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Enhanced Durability of High-Temperature Desulfurization Sorbents
for Fluidized-Bed Applications

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Enhanced Durability of Desulfurization Sorbents for Fluidized-bed Applications

CONTRACT INFORMATION

Contract Number DE-AC21-88MC25006

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Period of Performance September 21, 1988 to November 20, 1993

Schedule and Milestones

FY92 Program Schedule

	S	O	N	D	J	F	M	A	M	J	J	A	S
Zinc Titanate Testing													
— Sorbent Preparation													
— Bench Scale Testing													
— Advanced Formulations													
— Topical Report													
— 100-Cycle Test													
— Technology Transfer													

OBJECTIVES

The objectives of this project are to identify and demonstrate methods for enhancing long-term chemical reactivity and attrition resistance of zinc ferrite and zinc titanate sorbents to be employed for desulfurization of hot coal-derived gases in a

high-temperature, high-pressure (HTHP) fluid-bed reactor. The sorbent formulation specified for study during the base period of this project was zinc ferrite. Zinc titanate sorbents are being studied under two options to the base contract. Specific objectives of the zinc titanate sorbent development work are the following:

- Investigation of various manufacturing methods to produce zinc titanate sorbents in a particle size range of 50 to 300 μm ;
- Characterization and screening of the formulations for chemical reactivity, attrition resistance, and structural properties;
- Testing of selected formulations in an HTHP bench-scale fluidized-bed reactor to obtain an unbiased ranking of the promising sorbents;
- Investigation of the effect of various process variables, such as temperature, nature of coal gas, gas velocity, Zn to Ti ratio of the sorbent, on the performance of the sorbent;
- 100-cycle testing of the best formulation under HTHP conditions at 750 $^{\circ}\text{C}$ to determine its long-term chemical reactivity and mechanical strength;
- Transfer of sorbent manufacturing technology to private sector; and
- Generation of a database on sorbent properties and performance (e.g., rates of reaction, attrition rate) to be used in the design and scaleup of future commercial hot-gas desulfurization systems.

BACKGROUND INFORMATION

The U.S. Department of Energy/Morgantown Energy Technology Center (DOE/METC) is actively pursuing the development of hot-gas desulfurization systems for application to advanced integrated gasification combined cycle (IGCC) and integrated gasification fuel cell (IGFC) power plants. Zinc ferrite and zinc titanate are currently the leading mixed-metal oxide desulfurization sorbent candidates. Both of these sorbents have high sulfur capacities and can remove hydrogen sulfide (H_2S) from coal gasifier

gas down to a few ppm. They can be easily regenerated with inertdiluted air for multicycle operation.

Early testing of zinc ferrite and zinc titanate was conducted in fixed-bed reactor systems using cylindrical extrudates prepared by mixing the individual oxides, extrusion using a suitable binder, and calcination. However, the need for valves operating at HTHP conditions and highly exothermic regeneration imposes some restrictions on the efficient operation of the fixed-bed system. These problems are not as serious in moving- and fluidized-bed reactor systems that are currently being developed with DOE/METC sponsorship at General Electric (GE) and Research Triangle Institute (RTI), respectively.

Provided that suitable sorbents can be developed, fluidized-bed reactors offer several potential advantages over fixed-bed reactors. These advantages include excellent gas-solid contact, ability to continuously add or remove sorbent, excellent temperature control of the highly exothermic regeneration, use of small particles leading to faster overall kinetics, and continuous steady-state operation. However, highly attrition-resistant sorbents with good sulfur capacity that are capable of withstanding stresses induced by rapid temperature swings, chemical transformations, and fluidization and transport are required before fluidized beds can be employed successfully. Furthermore, the design of fluidized-bed reactors is usually based on empirical correlations and significant art is involved in design and scaleup, although recent developments of sophisticated mathematical models may soon overcome this barrier.

PROJECT DESCRIPTION

Earlier work in this program concentrated on the development of durable zinc ferrite sorbents. A 3 in.-I.D. bench-scale HTHP fluidized-bed

reactor was designed and constructed. Details of this test facility are given elsewhere (Gupta and Gangwal, 1991a). A number of sorbent manufacturing techniques including spray drying, impregnation, crushing and screening of durable extrudates, and granulation were investigated for producing fluidizable zinc ferrite sorbents in a particle size range of 50 to 300 μm with the desired chemical reactivity and attrition resistance. The spray drying technique proved to be unsuccessful in producing fluidizable zinc ferrite particles in the desired particle size range. Sorbent formulations prepared by impregnating up to 20 wt.% zinc ferrite on alumina had very low sulfur capacity and did not appear to be commercially viable. Although a fluidizable zinc ferrite sorbent prepared by crushing and screening of durable pellets, prepared by United Catalysts, Inc. (UCI) for GE's moving-bed reactor, had acceptable levels of chemical reactivity, it underwent excessive attrition in the bench reactor, resulting in 42 percent sorbent loss from the reactor over 100 cycles (Gupta et al., 1992).

Of the techniques investigated, granulation proved to be most successful and a number of zinc ferrite sorbent formulations were prepared using this technique. Testing of these sorbents in the HTHP bench reactor demonstrated that these sorbents possess sulfur capacity and attrition resistance as good as or better than sorbents prepared by crushing and screening. Results of bench-scale testing of selected sorbent formulations are described elsewhere (Gupta and Gangwal, 1991a).

Following the successful preparation and encouraging performance of the zinc ferrite sorbents, a 100-lb batch was manufactured to demonstrate the commercial viability of the proposed manufacturing method. The sorbent is planned to be tested later this year in DOE/METC's process development scale hot-gas desulfurization system.

With zinc ferrite sorbents, excessive sorbent loss was observed at a sulfidation temperature of 625 °C. It is thought that attrition of the sorbent in the reactor is primarily due to chemical transformations rather than mechanical forces. Possible chemical transformations responsible for attrition are excessive reduction of ZnFe_2O_4 and iron carbide formation (Gupta and Gangwal, 1991a; Gupta et al., 1992).

The applicability of zinc ferrite as a hot-gas desulfurization sorbent, therefore, is conservatively limited to below 550 °C and to moderately reducing coal gases, such as low Btu gas containing at least 15 percent water vapor. Higher temperatures, as shown in the study, led to excessive sorbent weakening.

Development and Testing of Zinc Titanate Sorbents

Following the success of the granulation technique with zinc ferrite sorbents, it was used to prepare a number of zinc titanate formulations. Efforts to produce fluidizable zinc titanate sorbents by spray drying were unsuccessful as evidenced by their poor overall performance both in terms of attrition resistance and chemical reactivity.

Zinc titanate sorbents have been previously demonstrated for desulfurization of severely reducing gases in a fixed bed and also they are reasonably stable up to 760 °C (Gangwal et al., 1988; Lew, 1990; Lew et al., 1992). Only ZnO component of the zinc titanate sorbent reacts with H_2S while TiO_2 provides the stability to the sorbent against ZnO reduction by CO and/or H_2 present in coal gas. Hence, the sulfur absorption capacity of zinc titanate sorbents is significantly lower than zinc ferrite sorbents.

A series of zinc titanate sorbent formulations were prepared using the granulation technique by varying the following:

- ZnO to TiO₂ molar ratio,
- Various binders,
- Various binder levels,
- Calcination conditions,
- Various structural additives, and
- Various catalytic components (e.g., Co, Mo, W).

UCI supplied two unoptimized zinc titanate formulations that served as baseline sorbents for comparison purposes.

A series of zinc titanate sorbents prepared by the granulation technique were characterized for screening purposes before testing in the HTHP fluidized-bed reactor. This characterization included chemical reactivity in a thermogravimetric analyzer (TGA), pore size distribution, BET surface area, attrition resistance, etc. Table 1 shows various structural and physical properties of the zinc titanate formulation that were selected for bench testing after this screening. All the sorbents tested had a particle size in the range of 100 to 300 μm . The formulation L-3758 was prepared by UCI, whereas formulations coded ZT in Table 1 were produced by RTI using the granulation technique.

Table 1. Physical Properties of Various Zinc Titanate Formulations

Sorbent	L-3758 ^a	ZT-5 ^b	ZT-2 ^b	ZT-7 ^b	ZT-4 ^b
Zn/Ti ratio	1.5	1.5	0.8	0.8	1.5
Pore volume (cc/g)	0.2757	0.2184	0.2073	0.2167	0.2229
Median pore diameter ($\text{\AA}$)	4144	2099	1889	1764	2157
BET surface area (m^2/g)	2.49	3.38	4.05	3.67	3.53

^aPrepared by UCI.

^bPrepared by RTI.

Ten 10-cycle runs were conducted in the HTHP bench-scale fluidized-bed reactor system. Table 2 shows the sorbent formulations and operating conditions used for various bench runs. The first run was conducted with the baseline zinc titanate formulation, L-3758, supplied by UCI, as discussed earlier. The remaining nine runs were conducted with the sorbent formulations that were prepared using the granulation technique.

Table 2. Summary of Various Bench Runs^a

Run No.	Sorbent Formulation	Temperature (°C)	Coal Gas ^b
1	L-3758	650	KRW gas (20% steam)
2	ZT-5	650	KRW gas (20% steam)
3	ZT-5	650	KRW gas (5% steam)
4	ZT-5	650	Texaco gas
5	ZT-2	650	KRW gas (5% steam)
6	ZT-2	650	Texaco gas
7	ZT-7	650	Texaco gas
8	ZT-4	650	Texaco gas
9	ZT-4	750	Texaco gas
10	ZT-4	750 ^c	Texaco gas

^a Operating conditions for sulfidation are given in Table 3.

^b Gas composition for various coal gases is given in Table 4.

^c This run was carried out at a U/U_{mf} value of 8.34; the sorbent charge was 500 g.

The total gas flow rate, including flow of steam, to the reactor was kept at approximately 35 slpm, except for Run Number 10, where this flow was doubled to study the effect of superficial gas velocity. Table 3 shows the typical bench-scale test conditions during sulfidation. The minimum fluidization velocity (U_{mf}) was calculated using the correlations provided by Kunii and Levenspiel (1990). The typical value of U_{mf} was estimated to be about 1.87 cm/s at 650 °C and 1.5 MPa for the sorbent in a 100 to 300 μm particle size range.

Because one of the objectives of this testing was to study the effect of various sulfidation gases on the sorbent performance, three different gas compositions were studied. Table 4 shows the average compositions and reducing powers of the

**Table 3. Bench-scale
Test Conditions**

Pressure:	1.5 MPa (220 psia)
Temperature:	650-750 °C
Gas Flow:	~35 slpm ^a
U_o/U_{mf} ^b :	3-4 ^c
Sorbent charge:	350 g ^d
Sorbent particle size:	100 to 300 µm

^a For Run no. 10, gas flow was 76 slpm.

^b Ratio of superficial to minimum fluidization velocity.

^c For Run no. 10, $U_o/U_{mf} = 8.34$.

^d For Run no. 10, sorbent charge = 500 g.

three gases used. Two KRW gas compositions are shown in Table 4, one with 5 percent steam and another with 20 percent steam. The high steam content of KRW gas here is after the water quench. This gas composition has been used for testing of zinc ferrite sorbents because of its low severity.

**Table 4. Composition of Various
Simulated Sulfidation Gases (vol. %)**

Gas	KRW Gas		Texaco O ₂ - blown Gas
	20% Steam	5% Steam	
H ₂	8.85	11.65	27.70
CO	15.01	18.97	39.44
CO ₂	6.89	6.75	13.10
H ₂ O	19.17	5.12	18.64
H ₂ S	0.44	0.55	1.12
N ₂	<u>49.54</u>	<u>56.95</u>	<u>0.00</u>
Total	100.00	100.00	100.00

Reducing Power (Quality Factor)			
CO/CO ₂	2.18	2.81	3.01
H ₂ /H ₂ O	0.46	2.27	1.49
(CO + H ₂)/ (CO ₂ + H ₂ O)	0.92	2.58	2.11

To describe the test procedure briefly, a typical bench run consisted of loading 350 g of sorbent

(as shown in Table 3) and bringing the unit up to the desired temperature and pressure. Sulfidation gas of the desired composition (shown in Table 4) was passed through the sorbent bed at a velocity three to nine times U_{mf} as discussed above. The flow of sulfidation gas was terminated when the outlet H₂S concentration reached around 500 ppmv which was defined as a breakthrough point. Regeneration of sulfided sorbent was then carried out with a gas containing 2 to 3 percent oxygen in nitrogen at temperatures up to 780 °C and gas flow rate similar to that of sulfidation to maintain a uniform quality of fluidization. The regeneration was terminated when sulfur dioxide (SO₂) in the off-gas fell below 250 ppmv. The sulfidation-regeneration cycle was repeated for the specified number of times. The sorbent was characterized before and after each run, e.g., at the end of 10 cycles.

RESULTS

As indicated in Table 2, the effect of the following process variables was investigated on the performance of zinc titanate sorbents:

- Method of sorbent preparation,
- Composition of fuel gas,
- Zn to Ti ratio of the sorbent,
- Sulfidation temperature, and
- Superficial gas velocity.

The effect of first three variables has been covered in RTI's 1991 paper (Gupta and Gangwal, 1991b), while the effect of temperature and superficial gas velocity is described here.

Effect of Sulfidation Temperature

Data taken on zinc titanate sorbents in a fixed bed in RTI's previous contract indicated severe mass transfer limitations at high temperatures (Gangwal et al., 1988; Woods et al., 1989). However, in the fluidized bed, since the particle

size is fairly small (0.1 to 0.3 mm) as compared to the sorbent size used in a fixed bed (~5 to 10 mm extrudates), the mass transfer resistances are not expected to dominate. This was confirmed with zinc ferrite sorbents which showed that the sulfur capacity and reaction rates for L-7 zinc ferrite formulation at 625 °C were more than 50 percent higher than that at 550 °C (Gupta and Gangwal, 1991a).

To verify this finding for zinc titanate sorbents, a series of runs were conducted using the ZT-5 formulation in a TGA at lower temperatures (350 to 500 °C). The lower temperatures were chosen to minimize mass transfer resistances. It was observed that the extent of conversion of ZnO into ZnS increased with an increase in temperature, indicating an increase in reaction rate with temperature. Preliminary calculations of activation energy for the sulfidation reaction indicated a value of about 15 kcal/mol. Similar values of activation energies are also reported by Lew (1990).

In addition to the TGA data, bench-scale data collected at 650 and 750 °C on ZT-4 sorbent were also compared to determine the effect of temperature on the breakthrough behavior. Figure 1 shows this effect. In this figure, first-cycle breakthrough curves are compared for ZT-4 (Runs no. 8 and 9). The reactivity of the sorbent at 750 °C as indicated by the time taken for breakthrough, is significantly higher than at 650 °C. If one were to express this behavior in quantitative terms, the curve at 750 °C will give rise to a rate constant which is about 2.2 times greater than the rate constant at 650 °C. Using the Arrhenius equation for these two temperatures will result in an activation energy value of about 15 kcal/mol. This value corroborates the activation energy obtained using TGA measurements as described above. This indicates that simpler TGA experiments at low temperatures may be used to obtain reasonable rate constants which can then be extrapolated for

use at higher temperature in a large commercial reactor.

A comparison of sulfur capture capacities at 650 and 750 °C is shown in Figure 2. The sulfur capture capacity at 750 °C remains constant at around 12 g sulfur per 100 g of fresh sorbent through 10 cycles. The capacity at 650 °C is 10 to 15 percent lower than at 750 °C because of the slower kinetics. These results suggest that operating the desulfurization reactor in the vicinity of 750 °C will lead to a significantly smaller reactor size due to the faster kinetics as compared to lower temperature, for instance, 550 °C.

Effect of Superficial Gas Velocity

As indicated in Table 2, nine out of ten 10-cycle tests were made at a superficial velocity that was about three to four times the minimum fluidization velocity. This value translated in a superficial velocity of 6 to 8 cm/s. Since commercial bubbling-bed hot-gas desulfurization fluidized-bed reactors are expected to operate at a velocity ranging between 0.5 to 1 ft/s, it was important to study the effect of superficial gas velocity. Thus, a 10-cycle run was conducted with ZT-4 at 750 °C and a superficial gas velocity of about 0.5 ft/s ($U/U_{mf} = 8.34$).

Figure 3 shows the H₂S breakthrough curves for cycles 1 to 10 during Run No. 10 (see Table 2) that was conducted at 750 °C. As can be seen, essentially no change in breakthrough behavior is observed with cycling. This result is similar to low velocity 10-cycle run (Run No. 9) for which capacity remained constant over the 10 cycles (see Figure 2). The sulfur capacity value of 13.42 g S/100 g fresh sorbent was obtained in this run. This represents a 60 percent capacity utilization. The prebreakthrough level of H₂S was consistently below 20 ppmv as can be seen from Figure 3.

A post-test characterization of the 10-cycle regenerated material indicated (in fact, following both 10-cycle runs [Runs 9 and 10 in Table 2] no significant change in the sorbent's structural properties despite the operation of sorbent at 750 °C. No evidence of zinc vaporization was seen as evidenced by the Zn and Ti contents of the fresh and reacted samples. The attrition resistance of the 10-cycle regenerated material was significantly higher than that of the fresh sorbent. This was consistently observed in other runs as well.

Figure 4 shows a comparison of the H₂S breakthrough curves for ZT-4 at 0.25 and 0.5 ft/s velocities at 750 °C, 15 atm and in Texaco gas in the first cycle. It is to be noted here that doubling the gas flow rate in the high-velocity run reduced the breakthrough time since the H₂S content of the feed gas was the same in both cases at about 12,000 ppm. Therefore, the reduction in breakthrough time shown in Figure 4 should not be viewed as a reduction in sorbent chemical reactivity.

In fact, the sulfur capacity for the sorbent at 0.5 ft/s actually increased by 11 percent from a value of 12.12 to 13.42 g S per 100 g of fresh sorbent. This increase in sulfur capacity due to an increase in gas velocity indicates that better contact between gas and particles may lead to a modest increase in global reaction rate.

Attrition Resistance

Loss of sorbent due to attrition in the form of fines from a fluidized-bed reactor is perhaps the most important concern that is impeding the commercialization of this technology. RTI's earlier single-hole attrition tester (described in Gupta and Gangwal, 1991a) was replaced with a three-hole attrition tester commonly used in the catalyst community. The design of this tester as shown in Figure 5 was based on the work of

Gwyn (1969). The details of the attrition test protocol can be found elsewhere (Gwyn, 1969; Bemrose and Bridgwater, 1987).

The attrition rate measurement procedure in this tester involved the following steps:

- Loading 50 g of the sample of a known particle size distribution;
- Passing a nitrogen/air at a flow rate of 7 to 21 slpm;
- Intermittently stopping the gas flow after every hour and weighing the filter/flask assembly to determine the amount of fines collected;
- Continuing the test up to 20 h (hourly readings were taken only for initial 5 h); and
- Collecting the remaining sample from the tube and measuring its weight and particle size distribution at the end of the test.

Figure 6 shows attrition rates of various sorbents as a function of time. These data were taken in the three-hole attrition tester described above at a gas flow rate of 15 slpm. The attrition rate shown in Figure 6 is defined as the amount of sorbent attrited per unit time. This rate is not a global rate but rather an instantaneous rate. For example, the attrition rate at a 2-h time is calculated as the amount of sorbent attrited and collected in the filter flask assembly between Hour 1 and Hour 2 divided by the duration which is 1 h.

In addition to the attrition rates of L-3758 and ZT-5, Figure 6 also shows the data for a specially prepared ZT-4 and a commercial fluid catalytic cracking (FCC) catalyst. As can be seen, L-3758 has the highest attrition rate, while ZT-4 and FCC catalyst have very low rates. The attrition rate for ZT-5 is somewhere in-between. The attrition rate

of ZT-4 is comparable to a commercial FCC catalyst. As discussed earlier, the reactivity of ZT-4 is also excellent with no zinc loss even at 750 °C. This sorbent is currently undergoing a 100-cycle test at 750 °C in the HTHP bench-scale reactor.

Sorbent Regeneration

Regeneration of sulfided zinc titanate is a highly exothermic reaction. The desirable reaction, $\text{ZnS} + (3/2) \text{O}_2 \rightarrow \text{ZnO} + \text{SO}_2$, occurs with an enormous heat of reaction (-70.7 kcal/mol of O_2 consumed). To prevent excessive temperature rise that may lead to sorbent sintering, an air-diluent mixture (typically air-steam or air-nitrogen) is used for the regeneration with an oxygen concentration of about 1 to 5 volume percent. On the other hand, if regeneration is not carried out at a sufficiently high temperature, a competing sulfation reaction, $\text{ZnS} + 2\text{O}_2 \rightarrow \text{ZnSO}_4$, may occur leading to incomplete regeneration. Experience with fixed-bed zinc titanate sorbents (Gangwal et al., 1988) led to a temperature window of 725 to 780 °C for elevated pressure regeneration. A temperature of 760 °C (1400 °F) was found to be ideal for preventing both sulfate formation and excessive surface area loss due to sorbent sintering.

Regenerations were conducted on fluidizable zinc titanate as a function of oxygen concentration to evaluate temperature rise, regeneration stoichiometry, regeneration rate, and residual sulfate formation. All of these experiments were conducted with an inlet regeneration flow rate of 35 slpm.

Four separate regenerations were conducted at inlet O_2 concentrations of 2, 2.5, 3, and 3.5 volume percent. To approximately reach the target temperature of about 760 °C, different initial temperatures were used in each case; these were 735, 722, 707, and 695 °C for 2, 2.5, 3, and

3.5 volume percent O_2 , respectively. Since this is a batch reactor, sorbent temperature would rise until a quasi-steady state would be reached. This behavior is demonstrated in Figure 7. At this steady state, the heat generation due to the reaction equals the sum of the net heat carried out by the gas, the heat uptake by the sorbent, and the heat loss from the sorbent to the reactor wall (sorbent cage). Note that the steady-state periods decrease as O_2 concentration increases, indicating faster regeneration.

The SO_2 in the effluent gas was measured during this steady-state period. This is shown in Table 5, where the experimental value is compared to the stoichiometric value assuming the stoichiometry to be $\text{ZnS} + (3/2) \text{O}_2 \rightarrow \text{ZnO} + \text{SO}_2$. The agreement is excellent, indicating that essentially all of the O_2 is converted to SO_2 . This provides indirect evidence of the absence of sulfate formation during the steady-state periods, which were typically at temperatures of 752 to 761 °C during the four regenerations. Thus, 760 °C appears to be a reasonable temperature to prevent sulfate formation. This corroborates RTI's earlier fixed-bed results (Gangwal et al., 1988).

Table 5. Comparison of Measured SO_2 with Stoichiometric SO_2 During Quasi-Steady-State Period of Regeneration (vol %)

Inlet O_2	SO_2	Stoichiometric SO_2
2.0	1.42	1.33
2.5	1.77	1.67
3.0	2.10	2.00
3.5	2.43	2.33

Other Reactor Design Issues

In addition to the issues discussed above, a number of other reactor design issues were also addressed in this study including kinetics of

sulfidation and regeneration, sulfate formation during regeneration, zinc vaporization, effect of sulfidation on the sorbent attrition, fate and effect of NH_3 , fate and effect of HCl , and extent of shift reaction. Also a relatively simple mathematical model was developed that assumed well-mixed solid phase and plug flow of gas. This model reasonably predicted the breakthrough behavior in the batch HTHP reactor using a rate constant based on TGA measurements. Furthermore, a series of conceptual commercial systems are being evaluated involving a continuous sorbent circulation between sulfider and regenerator. The sulfider and regenerator could be both bubbling beds, or a combination of riser (transport reactor) and a bubbling bed, or a circulating fluidized bed and a bubbling bed depending on the process operating conditions.

Injection of hydrochloric acid (HCl) and ammonia (NH_3) into a fluidized bed of zinc titanate at up to 750°C did not appear to have any deleterious effect on the performance of the sorbent. At a superficial contact time of 0.63 s, at 1 atm and 744°C , about 50 percent of the inlet NH_3 was decomposed by a molybdenum-doped zinc titanate (ZT-13). This translates into a first-order rate constant for NH_3 decomposition by this sorbent of 1.1 per s. Furthermore, the presence of HCl in the coal gas significantly enhanced the desulfurization reactivity of zinc titanate. Some HCl was permanently retained by the sorbent.

To demonstrate the commercial potential of the granulation technique, two 80 lb batches of sorbent with zinc to titanium mol ratios of 0.8 and 1.5 were prepared. These large batches will be tested in DOE/METC's pilot-scale unit.

FUTURE WORK

Currently, a 100-cycle test is in progress with ZT-4 formulation to demonstrate its long-term chemical reactivity and attrition resistance. A 500

kg batch of the sorbent will be produced to demonstrate the granulation technique at a semi-commercial scale. Furthermore, transfer of the zinc titanate sorbent production technology to the private sector will be actively pursued.

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Figure 1. ZT-4 Breakthrough Curves at 650 and 750 °C in Texaco Gas

Figure 2. Sulfur Capacities of ZT-4 at 650 and 750 °C

Figure 3. Breakthrough Curves for ZT-4, Texaco Sulfidation Gas at 750 °C

Figure 4. Breakthrough Behavior of ZT-4 at 750 °C at Low and High Superficial Velocities

Figure 5. Schematic of a Three-hole Attrition Tester

Figure 6. Attrition Rates of Various Sorbents Measured in 3-hole Attrition Tester (15 slpm)

Figure 7. Regeneration Temperature Profile for ZT-4 in Texaco Gas

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