

Small Scale Evaluation of the Combustion  
and Emission Characteristics of SRC Oil\*

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INTRODUCTION

A potential alternate approach to the use of petroleum-based fuels in conventional combustion systems is liquid fuels derived from coal. In the present study, the combustion and emission characteristics of SRC fuel oil (a synthetic liquid fuel derived from coal) were evaluated in a laboratory boiler at a scale of 3 million Btu/hr. The facility was designed to simulate the combustion conditions found in large utility boilers. The synthetic liquid fuel was produced by the solvent refined coal process (1)\*\* at the Department of Energy funded, and Gulf operated Solvent Refined Coal Pilot Plant.

The high nitrogen content (approximately 1% to 1.5% by weight) of the solvent refined coal oil (SRCO) is potentially a cause of high nitrogen oxides (NO<sub>x</sub>) emissions from conventional combustion systems. It is known that in the combustion of fuels containing chemically bound nitrogen, a fraction of this nitrogen combines with oxygen in the air to form nitrogen oxides which are emitted as pollutants in the flue gases. One percent by weight of nitrogen in a typical fuel oil has a potential of producing about 1,300 ppm (dry) of nitrogen oxides in boiler flue gases at 3% excess oxygen if all nitrogen in the fuel is converted to nitrogen oxides. For conventional combustion configurations, approximately 20% to 50% of the fuel nitrogen is converted to NO<sub>x</sub> with the percentage conversion decreasing as the nitrogen content of the fuel increases. Other variables such as excess air level and temperature play a lesser role (2,3). However, combustion modifications can be used to limit the conversion of fuel nitrogen to levels considerably less than the normally encountered 20% to 50%. These methods have been satisfactorily and repeatedly demonstrated on utility boilers. Additional nitrogen oxides are formed in high-temperature burner flame zones by oxidation of a small portion of the nitrogen in the combustion air.

The objective of this study was to document the combustion characteristics and the emissions of NO<sub>x</sub>, SO<sub>x</sub>, and particulates while burning SRC fuel oil in a boiler. In particular, the sensitivity of the emissions to load and excess air variations as well as air preheat, staged combustion, and flue gas recirculation were determined. These small scale test results can then be used to aid in assessing the performance of this fuel in a typical full scale utility boiler.

During the investigation, direct comparisons of the emission characteristics of the coal-derived fuel were made to those from a typical low-sulfur #6 fuel oil (0.24% nitrogen by weight) and a #2 oil with a nitrogen content of 0.024% by weight. Selected characteristics of the three fuel oils are shown in Table 1 along with the analysis of the western Kentucky coal from which the SRC oil was derived.

\*Sponsored by Gulf Mineral Resources, Co., Denver, Colorado.

\*\*Numbers in parentheses correspond to references at the end of the paper.

No attempt was made to explore the possible changes in storage and handling procedures which might be necessary to fire the coal-derived oil in a boiler originally equipped to fire residual, distillate oils or other fuels.

TABLE 1. TYPICAL FUEL CHARACTERISTICS

	Western Kentucky Coal	SRCO	#6 Oil	#2 Oil
C, wt %	72.2	86.6	86.61	86.82
H, wt %	5.0	8.38	12.25	12.69
N, wt %	1.4	1.12	0.24	0.024
S, wt %	3.6	0.26	0.28	0.11
Ash, wt %	10.5	0.008	0.016	0.003
O <sub>2</sub> , wt % (by difference)	7.3	3.63	0.6	0.35
Gross Heat of Combustion, Btu/lb	13,150	17,040	19,150	19,190
API Gravity, 60 °F	--	8.3	2.3	32.3
Viscosity, SSU at 140 °F	--	35.6	324 (100°F)	34

#### APPARATUS

The basis of the combustion facility is a modified 80-HP firetube boiler which for these tests was fired at a rate of 3 million Btu/hr. The combustion modeling principles used in designing this facility to simulate combustion conditions in full scale utility boilers are discussed in Reference 4. The apparatus, shown in Figure 1, can be divided into five groups of components: (1) fuel supply, (2) air supply, (3) burner, (4) boiler furnace, and (5) instrumentation.

The oils were drawn from 55 gallon drums and delivered to the burner with a plunger type positive displacement metering pump. During tests with the #6 oil, the drums were heated to raise the oil to its pumping temperature and electrically heated to its firing temperature just upstream of the oil gun.

Air from an indirect-fired preheater passed through an insulated duct and a venturi meter to two valves which were then used to regulate the flow split between the burner air and second-stage air. For tests involving two-stage combustion, the second-stage air passed down an insulated duct, through another venturi meter, then to a perforated torus inside the combustion chamber. The secondary air was injected from this torus radially toward the axis of the combustion chamber through 32 orifices each 9/16" in diameter. Downstream of the burner air valve, the burner air flow was split into two ducts which enter the windbox from opposite sides. Recirculated flue gas, when used, was added to the combustion air upstream of the air preheater.

The burner used in this study was a scaled down version of a typical utility boiler oil burner. The burner utilizes a single 16-vane variable vane-angle air register for imparting swirl to the air flow. During these tests, the vanes were fixed at 20 deg. For the test results reported in this paper, a 30 deg. hollow cone mechanical type atomizer was used to deliver the oil to the combustion chamber. A more complete description of the burner can be found in Reference 5.

The boiler shell was an 80-HP Scotch dry-back type. At a firing rate of 3 million Btu/hr, the boiler's volumetric firing intensity was 38,500 Btu/hr-ft<sup>3</sup>, which is typical of oil-fired utility boilers. The steam produced by this boiler is vented at one atmosphere. Also, the laboratory boiler's combustion chamber was fitted with a stainless steel liner to give wall temperatures of about 800 °F, also typical of utility boilers.

The flue gas concentrations of NO, O<sub>2</sub>, CO, and SO<sub>2</sub> were analyzed continuously using a Thermo Electron Corp. chemiluminescent nitric oxide analyzer, a Beckman Model 742 oxygen electrolytic analyzer, an Horiba Model PIR2000 nondispersive infrared carbon monoxide analyzer, and a Dupont 411 photometric analyzer for sulfur dioxide. Smoke levels were determined using a Bacharach smoke tester (ASTM D2156-65) and reported as Bacharach smoke spot numbers, the scale of which consists of a series of ten spots from 0 to 9. Total particulate loadings were determined using EPA Method 5.

#### TEST RESULTS

The combustion and emission characteristics of the SRC oil were evaluated over a range of operating parameters typical of large utility boilers. With the exception of the variable air preheat tests, the test results reported were obtained at a nominal condition of 550 °F combustion air temperature and a firing rate of 3 million Btu/hr. Results will be presented for the following methods of controlling NO:

reduced excess air	fuel blending
staged combustion	ammonia injection
flue gas recirculation	water injection for smoke suppression
reduced air preheat	fuel additives for smoke suppression

The methods listed in the left-hand column above were investigated early in the testing. It was found that while the combustion modifications were effective in controlling nitric oxide, they were limited in their degree of effectiveness due to a tendency of the SRCO to smoke when the control methods were fully implemented. This greater tendency of the SRC oil to smoke than the other fuels tested is thought to be due to the high aromatic content of the coal-derived liquid.

The effect of excess air and staged combustion on the nitric oxide emissions for the SRCO along with the #6 and #2 oil are shown in Figure 2. The open symbols are single stage combustion and the closed symbols are two-stage combustion tests. During the staged combustion tests, the overall excess air level was maintained at 16% (3% overall excess O<sub>2</sub>). Figure 2 shows that for single-stage combustion of SRCO, the NO produced is very sensitive to the excess air level and significantly higher than the NO emissions from the #6 and #2 oil. For two-stage combustion, the NO produced reached a minimum at about 80% A<sub>B</sub> (A<sub>B</sub> is the theoretical air at the burner and A<sub>0</sub> is the overall theoretical air; for single stage combustion, A<sub>B</sub> = A<sub>0</sub>), with further reductions in burner air flow resulting in an increase in the NO emissions. This effect has been observed by other investigators (6-9) and is attributed to NO formation during combustion in the second stage region.

When flue gas recirculation, at rates up to 20%\*, was utilized in conjunction with staged combustion, no further reductions in the nitric oxide emissions were observed. Gas recirculation could be expected to have greater effect in boilers in which the heat release per unit area is very high. These units would tend to have higher contribution of thermal NOx, and the use of recirculation would tend to reduce the thermal NO more noticeably.

The effect of the combustion air temperature on the NO emissions is shown in Figure 3 for the SRCO during single stage combustion. This data shows there is a strong effect of the combustion air temperature on the NO emissions (approximately 9 ppm/25 °F, at 120% excess air) and that the sensitivity of the NO emissions to combustion air temperature increases with an increase in the excess air level.

\*Mass of recirculated flue gas/sum of combustion air and fuel flow.

Fuel blending was also investigated as a means of firing the SRCO while limiting the NO and particulate emissions. The NO emissions from blends of SRCO and #6 oil are shown in Figure 4 for both single and two stage combustion.

The homogeneous gas phase reduction of NO by ammonia injection into the SRCO combustion products was also investigated during this study. The reductions in NO which were achieved were in agreement with those obtained and reported with other fuels (10).

Fully implementing the nitric oxide control techniques with the SRC oil, in particular staged combustion, was limited by the tendency of the oil to form high levels of smoke and particulates. This effect is illustrated in Figure 5 where the Bacharach smoke numbers for single stage and two stage firing of the SRCO and #6 oil are compared. During the two stage tests the stack gas oxygen concentration was maintained at 3% (dry basis). For single stage firing, the data in Figure 5 show that the SRCO tends to smoke more than the #6, note that even at 40% excess air ( $A_B = 140\%$ ), a No. 2 smoke spot is obtained. Although for excess air levels above about 10% to 15%, the performance is acceptable in this unit. A striking difference in the performance in the two fuels is seen for two stage combustion conditions. The #6 oil produced a gradual increase in the flue gas smoke level as the first stage was operated more fuel-rich. With the SRCO, large increases in the stack smoke levels were obtained even at moderate staging conditions; a smoke number of 9 was obtained when the burner was operated at  $A_B = 102\%$ . This smoking tendency is suspected to be a consequence of the high aromatic content of the SRCO which is on the order of about 60% based on the carbon-to-hydrogen ratio.

This trade-off in NO and particulate emissions is further illustrated in Figure 6. These results show that in this particular system, staged combustion cannot be used to reduce the NO emissions below the 1974 EPA New Source Performance Standards (NSPS) without exceeding the 1974 NSPS particulate standard. A similar situation will likely exist in a full size unit although, quantitatively, the trade-off may differ from the laboratory scale results.

A number of methods were tested to limit the smoke and particulate formation while implementing staged combustion with the SRCO. These included steam atomization instead of mechanical atomization, water injection into the combustion air, and the use of combustion improving fuel additives (alkali and manganese based).

In this unit the NO and smoke levels were similar for both steam atomization and mechanical atomization. Utilizing water injection into the combustion air (at a rate equal to 7% of the oil flow, volumetric basis) along with staged combustion, the nitric oxide emissions could be reduced to about 260 ppm prior to the onset of smoking. This is about 40 ppm lower than the levels previously obtained with staged combustion alone.

Fuel additives have been used with varying degrees of effectiveness to control smoke emissions from combustion systems. A recent study by Battelle (11) has shown certain additives to be effective in reducing smoke with single stage firing of #6 and #2 oil although the additives may result in an increase of total particulate loadings.

During the present study, various additives were used with the SRCO while firing in a staged combustion mode. The additives chosen for evaluation were: barium naphthenate, calcium naphthenate, and CI-2 (Ethyl Corp. proprietary, manganese based). The naphthenates produced the best results in the Battelle study (11), with CI-2 being less effective. In the present tests, the additive concentrations ranged from 50 to 350 ppm of the primary metal in the oil.

All three additives altered the smoking characteristics of the SRCO with both single stage and two stage combustion. However, the manganese-based additive was most effective in achieving low NO emissions (e.g., lower  $A_B$  at the burner). It was also found that the naphthenates altered the NO formation as well as the smoke formation. As a result, the NO emissions with staging were approximately 30 to 50 ppm higher than for the base condition without the naphthenate additive.

Particulate loadings were determined while operating under staged combustion conditions with the manganese-based additive (CI-2). The results of these tests are presented in Table 2.

TABLE 2. PARTICULATES AND NO EMISSIONS  
WITH SRCO AND CI-2 ADDITIVE

Test No.	1	2	3	4
Additive Concentration (ppm manganese)	0	0	0	345
$A_0$ Total Air, % Theor.	114.0	117.1	119.0	112.9
$A_B$ Burner Air, % Theor.	114.0	103.0	83.0	77.0
Excess $O_2$ , % dry	2.7	3.2	3.5	2.5
CO, ppm dry	35	35	135	40
NO, ppm dry (corr to 3% $O_2$ )	467	344	231	226
Smoke Number	0	3	< 9	8.5
Particulates, lb/MBtu	0.016	0.0168	0.344	0.068

As seen in Table 2, the additive was effective in limiting the particulate emissions during staged combustion. Also, the high particulate emission during Test No. 3 (staged combustion without the fuel additive) is due to carbon formation. Further, the amount of particulate contributed by the additive during Test No. 4 is apparently small. Based on the manganese content in the oil, the manganese would be expected to contribute to the particulates on the order of  $0.014 \text{ lb}/10^6 \text{ Btu}$ . The ash in the fuel contributes at most  $0.004 \text{ lb}/\text{MBtu}$  to the flue gas particulate loading. It appears that the smoke emissions of the SRCO can be controlled on a larger unit with a fuel additive such as CI-2 when two stage or off-stoichiometric firing is used to reduce the nitric oxide emissions. It should be pointed out that tests were not conducted to determine the minimum additive concentration necessary to prevent smoke formation.

In general, the solvent refined coal oil appears to be a useful boiler fuel but its high nitrogen content dictates the need for applying NO control techniques to the system.

Since the SRCO is a very good solvent, compatibility of the oil with typical seals, O-rings, etc, used in boiler applications needs to be investigated.

The major problems encountered with the SRCO during this study were the high NOx emissions without NOx control methods coupled with the smoking tendency upon implementation of combustion modifications for NOx control. However, these small

scale tests show that control techniques are effective in reducing the NOx emissions. The carbon monoxide emissions were also found to be low during the tests and the SO<sub>2</sub> emissions were within the expected range based on the low-sulfur content of the SRCO.

In the laboratory tests, variables such as the location of second stage air addition, atomizer design, air swirl setting, etc. were not fully investigated. With a more extensive effort, lower NOx levels than demonstrated in this study may be possible on many large scale boilers. In addition, low NOx designs for boilers and burners may be expected to further aid in minimizing NO emissions from the combustion of the SRC oil.

#### CONCLUSIONS

The following specific conclusions can be drawn from the results of these small scale tests:

1. The combustion performance of the solvent refined coal oil is equivalent to that of typical utility type fuel oils. It is volatile (similar to #2 oil) and does not require preheating to achieve an acceptable viscosity for pumping or atomization.
2. Potential problems with furnace slagging and metal wastage occasionally encountered with coal combustion should be negligible with SRCO because of its low sulfur and ash contents.
3. Nitric oxide emissions could be maintained at about 0.4 lb/10<sup>6</sup> Btu for the SRCO utilizing combustion conditions typical of many large utility boilers. This was accomplished with two-stage combustion and 3% excess oxygen in the flue gas. At this condition, low stack gas concentrations of carbon monoxide and particulates were maintained.
4. Nitric oxide emissions could be reduced below 0.3 lb/10<sup>6</sup> Btu for the SRCO by
  - (1) blending the SRCO with other petroleum-based fuel oils having much lower fuel nitrogen and then firing with two stage combustion, or
  - (2) using a fuel additive containing manganese and then firing with two stage combustion.Acceptably low stack gas concentrations of carbon monoxide, smoke, and particulates were obtained.
5. Air preheat has a significant effect on the NOx emissions while firing SRCO.

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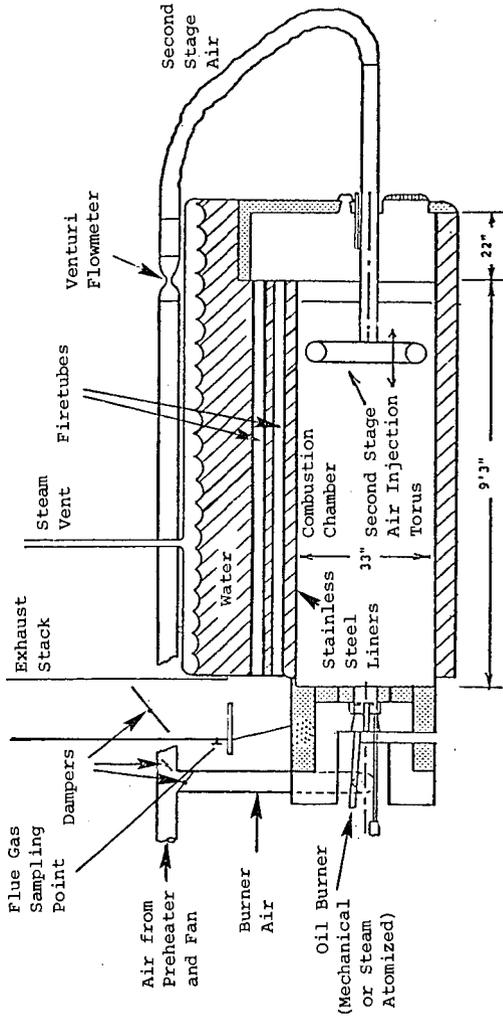


Figure 1. Schematic of 80 horsepower boiler.

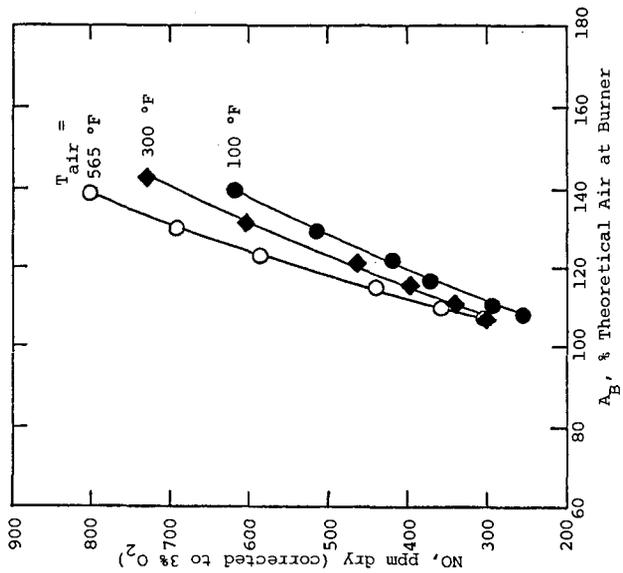


Figure 3. Effect of air preheat on NOx emissions from SRCO; single stage combustion.

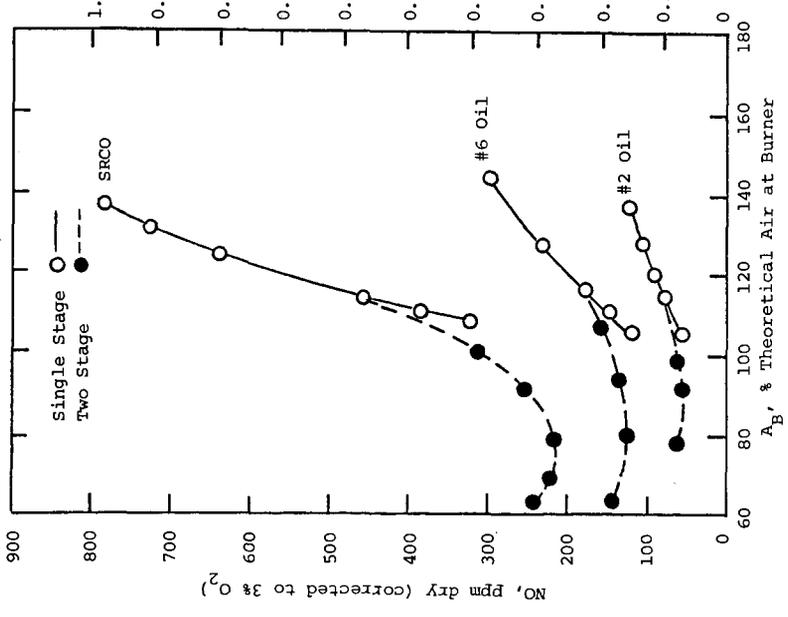


Figure 2. NOx emissions from SRCO, #6 oil, and #2 oil (single-stage and two-stage combustion).

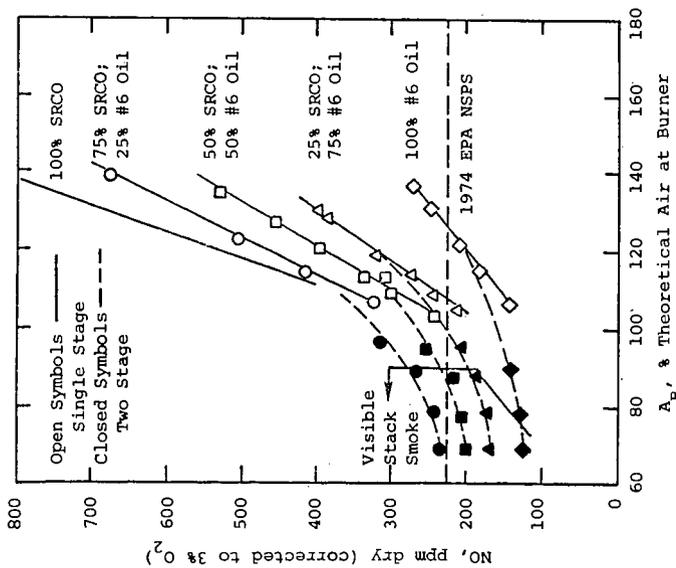


Figure 4. NO emissions from blends of SRCO and #6 oil.

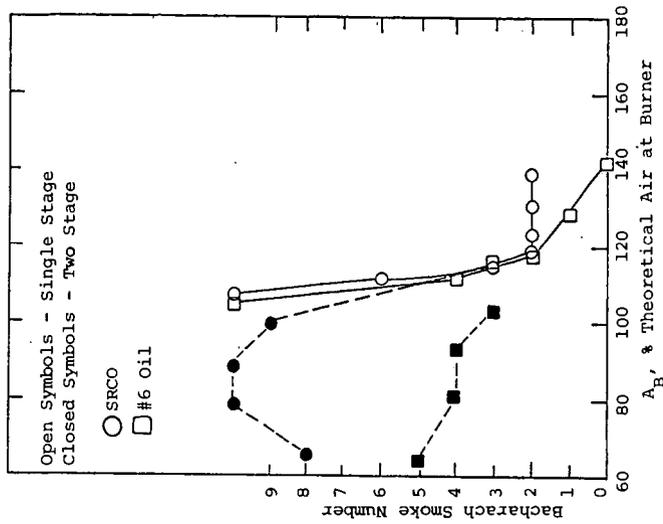


Figure 5. Smoke levels for SRCO and #6 oil.

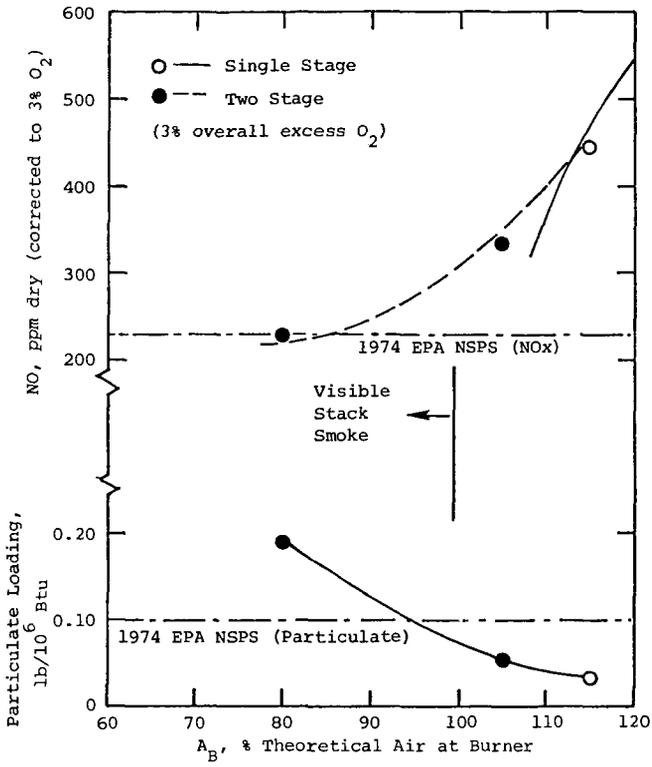


Figure 6. Particulate and NO emissions - SRCO.