Quarterly Technical Progress Report

Sixth Report
October 15, 2000 – January 15, 2001

Title: *A Novel CO₂ Separation System*

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Sponsor: U.S. Department of Energy

Contract DE-AC26-98FT40421

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Reporting Period: July 16, 2000 – October 15, 2000

PROGRESS

TDA presented summaries of our progress on the project and our plans for Phase III to DOE-NETL on January 10, 2001.

Appendix A presents the Executive Summary.

Appendix B presents the detail data on the work performed and Appendix C presents the plans for Phase III.

FUTURE PLANS

Kellogg, Brown, and Root (KBR) will complete their testing and prepare a report.

TDA will prepare a topical report and a Phase III proposal.

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Appendix A A NOVEL CO₂ SEPARATION SYSTEM

Dr. Robert J. Copeland

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January 10, 2001

Executive Summary

National Energy Technology Laboratory;
U.S. Department of Energy

TDA Research Inc. • Wheat Ridge, CO 80033 • www.tda.com

Introduction/Objectives

- **Current technologies for capturing CO₂ are in-efficient and expensive**
 - 9% to 37% energy penalties
 - Cost from \$18 to \$72 per metric ton of CO₂
- **Objectives**
 - Sequester most to all of the CO₂
 - Generate electricity at high efficiency and low costs: <\$10/ton Carbon (\$2.73/ton CO₂)
 - Usable for GTCC, Fuel Cells, GT and any fossil fuel (after gasification or other pre-treatment)

TDA's Approach

- **Use a chemical sorbent to transfer the energy in the fossil fuel to heat air in a power generation cycle**
 - Natural gas (CH₄), Oil (Diesel Fuel), Gasified Coal
 - No carry over of N₂ to dilute the CO₂
- **Condense the water**
 - High purity CO₂ at pressure
- **Sorbent Energy Transfer System = SETS**

7

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Sorbent Energy Transfer System (SETS) Schematic (M = metal)

No Additional Energy Required for CO₂ Separation

We oxidize the fuel in two steps for the same net reaction: full oxidation of the fuel to water and CO₂

Step 1) $\text{NiO} + \text{H}_2 = \text{Ni} + \text{H}_2\text{O} @ 800^\circ\text{C}$
 $\Delta H = -3.238 \text{ kcal}; \Delta G = -10.902 \text{ kcal}; K = 1.661(10)^2$

Step 2) $\text{Ni} + 0.5 \text{ O}_2 = \text{NiO} @ 800^\circ\text{C}$
 $\Delta H = -56.116 \text{ kcal}; \Delta G = -34.160 \text{ kcal}; K = 9.066(10)^6$

Net $\text{H}_2 + 0.5\text{O}_2 = \text{H}_2\text{O} @ 800^\circ\text{C}$
 $\Delta H = -59.354 \text{ kcal}; \Delta G = -45.063 \text{ kcal}; K = 1.506 (10)^9$

9

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How We Keep Capital Costs Low

- **Fluidized bed & transport reactors are very high throughput devices**
 - Reducing reactor = Fluidized bed
 - H₂ & CO (CH₄) slip = loss of energy
 - Longer contact times, less slip
 - Oxidizing reactor = Transport reactor
 - O₂ slip inherent in the system, always excess
 - Transport allows better thermal control in the stream with the greatest heat generation
- **Sorbent reactive area is CHEAP!**
 - @ 1m²/g, \$5/lb = \$0.0101/m² = \$0.00102/ft²
 - ~100μ particles ∴ very high rates of H₂/CO and O₂ transport to sorbent & small reactor volumes

10

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Key Phase II Research Areas

- Development of a high temperature, strong, attrition resistant, chemically active sorbent usable in fluidized beds/transport reactors
 - Cu – did not have high temperature stability
 - **Fe – usable to 800°C (1,472°F)**
 - **Ni – usable to 1,050°C (1,922°F) but still in development**
- Show sorbents can meet requirements
 - TDA - Screening & small fluidized bed (1.5" Dia., 2.8" bed)
 - Kellogg Brown, & Root (KBR):
 - Scalable fluidized bed reactor (6" Dia.; 13 inch bed)
 - Systems analysis – Cost & efficiency of CO₂ capture
 - Louisiana State University (LSU) – GTCC
 - TDA – UltraFuelCell (UFC) with help from NETL

13

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Fe Sorbent has long Life (precursor to TDASETS)

135 psig, 165.15 g. / 80 ml., 720 °C

14

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New Ni Sorbent Works at High Temperature (1,050°C = 1,922°F)

New Ni Sorbent:
 AI = 1.8%/h;
 30 psig,
 150.74 g
 82 ml
 1.5" Dia.
 2.8" bed height

15

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Sorbent Consumes All the O₂ until Breakthrough

Same effect
 seen in Fe
 sorbents and
 in the KBR
 fluidized bed
 reactor tests

16

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Reactor Design Affects H₂ Outlet

KBR fluidized bed
reactor, 6" Dia. 13" bed

Dry gas concentration/3.4
= wet gas concentration

17

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TDASETS can have a LONG LIFE

Sorbent Identification Lot N9925548

TDASETS

Bulk Density of Fresh Sorbent 82.4 lb/ft³ (1.32 gm/cc)

1.8 g/cc

D₅₀ after 5 cycles in MC test 115 μm

D₅₀ after 10 cycles in MC test 100 μm

TDA attrition index for fresh

17

2.5

TDA attrition index after 5 cycles in TRTU test¹

11

TDA attrition index after 10 cycles in TRTU test¹

9

KBR estimate of Long term attrition rate,

Lot N9925548 lb/lb circulated 0.55x10⁻⁶

Long term attrition rate,

TDASETS (Fe) lb/lb circulated

~1x10⁻⁶

Cycle life approximately 1,000,000 cycles

18

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Process Diagram of UFC/GT/SETS (Ni-sorbents)

SETS Components

19

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With Long Life Sorbents SETS is LOW COST

50 MW_e, UltraFuelCell, Ni Sorbent, CY 2000\$

20

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Conclusions

- **TDASETS (Fe) is performing well but is temperature limited to 800°C (1,472°F)**
 - High attrition resistance
 - Long chemical life
 - Adequate O₂ capacity
 - Good kinetics
- **Ni for higher temp. being improved**
 - High attrition resistance
 - Good O₂ capacity
 - Good kinetics
 - But yet to produced and tested in larger scale

21

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Conclusions (Cont'd)

- **SETS has potential for low cost**
 - GTCC ~5% efficiency loss \$15-\$18/ton CO₂ (900°C sorbent)
 - SETS in an UltraFuelCell evaluated (1,050°C, Ni sorbent)
 - 2% loss in efficiency, 1050°C max sorbent
 - Cost less than \$10/ton CO₂ in large plants (>50 MW_e)
 - Low Temperature limit (800°C increases costs to \$15/ton)
 - Most of SETS Cost is CO₂ Compression (equipment and power)
- **CO₂ Value (EOR) \$15 to \$44/ton CO₂**
 - i.e., > costs

Costs and efficiencies independently calculated by LSU (240 MW_e GTCC) and NETL (4 MW_e UFC)

22

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Why SETS Works So Well

- **No additional energy for CO₂ separation**
- **High Throughput reactors
= low capital costs**
- **Sorbent lasts forever (almost)**

23

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Recommendations

- **Develop higher temperature sorbent
1050°C = 1,922°F**
 - Improve costs for both GTCC and UFC
 - Evaluate potential near term applications
 - Partial oxidation of NG to CO + 2H₂ for FT liquids and other chemicals (e.g., Alaska North Slope NG)
 - Inert gas generator
- **Demonstrate full cycle in fluidized bed (reducing) & transport reactor (oxidizing)**
 - Shows full cycle
 - Ability to test for a very large number of cycles since it provides continuous operation

24

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Appendix B

A NOVEL CO₂ SEPARATION SYSTEM

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January 10, 2001

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A NOVEL CO₂ SEPARATION SYSTEM

- ***Introduction***
- ***TDA Screening and Testing of Sorbents***
- ***KBR Testing of Sorbents***
- ***Systems Analyses***
- ***Conclusions and Recommendations***
 - *Near term commercialization opportunities*

Energy penalties for CO₂ capture

Fuel	Today	Future
Conventional Coal	27-37% (Herzog and Drake, 1993)	15% (Mimura et al, 1997)
Gas	15-24% (Herzog and Drake, 1993)	10-11% (Mimura et al, 1997)
Advanced Coal	13-17% (Herzog and Drake, 1993)	9% (Herzog and Drake, 1993)

Increases cost of electrical power by up to 50%

27

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CHEMICAL LOOPING COMBUSTION (CLC) Ishida et al. (1987)

The chemical loop used redox metal oxides (e.g., the reduction of NiO to Ni) to transfer energy from hydrocarbon fuel (e.g., natural gas), to the metal and fully oxidize the fuel to CO₂ and H₂O. The metal was reoxidized to heat air in a gas turbine combined cycle plant. To separate CO₂ product, condense H₂O and remove liquid

Reduction of NiO to Ni by CH₄ (and other hydrocarbons) was **endothermic**, some of the heat from the gas turbine exhaust was recovered in the endothermic reaction and released when the nickel was oxidized in air

Chemical-looping combustion system patented by Tokyo Electric Power Co., Inc., (US Pat. 5,447,024)

Fe₂O₃ <-> FeO and Mn₃O₄ <-> MnO also investigated

A fluidized-bed combustion process with inherent CO₂ separation; Application of chemical-looping combustion by Anders Lyngfelt, Bo Leckner and Tobias Mattisson Dept. of Energy Conversion, Chalmers University of Technology 412 96 Göteborg, Sweden Accepted (2000) for publication in *Chemical Engineering Science*

28

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Literature data on oxygen carriers in CLC

	Carrier/support		Red. gas	Tred.,C	Tox.,C	Dp,mm
Nakano et al., 1986	Fe ₂ O ₃ , Fe ₂ O ₃ /Al ₂ O ₃	Fe ₂ O ₃ /Ni	H ₂ H ₂ /H ₂ O	700-900	800-1000	0.007
alshida & Jin, 1994	NiO/YSZ, NiO	Fe ₂ O ₃ /YSZ Fe ₂ O ₃ /Al ₂ O ₃	H ₂	600,800,1000	700,900,1100	1-3
Ishida et al., 1996	NiO/YSZ		H ₂	600,800,1000	600,800,1000	1.8
blshida & Jin, 1996	NiO,	NiO/YSZ	H ₂	600	1000,1200	2
Jin et al., 1998	NiO/YSZ, Fe ₂ O ₃ /YSZ	Co ₃ O ₄ /YSZ, CoO-NiO/YSZ	H ₂ ,CH ₄	600	1000	1.8
clshida et al., 1998	NiO/YSZ NiO/Al ₂ O ₃ NiO/TiO ₂	Fe ₂ O ₃ /YSZ Fe ₂ O ₃ /Al ₂ O ₃ Fe ₂ O ₃ /TiO ₂	H ₂ /N ₂ CO/N ₂ CO/CO ₂ CO/N ₂ /CO ₂ CO/N ₂ /H ₂ O	550,600,700, 800,900		
dJin et al., 1999	NiO/Al ₂ O ₃ , NiO/TiO ₂ , NiO/MgO, CoO/Al ₂ O ₃ , CoO/TiO ₂ ,	CoO/MgO, Fe ₂ O ₃ /Al ₂ O ₃ , Fe ₂ O ₃ /TiO ₂ , Fe ₂ O ₃ /MgO	H ₂ H ₂ O/CH ₄	600 700	1000 1000	2.1,1.8
elshida et al., 1999	NiO/Al ₂ O ₃		H ₂ (TGA) H ₂ /Ar (CR)	900	900	0.07
fHatanaka et al., 1997	NiO		CH ₄	400 - 700		0.07

a)effect of H₂O on oxidation, effect of particle size, b)no NO_x formation at 1200 C,
c) study of carbon deposition, d)effect of pressure, e)data from continuous CLC reactor,
f)gas measurement with gas chromatography

29

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Approach for SETS

- Like the CLC we use a chemical sorbent to transfer the energy in the hydrocarbon fuel to heat air at high pressure
- **Sorbent Energy Transfer System = SETS**
 - Thermally neutral reduction reactor
 - Avoids high cost of recuperative heat exchanger in CLC
 - Use sorbent heat capacity to balance heat
- **Condense the water**
 - High purity CO₂ at pressure

30

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Schematic Diagram of the SETS-NGCC Process (LSU Aspen Model)

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SETS Reactors

How We Keep Capital Costs Low

- **Fluidized bed & transport reactors are very high throughput devices**
 - Reducing reactor = Fluidized bed
 - H_2 & CO (CH_4) slip = loss of energy
 - Longer contact times, less slip
 - Oxidizing reactor = Transport reactor
 - O_2 slip inherent in the system, always excess
 - Transport allows better thermal control in the stream with the greatest heat generation
- **Sorbent reactive area is **CHEAP!****
 - @ $1m^2/g$, $\$5/lb = \$0.0101/m^2 = \$0.00102/ft^2$
 - $\sim 100\mu$ particles $\therefore$ very high rates of H_2/CO and O_2 transport to sorbent & small reactor volumes

33

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Fluidized Bed/Transport Reactor Sorbent Requirements

- **Sorbent must have very long chemical life**
 - Previous work has demonstrated long life in these chemicals
- **Sorbent must be VERY attrition resistance**
 - At $1(10)^{-6}lb$ loss per lb circulated, 2.5% oxygen loading, 4% O_2 removal from air stream, dust load ~ 2 ppm(wt) in the air
 - Sorbent $\sim 10x$ better in attrition than FCC catalysts
 - Barrier filters are not affordable
 - increase cost $\sim 5X$, based on data from KBR in Phase I
- **TDA focused its research on developing a very strong sorbent (i.e., attrition resistant), which was the most difficult part of the research**

34

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How We Minimize Losses

No Added Energy for CO₂ Separation
We oxidize the fuel in two steps for the same
net reaction as combustion:
Full oxidation of the fuel to water and CO₂

Step 1) $\text{H}_2(\text{g}) + 3\text{Fe}_2\text{O}_3 = 2\text{Fe}_3\text{O}_4 + \text{H}_2\text{O}(\text{g})$
 $\Delta H = -1.515 \text{ kcal}; \Delta G = -24.416 \text{ kcal } K = 9.395(10)^4$

Step 2) $2\text{Fe}_3\text{O}_4 + 0.5 \text{ O}_2(\text{g}) = 3\text{Fe}_2\text{O}_3$
 $\Delta H = -57.839 \text{ kcal}; \Delta G = -20.646 \text{ kcal } K = 1.603(10)^4$

Net $\text{H}_2(\text{g}) + 0.5\text{O}_2(\text{g}) = \text{H}_2\text{O}(\text{g}) @ 800^\circ\text{C}$
 $\Delta H = -59.354 \text{ kcal}; \Delta G = -45.063 \text{ kcal } K = 1.506 (10)^9$

H₂ shown, CO to CO₂ similar

35

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SETS Oxidizes H₂ & CO to PPM Levels

Equilibrium calculation for Fe

$3\text{Fe}_2\text{O}_3 + \text{H}_2/\text{CO} \rightarrow 2\text{Fe}_3\text{O}_4 + \text{H}_2\text{O}/\text{CO}_2$

36

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No Additional Energy Required for CO₂ Separation

We oxidize the fuel in two steps for the same net reaction: full oxidation of the fuel to water and CO₂

Step 1) $\text{NiO} + \text{H}_2 = \text{Ni} + \text{H}_2\text{O} @ 800^\circ\text{C}$
 $\Delta H = -3.238 \text{ kcal}; \Delta G = -10.902 \text{ kcal}; K = 1.661(10)^2$

Step 2) $\text{Ni} + 0.5 \text{ O}_2 = \text{NiO} @ 800^\circ\text{C}$
 $\Delta H = -56.116 \text{ kcal}; \Delta G = -34.160 \text{ kcal}; K = 9.066(10)^6$

Net $\text{H}_2 + 0.5\text{O}_2 = \text{H}_2\text{O} @ 800^\circ\text{C}$
 $\Delta H = -59.354 \text{ kcal}; \Delta G = -45.063 \text{ kcal}; K = 1.506 (10)^9$

37

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Project organization

38

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A NOVEL CO₂ SEPARATION SYSTEM

- **Introduction**
- **TDA Screening and Testing of Sorbents**
- **KBR Testing of Sorbents**
- **Systems Analyses**
- **Conclusions and Recommendations**
 - *Near term commercialization opportunities*

39

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SETS Sorbent Development

- **Initially evaluated low cost Cu and Fe sorbents**
 - **Cu sorbents high capacity, exothermic, long chemical life, but agglomerated in fluidized bed reactor**
 - Fe sorbents low capacity, long chemical life, stable up to 800°C (1,472°F)
 - Tests at 900°C showed agglomeration in fluidized bed
 - Fe not reforming catalyst and therefore is very slow at oxidizing CH₄
 - Fe sorbents relatively low cost
- **TDA began developing Ni sorbents late in project**
 - Ni sorbents: high capacity, long chemical life, NON-agglomerating to 1050°C
 - Ni more expensive sorbent but is a reforming catalyst and therefore it can reform and then oxidize CH₄

40

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Sorbents Screened & made Fluidizable

- Sorbents made as pellets initially and screen based on crush strength to optimize:
 - Firing temperature
 - Starting materials
 - Composition of each starting material
- TDA then spray dried limited number of sorbents and re-optimized based on the Attrition Index (AI)

41

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TDA's High Temperature High Pressure (HTHP) Test Facility

- **Fluidized bed Reactor**
 - 3" Inconel pressure vessel with a 24" tall Inconel insert
 - 1.5" ID, 2.8" sorbent height
 - $P_{max} = 100$ psig @ 1050°C
- **Automated**
 - Flow of gases, H_2 , CO, CO_2 , CH_4 , N_2 , and air (mass flow Meters)
 - H_2O HPLC pump, in reactor boiler
 - Continuous On-line monitors: O_2 , CO, CO_2 , CH_4
 - GC analysis for H_2 and N_2
 - Computerized data acquisition & recording to disk

42

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Fe Sorbent has long Life (precursor to TDASETS)

135 psig, 165.15 g. / 80 ml., 720 °C

Sorbent Properties

- **Fe sorbent in 59 cycle test (small batch ~2 lbs)**
 - Fresh AI = 0.64%/h, density 2.16 g/cc
 - Cycled DI = 1 (better than our zinc ferrite H₂S sorbents previously tested at KBR with estimated life of 1.8 million cycles {0.55(10)⁻⁶ lb loss per lb circulated})
- **TDASETS (Fe sorbent, large batch ~100 lbs)**
 - Fresh AI = 2.5%/h, density 1.8 g/cc
 - Difference in density (and AI) due to spraying (same starting materials and firing temperature)
- **NiO impregnated on Alumina**
 - AI relatively low, similar to FCC
- **New Ni sorbent**
 - Fresh AI = 1.8%/h, density 1.8 g/cc
 - Chemically active and stable to 1050°C

AI = Attrition Index, ASTM apparatus at TDA
DI = Davison Index, KBR tests

44

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900°C Ni sorbent tests at TDA

8.5% NiO on Alumina O₂ Load (moles O₂) during reduction cycle

45

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New Ni Sorbent Works at High Temperature (1,050°C = 1,922°F)

New Ni Sorbent:
AI = 1.8%/h;
30 psig,
150.74 g
82 ml

46

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Sorbent Consumes All the O₂ until Breakthrough

Same effect seen in Fe sorbents and in the KBR fluidized bed reactor tests

47

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Sorbent Selection for Large Batch

- **Selected Fe based sorbent for tests in a scalable fluidized bed at Kellogg Brown & Root (KBR)**
 - TDASETS was spray dried at Coors Tek but fired at TDA (ovens at Coors committed)
 - Slightly less dense than the precursor
 - Ni sorbents showing good chemical stability but we did not have the sorbent sufficiently developed when we had to make the decision for sorbent production
- **Ni based sorbent continuing to be improved: better attrition, chemical activity, stable to 1050°C (1,922°F)**
 - Finalize development in Phase III
 - Transfer technology to Saint-Gobain NorPro Corporation, Akron, OH (formerly Norton), commercial vendor

48

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A NOVEL CO₂ SEPARATION SYSTEM

- *Introduction*
- *TDA Screening and Testing of Sorbents*
- ***KBR Testing of Sorbents***
- *Systems Analyses*
- *Conclusions and Recommendations*
 - *Near term commercialization opportunities*

49

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KBR Testing 50 Cycles

KBR fluidized bed reactor

- 24 lbs of TDASETS
- 6" dia, ~13" bed height (~16" expanded)
- 8 ft tall reactor
 - From previous work
- 1,400°F = 760°C nominal reactor
- 1472°F = 800°C max. allowed in sorbent

Pre-heater

50

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Reducing Gas Flows at KBR

Inlet Conc Req'd by TDA	With N ₂ Dilution for tests	Flowrate SCFH	Conc of Prod. Gas *
• CO ₂ 21.5%	19.4%	7.80	65.5
• H ₂ 5.2%	15.0%	6.00	0.0
• H ₂ O 73.1%	55.5%	22.20	0.0
• N ₂ 0.2%	10.1%	4.00	34.5
• Total 100.0%	100.0%	40.00	100.0

*Nominal outlet at the analyzers after steam is condensed.

Note all tests flow at 40 SCFH total and the above gas concentrations unless otherwise noted

Oxidations are also 40 SCFH with 4 to 8% O₂ (N₂ diluted air)

51

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SETS Oxidizes H₂ to Very Low Levels

Dry gas concentration/3.4
= wet gas concentration

52

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Reactor Design Affects H₂ Outlet

TDA SETS Sorbent –1,400°F (760°C) Multi-Cycle Test Conditions

50 Cycle Test

- KBR now conducting a 50 cycle tests at 15% H₂ in the inlet, 40 SCFH total flow to evaluate the durability of the sorbent
- Expect completion of these tests in the week of January 17, 2001
- Will provide the data for calculating the loss rate of the sorbent (i.e., 1/ average cycle life)

55

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Estimated Attrition Data

Sorbent Identification Lot N9925548	TDASETS
Bulk Density of Fresh Sorbent 82.4 lb/ft ³ (1.32 gm/cc)	1.8 g/cc
D ₅₀ after 5 cycles in MC test 115 μ m	
D ₅₀ after 10 cycles in MC test 100 μ m	
TDA attrition index for fresh	17 2.5
TDA attrition index after 5 cycles in TRTU test ¹	11
TDA attrition index after 10 cycles in TRTU test ¹	9
KBR estimate of Long term attrition rate,	
Lot N9925548 lb/lb circulated	0.55x10⁻⁶
Long term attrition rate,	
TDASETS (Fe) lb/lb circulated	~1x10⁻⁶
Cycle life approximately 1,000,000 cycles	

56

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- ***Introduction***
- ***TDA Screening and Testing of Sorbents***
- ***KBR Testing of Sorbents***
- ***Systems Analyses***
- ***Conclusions and Recommendations***
 - *Near term commercialization opportunities*

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NGCC = 55.7%
without CO₂ cap

LSU Estimated Costs

	NGCC		SETS-NGCC Simulation	
	Actual	Simulation	Fe ₂ O ₃ -CuO-Al ₂ O ₃	Fe ₂ O ₃ -Al ₂ O ₃
CH ₄ Feed Rate, kg/hr	31900	31900	31500	31600
Net Generating Capacity, MWe	242	247	232	232
LHV Efficiency, %	55.6	55.7	53.0	52.9
Carbon Capture, metric ton/yr	0	0	900°C sorbents	
	0	0	280302	282038
%	-	-	49.1	49.2
\$/ton CO ₂	-	-	15.82	18.33

All annual costs were based on a 75 % on-stream factor (6570 operating hours per year). Incremental capital cost was based on an annual capital recovery of 10%, while the base case unit costs of natural gas, sorbent, and boiler feed water were taken to be \$4.00 per million Btu, \$6.50 per pound, and \$0.83 per thousand gallons, respectively. The base case sorbent replacement rate was taken to be 1 pound per 10⁶ pounds circulated in each reactor pass

59

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Higher Temperatures Increase CO₂ Capture & Reduce Efficiency but Reduce \$/ton CO₂

Process Diagram of UFC/GT/SETS (Ni-sorbents)

61

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Costs Decrease with Large Plants

62

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Most of SETS Cost is CO₂ Compression (equipment and power)

	\$/ton CO ₂
SETS Components	7.10
Transport Reactors	2.26
CO ₂ Compressor	3.35
Condenser	1.50
Operating Expenses	2.62
Added Fuel Cost	2.50
Sorbent Replacement	0.12
Impact on Balance of Plant	0.29
Fuel Pump	0.12
Fuel Processing	0.04
Heat Exchange	1.50
Power Generation	-1.35
Total Cost of CO₂ Removal	10.01

50 MW_e, UltraFuelCell, Ni Sorbent, CY 2000\$

63

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With Long Life Sorbents SETS is LOW COST

50 MW_e, UltraFuelCell, Ni Sorbent, CY 2000\$

Process Diagram of UFC/GT/SETS (Fe-sorbents)

Sensitivity Analysis on Fuel Cost

States where SETS & EOR can be applied

Legend (Annual Quads)
 3.0
 1.5-2.0
 1.0-1.5
 0.5-1.0
 0.3-0.5
 0.0-0.3
 Total = 24.8 Quads

Oil Producers and Large Power Consumers:

- Texas
- California
- Louisiana
- Oklahoma
- & others

Projected Year-2010 Combustion of Fossil Fuels for Electricity (Source: DOE, 1989).

67

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Conclusions

- **TDASETS (Fe based) is performing well but is temperature limited to 800°C (1,472°F)**
 - Excellent attrition resistance
 - Adequate oxygen loading
 - Multiple cycle tests at KBR shown ability to oxidize H₂ and CO to very low levels
 - 15 of 50 cycles completed as of this writing
- **Limited testing with Ni based sorbent**
 - Adequate attrition resistance
 - Good oxygen loading
 - Capable of 1050°C (1922°F) operation

68

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Conclusions Cont'd

- **SETS in a GTCC evaluated by LSU**
 - ~5% loss in efficiency (from 55.7% to 52.9%)
 - \$15 to \$18/ton CO₂ cost with 900°C sorbent
- **SETS in an UltraFuelCell evaluated**
 - 4 MW_e UFC analyzed by Robert James of NETL
 - 2% loss in efficiency, 1050°C max sorbent
 - 50 MWe and other cases by TDA
 - Cost less than \$10/ton CO₂ in large plants
 - Low Temperature limit (800°C increases \$10/ton to \$15)
- **Value of CO₂ to EOR \$15 to \$44/ton CO₂**
 - Greater than costs

69

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Why SETS Works So Well

- **No additional energy for CO₂ separation**
- **High Throughput reactors**
= low capital costs
- **Sorbent lasts forever (almost)**

70

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Recommendations

- **Develop higher temperature sorbent**
1050°C = 1,922°F
 - Better CO₂ capture costs for both GTCC and UFC
 - Near limit for high strength, weldable super alloys for reactor and lines
- **Demonstrate the real cycle in the preferred reactors**
 - Fluidized bed (reducing)
 - Transport reactor (oxidizing)
 - Ability to test for a very large number of cycles since it provides continuous operation

71

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Potential Near Term Applications

- **Partial oxidation of NG to CO + 2H₂**
 - for FT liquids (e.g., Alaska North Slope NG)
 - other chemicals
- **Inert gas generator**
 - N₂ very low O₂ with co-generated heat (steam)
 - CO₂ for chemical use (e.g., urea)
- **EOR**
 - CO₂ + Steam with GT
 - Co-generated power
 - Near term carbon sequestration without TAXES

72

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Appendix C

A NOVEL CO₂ SEPARATION SYSTEM

Phase III Plans

January 10, 2001

**VISIT TO NETL
U.S. DEPARTMENT OF ENERGY**

TDA Research Inc. • Wheat Ridge, CO 80033 • www.tda.com

Phase III Objectives

- **Improve Ni based sorbents**
 - Show ability for extended cycling at 1050°C
 - Transfer technology to a commercial vendor Saint-Gobain NorPro Corporation (formerly Norton Chemical Process Products Corporation)
- **Show performance in preferred reactors**
 - Oxidation – transport reactors
 - Reduction – fluidized bed reactors
- **Generate data on attrition rate**
 - Large number of cycles on one batch of sorbent,
 - measure losses

Project organization

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Phase III SETS Reactors at KBR

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Phase III KBR Test Conditions

Application	Pressure	Temperature
Fuel Cell: Low Temperature	1.5 to 4 atm (8 to (45 psig)	800°C
High Pressure Fuel Cell	1.5 to 4 atm (8 to (45 psig)	900°C up to 1050°C
GTCC	6.8 atm (100 psia)	800 up to 1050°C
Steam Reforming	6.8 atm (100 psia)	Up to 1050°C

77

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Phase III Tasks

- **Task 1: Improve Sorbents**
 - High temperature Ni
 - TDA & NorPro
- **Task 2. Design the small scale SETS system**
 - TDA & KBR
- **Task 3. Fabricate & check out the small scale SETS system (KBR)**
- **Task 4. Test the Low Temperature sorbent**
 - TDA & KBR
- **Task 5. Tests the High Temperature sorbent**
 - TDA & KBR
- **Task 6. Revised Economic Analysis (TDA)**
- **Task 7. Reporting**

78

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Phase III Schedule

79

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Phase III Major Milestones

	Date	Month #
TDA receives Phase III award from DOE	July 2001	1
Subcontract placed with KBR	October 2001	4
a. SETS system design completed	February 2002	7
b. Fabrication & check out completed	November 2002	16
c. Tests with low temperature sorbent	February 2003	19
d. Tests with high temperature sorbent	April 2003	22
e. Final report on Phase III	May 2003	23
Subcontract placed with Norton	October 1, 2001	4
a. Sorbents received	January 2002	6
b. Sorbents screened	May 2002	10
c. Pre-commercial quantity produced	October 2002	15
TDA 's responsibilities		
a. High temperature in-house sorbents	October 2001	4
b. Screen Norton sorbents	May 2002	10
c. Estimated cost of CO ₂ capture	April 2003	22
d. Analysis of commercial uses	May 2003	23
e. Final Report to DOE	June 2003	24

80

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