic data at  $900^\circ C$  was used to estimate the quantity of oil shale necessary to meet the  $SO_2$  emission standard of  $1.2 \text{ lb } SO_2 \text{ emitted}/10^6 \text{ Btu released}$  in a combustor.

The  $SO_2$  reactivity curves (Fig. 2) are not in a useful form but must be converted to  $SO_2$  retention vs Ca/S ratio curves for prediction of the quantity of calcareous material necessary per unit of coal to meet the  $SO_2$  emission standard. Sulfur dioxide retention is the percentage of the  $SO_2$  that reacts with the bed material and thus is retained in the bed. The Ca/S ratio is the ratio of the moles of calcium in the sorbent feed stream to the total moles of burned sulfur. In making this conversion, a fluid-bed desulfurization equation was used (Kearins *et al.*, 1975).

$$U = \frac{1}{Ca/S} \left[ 1 - \frac{V}{kH\epsilon} \left( 1 - e^{-\frac{kH\epsilon}{V}} \right) \right] \quad (1)$$

This fluid-bed desulfurization equation gives the calcium utilization,  $U$ , as a function of the "average" reaction rate constant of the particles in the bed (provided the superficial gas velocity and bed height are known). Thus in order to determine  $U$ , the "average" rate constant,  $k$ , must be obtained, using the kinetic information shown in Fig. 1. (See Keairns *et al.*, 1975 for calculation details). The predicted  $SO_2$  retention for oil shale are shown in Fig. 3 for a fluidized bed operated at  $3.9 \text{ m/s}$  with a bed height of  $1.1 \text{ m}$ .

Curves 1 and 2 in Fig. 3 represents the projected performance of spent oil shale in capturing  $SO_2$  in a FBC at  $800$  and  $900^\circ C$ , respectively and at the specified conditions of bed height and gas velocity. Curve 3 in Fig. 3 represents the projected performance obtainable using virgin oil shale at

900°C. The spent shale requires a lower Ca/S ratio than does the virgin oil shale due to its higher shale-SO<sub>2</sub> reactivity (Fig. 1).

#### Evaluation of Oil Shale Sorbent for AFBC Sulfur-Removal Systems

The results in Fig. 3 were used to estimate the number of kilograms of oil shale necessary per kilogram of coal to meet the SO<sub>2</sub> emission standard and are compared with previous limestone results. The analysis was performed for 3% and 4.3% sulfur coals both having a 28,319 kJ/kg (12,183 Btu/lb) heating value. The spent oil shale contained 33.5 wt % CaCO<sub>3</sub> and 0.66 wt % sulfur. The SO<sub>2</sub> emission standard allows only 0.73 kg of sulfur to be emitted per 100 kg of such a coal.

For a coal containing 3% sulfur, this emission standard requires that 75.6% of the sulfur from the coal be retained by the bed material, which could be accomplished at a Ca/S ratio of only 1.6 at 900°C (see Fig. 3 Curve 2). However, the spent oil shale contains 0.66 wt % S. This sulfur is introduced into the boiler in addition to the sulfur in the coal. Approximately 78% of the sulfur in the shale is expected to convert to SO<sub>2</sub>, based on wet chemical analysis of the initial and sulfated shale. To meet the SO<sub>2</sub> emission standard of no more than 0.73 kg of sulfur being emitted per 100 kg of coal, the Ca/S ratio must be increased to 1.9 and 78.4% of the total sulfur fed to the boiler must be removed. This requires that 58 kg of spent shale, which contains 0.37 kg of sulfur (of which 0.29 kg converts to SO<sub>2</sub>), be fed to the combustor for each 100 kg of coal containing 3% S and 28.319 kJ/kg. These results are shown in Table III below.

If virgin oil shale were used as the sorbent, the introduction of each 100 kilogram of oil shale would introduce 0.89 kg of sulfur, of which 0.73 kg would convert to SO<sub>2</sub>. This oil shale would also add approximately 7020 kJ/kg (3020 Btu/lb), helping to offset the sulfur input from the shale. A Ca/S

ratio of 3.1 would be required to meet the  $\text{SO}_2$  emission standard, and thus approximately 1.4 kg of virgin oil shale/kg of coal would be necessary.

For a coal containing 4.3% sulfur and having the same heating value of 28,319 kJ/kg, it is estimated that spent oil shale would not remove sufficient  $\text{SO}_2$  to meet the emission standard regardless of the quantity used. This result assumes that a large fraction of the sulfur in the shale is released. The higher sulfur content of the coal (4.3 vs 3%) requires that a greater percentage of the  $\text{SO}_2$  be retained by the shale. If the shale contained no sulfur, 83%  $\text{SO}_2$  retention would be necessary, requiring a Ca/S ratio of 3 or 1.3 kg of shale/kg of coal. However, laboratory results suggest that 78% of the sulfur in the shale should be released, requiring a higher percent  $\text{SO}_2$  retention and thus a higher Ca/S ratio in the combustor. Increasing the Ca/S ratio above 3 changes the  $\text{SO}_2$  retention only slightly (Fig. 3). Therefore, the introduction of larger quantities of shale, which would add more sulfur to the boiler would be detrimental. If the sulfur in the shale is not released in a FBC contrary to what was found in the laboratory, then the projection of 1.3 kg of shale/kg of coal may be a reasonable estimate of shale requirements.

If virgin oil shale is used with a coal containing 4.3% sulfur, a Ca/S ratio of 4.3 would be required to meet the  $\text{SO}_2$  standard. This would require feeding to the combustor 3.3 kg of oil shale with a heating value of 23,550 kJ (10,131 Btu) and containing 0.29 kg S (of which 0.24 kg S would convert to  $\text{SO}_2$ ) for each kg of 4.3% S coal with a heating value of 28,319 kJ/kg.

The estimated oil shale requirements for a 3% and 4.3% S coal in a fluidized bed operated at 3.8 m/s with a bed height of 0.83 m are compared with requirements of Tymochtee dolomite, Greer limestone, and Germany Valley limestone (Snyder *et al.*, 1977b) in Table III. The Ca/S ratio for the

oil shale is similar to that of Greer limestone, a reactive stone used by Pope, Evans, and Robbins at their Rivesville FBC pilot plant. However, since the oil shale has a low  $\text{CaCO}_3$  content in comparison to the limestones and dolomites, the shale requirements are projected to be considerably larger than for the other stones.

It should be noted that these estimates are only for atmospheric FBCs operated at a high superficial gas velocity, not the pressurized FBCs. Decreasing the velocity and/or increasing the boiler pressure should decrease shale requirements substantially. Also, if Western low-sulfur coal (1-2% sulfur) is used in a FBC, the shale requirement would be reduced by a factor of approximately 4.

#### Evaluation of Oil Shale Use in a FBC-CBC Plant

For an FBC system that employs a carbon burnup cell (CBC),  $\text{CaSO}_4$  in the partially sulfated oil shale decomposes at the high operating temperature of a CBC (1000-1100°C) due to the reaction of  $\text{CaSO}_4$  with  $\text{SiO}_2$  to release  $\text{SO}_2$ , as discussed above. At 1100°C, 50% of the  $\text{CaSO}_4$  in a previously sulfated oil shale was converted to  $\text{CaO}$  and  $\text{SO}_2$  in only 10 min. If oil shale is used in a FBC-CBC system, the  $\text{SO}_2$  in elutriated partially sulfated oil shale might be released in the CBC. Thus, more  $\text{SO}_2$  would have to be retained in the combustor. It is estimated that  $\text{SO}_2$  retention in the FBC would have to be increased to 95% to meet the  $\text{SO}_2$  emission standard for 4.3% sulfur coal assuming that only 5% of the bed material elutriates from the bed. The results of this evaluation indicate that use of oil shales in a FBC-CBC system should not be considered.

#### Attrition Results

It was speculated that due to the high silica content of oil shales, they would be considerably more attrition-resistant than are limestones

or dolomites. Therefore, the attrition tendencies as bed materials of virgin Green River oil shale, Tymochtee dolomite, Greer limestone, and Germany Valley limestone were determined. In the limestone and dolomite tests, simultaneous calcination and sulfation occurred. From weight changes and chemical analyses of original material, final overhead, and final bed material, the percentage of original material that remained in the bed was determined. The amount of attrition in 2 h was the percentage of original material collected overhead. In the virgin oil shale test, simultaneous kerogen combustion, calcination, and sulfation occurred. Again, chemical analyses and weight-change information were used to determine the percentage of original material collected overhead.

Of the original oil shale, 22 wt % was collected overhead. The attrition results for Tymochtee dolomite, Greer limestone, and Germany Valley limestone were 3%, 11%, and 38% respectively. These results suggest that the attrition rate of oil shale is not unlike that of limestones and dolomites.

### Conclusions

Laboratory analyses suggest that the calcium in oil shales has a high reactivity with  $\text{SO}_2$  and can be used in fluidized-bed coal combustors to reduce  $\text{SO}_2$  emissions. It is predicted that more oil shale than limestone or dolomite would be required to meet the  $\text{SO}_2$  emission standard since the calcium content of shales is relatively low. Also, the Green River shale contains approximately 1% sulfur, which may be released as  $\text{SO}_2$  in a FBC. The use of shales may be desirable if the FBC is operated at low superficial gas velocities (less than 3.2 m/s) or with low-sulfur coals (containing less than 3% sulfur). The oil shales should not be used in a FBC-CBC unless the shale elutriation rate is minimal, since at the temperature (1000-1100°C) which a CBC operates, the  $\text{CaSO}_4$  and the silicates in the elutriated shale react to release  $\text{SO}_2$ .

The geographic location of shale is a consideration. It may be desirable to use Western shale in FBC units in the Western United States in order to minimize transportation costs.

The attrition rate of Green River oil shale was similar to that of limestones and a dolomite.

Only one oil shale, Green River oil shale, was used in this evaluation. Since the  $\text{SO}_2$  reactivity and attrition rates of limestones vary widely, a large variation is also expected for oil shales. Thus these results are not necessarily applicable to all oil shales. The Green River oil shale was not tested in an experimental FBC in which performance may differ from the results reported. Since all oil shales contain much less calcium than limestone, further investigations were not considered.

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#### Nomenclature

Ca/S = calcium to sulfur mole ratio

K = average particle reaction rate constant,  $\text{s}^{-1}$

U = calcium utilization, fraction

V = superficial gas velocity, m/s

$\epsilon$  = bed voidage, assumed to be 0.5

H = fluidized-bed height, m

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Table I. Concentrations (in wt. %) of Major Constituents of Calcareous Stones

	CaCO <sub>3</sub>	MgCO <sub>3</sub>	Fe <sub>2</sub> O <sub>3</sub>	Al <sub>2</sub> O <sub>3</sub>	SiO <sub>2</sub>	Na <sub>2</sub> O	K <sub>2</sub> O	S
Green River Virgin Oil Shale	27.7	13.8	2.60	4.14	30.1	2.19	1.21	0.89
Green River Spent Oil Shale	33.5	16.7	3.14	5.0	36.4	2.64	1.46	0.66
Tymochtee	51.8	43.3	0.41	1.46	3.61	0.07	--	--
Greer	80.4	3.50	1.24	3.18	10.34	2.23	--	--
Germany Valley	97.8	0.6	0.1	1.8	0.2	0.25	--	--

**Table II. X-Ray Diffraction Analyses of Virgin, Spent, Calcined, and Sulfated Green River Oil Shale**

Sample History	Constituents Identified by X-Ray
Virgin Oil Shale	Major: $\text{CaMg}(\text{CO}_3)_2$ , $\text{NaAlSi}_3\text{O}_8$ Minor: $\text{CaCO}_3$ , $\alpha\text{-SiO}_2$
Spent Oil Shale (heated to 400°C, 3 h)	Major: $\text{CaMg}(\text{CO}_3)_2$ , $\alpha\text{-SiO}_2$ , $\text{Na}_2\text{AlSiO}_3\text{O}_8$ Minor: $\text{CaCO}_3$ , $\text{NaCaAlSi}_3\text{O}_8$
Precalcined at 900°C	Major: $\text{CaO}$ , $\text{MgO}$ , $\alpha\text{-SiO}_2$ Minor: $\text{NaAlSi}_3\text{O}_8$ , $\text{Ca}_2\text{MgSi}_2\text{O}_7$
Precalcined, then sulfated at 750°C	Major: $\text{CaSO}_4$ Minor: $\text{NaAlSi}_3\text{O}_8$ , $\alpha\text{-SiO}_2$ , $\text{CaSO}_4 \cdot 3\text{MgSO}_4$
Precalcined, then sulfated at 900°C (Same results as when simultaneously calcined and sulfated at 900°C)	Major: $\text{CaSO}_4$ , $\text{NaAlSi}_3\text{O}_8$ Minor: $\text{Fe}_3\text{O}_4$ , $\alpha\text{-SiO}_2$ , $\text{Ca}(\text{Fe},\text{Mg})\text{Si}_2\text{O}_6$
Precalcined, then sulfated at 1000°C (Same results as when simultaneously calcined and sulfated at 1000°C)	Major: $(\text{Ca Fe Mg})\text{SiO}_3$ , or $\text{Ca}(\text{Fe}, \text{Mg})\text{Si}_2\text{O}_6$ , $\text{CaSO}_4$ , $\text{NaAlSi}_3\text{O}_8$ Minor: $\alpha\text{-SiO}_2$
Precalcined, then sulfated at 1100°C (Same results as when simultaneously calcined and sulfated at 1100°C)	Major: $\text{Ca}_2\text{MgSi}_2\text{O}_2$ , $\text{Ca}_2\text{MgSi}_2\text{O}_7$

**Table III.** Required Quantities of Green River Oil Shale, Green Valley Limestone, Greer Limestone, and Tymochtee Dolomite to Meet SO<sub>2</sub> Emission Standard<sup>a</sup>

Calcium Based Stone	Ca/S Ratio Required To Meet EPA Standards		kg of Stone/kg of Coal to meet EPA SO <sub>2</sub> Standard	
	3% S Coal	4.3% S Coal	3% S Coal	4.3 S Coal
Spent Oil Shale <sup>b</sup>	1.9	not possible	0.58	not possible
Virgin Oil Shale <sup>c</sup>	3.1	4.3	1.4	3.3
Germany Valley Limestone	3.8	7.5	0.36	1.0
Greer Limestone	3.1	3.8	0.36	0.6
Tymochtee Dolomite	1.0	1.5	0.18	0.4

<sup>a</sup>Basis: 28,319 kJ/kg coal; FBC operated at 3.2 m/s gas velocity and 0.91-m bed depth.

<sup>b</sup>Spent shale contains 0.66% S.

<sup>c</sup>Virgin oil shale has a heating value of 7020 kJ/kg and contains 0.9% sulfur.

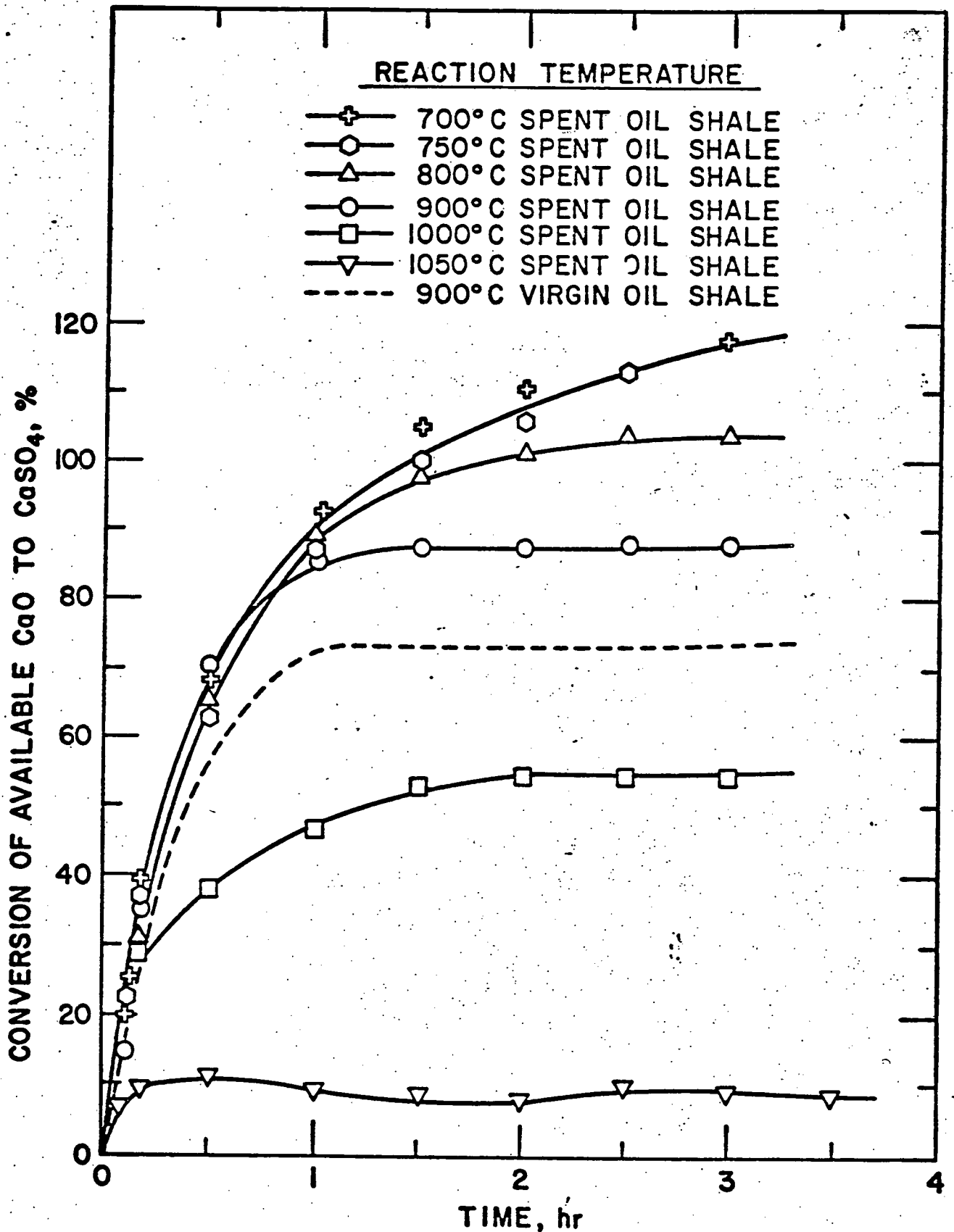


Fig. 1. Conversion of Precalcined CaO to CaSO<sub>4</sub> in Spent Green River Oil Shale at 700 to 1050°C. Reaction conditions, -50 +70 mesh material precalcined in 20% CO<sub>2</sub>-balance N<sub>2</sub>; sulfation gas, 0.3% SO<sub>2</sub>-5% O<sub>2</sub>-20% CO<sub>2</sub> in N<sub>2</sub>.

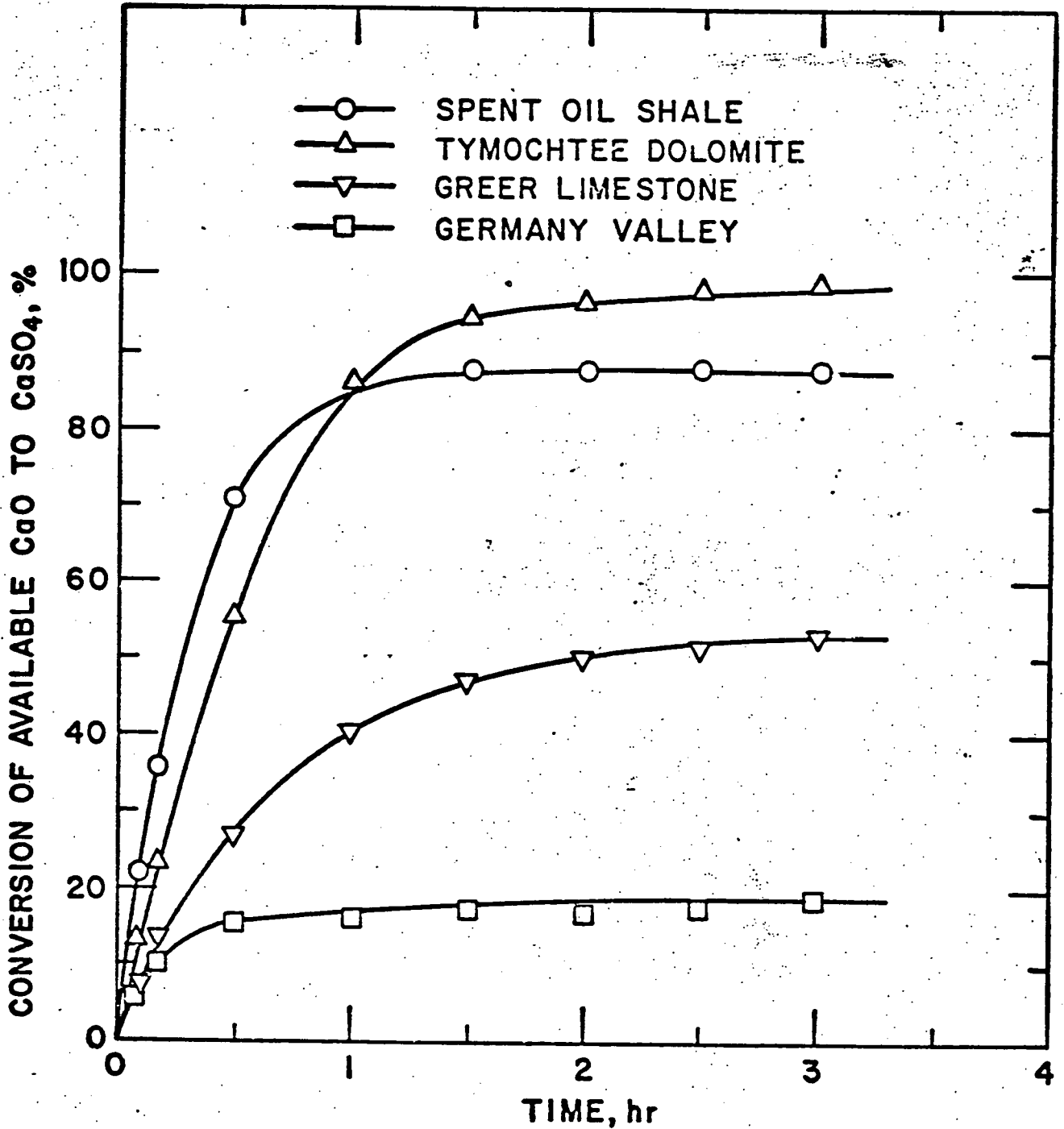


Fig. 2. Conversion of CaO to CaSO<sub>4</sub> in Spent Green River Oil Shale, Tymochtee Dolomite, Greer Limestone, and Germany Valley Limestone using 0.3% SO<sub>2</sub>-5% O<sub>2</sub>-20% CO<sub>2</sub> in N<sub>2</sub> at 900°C.

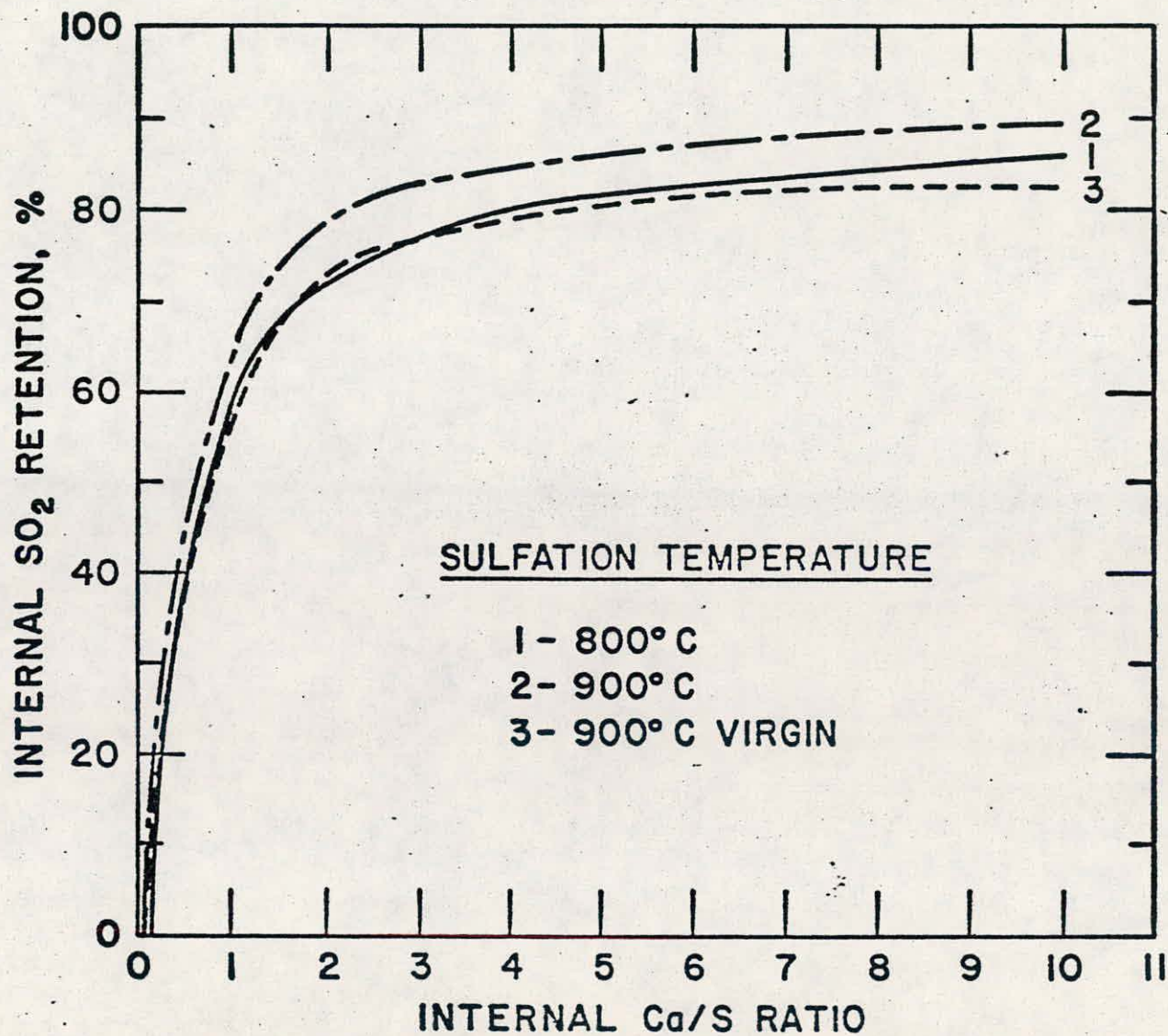


Fig. 3. Predicted SO<sub>2</sub> Retention vs. Ca/S Ratio for Oil Shale at Various Temperatures.