# INTEGRATED DRY NOx/SO2 EMISSIONS CONTROL SYSTEM

FINAL REPORT, VOLUME 2: PROJECT PERFORMANCE AND ECONOMICS

## Appendix F

## BENCH SCALE TEST REPORT
## BY
## COLORADO SCHOOL OF MINES

## SIMULTANEOUS REMOVAL OF $SO_2$ AND $NO_x$

## BY SELECTED SODIUM BASED DRY SORBENTS

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# CHAPTER I

# INTRODUCTION

## 1.1 Background and Objectives

In recent years, international pressures to decrease $NO_x$ emissions are becoming as strong as those regarding $SO_2$. Until now the technology of choice to achieve this requirement is selective catalytic reduction, SCR. Due to the high investment and operation costs of the SCR process, the interest in the development of lower-cost $NO_x/SO_2$ abatement process has been renewed(1), (2).

Now it is well established that Sodium Bicarbonate is a very effective reagent for $SO_2$ removal in flue gas by a low investment cost dry injection process(3), (4), (5). Researchers working for the Electric Power Research Institute, EPRI, have investigated the use of sodium compounds as dry desulfurization agents since 1965. In their final report, EPRI GS-6850, published in 1990(6), they found that, of the five sodium sorbents evaluated, sodium bicarbonate and sodium sesquicarbonate exhibited the best performance, with 70-90% sulfur dioxide removal for subbituminous coals. The most important parameters for achieving high sulfur dioxide removals were flue gas temperature and sorbent particle size. Laboratory investigations into the reaction mechanism showed a complex system chemistry. A sodium sorbent, sulfur dioxide, nitric oxide, and oxygen are all required for nitrogen dioxide generation. Of several additive materials evaluated for effectiveness in mitigating nitrogen dioxide production, the two most promising were urea and anhydrous ammonia. However, the study on additive effects on nitrogen dioxide removal is not included in this report. EPRI's work also revealed that the amount of nitrogen oxide removal that was possible was a direct function of the amount of sulfur dioxide captured. In the sorbent-$NO_x$-$SO_2$ reaction system, they found that the higher the $SO_2$ concentration entering the system, the higher the $NO_x$ removal potential. The optimum temperature for $NO_x$ removal appears to be 350°±75°F. Furthermore, it appears as if oxidation of NO to $NO_2$ only occurs on the surface of the sodium and when $SO_2$ is actively being reacted with the sorbent.

Public Service Company of Colorado has received a contract from the Department of Energy Clean Coal Program to develop a commercial scale demonstration project which includes utilization of a sodium based dry scrubbing retrofit process for $SO_2$ and $NO_x$ removal from power plant flue gases. Sodium based scrubbing agents, such as sodium bicarbonate have the advantage over calcium based agents in that they are much more reactive. For example, direct injection of solid sodium bicarbonate into a flue gas stream prior to a fabric filter particulate removal system in an actual power plant can result in an 80% $SO_2$ removal efficiency. Such a system can be added to an existing power plant much easier than a calcium based wet scrubbing system, and operating costs are much less. Sodium bicarbonates can also significantly reduce $NO_x$ emissions. However, NO that is formed in the furnace is converted in the process to $NO_2$, which is a brown colored gas. The net effect is a flue gas with significantly lower levels of

$NO_x$ pollutants, unfortunately with the characteristic brown plume of $NO_2$, which is visually offensive.

As part of their contract, we have performed bench scale studies to develop a kinetic model from experimental measurements of this reaction system, with the objective of gaining an understanding of the kinetics of $NO_2$ formation, with ultimate goals of minimizing its formation. Among the variables to be investigated include: water vapor concentration in the feed, reaction temperature, concentrations of $SO_2$ and $NO_x$ in the flue gas, and choice of solid (sodium bicarbonate versus sodium sesquicarbonate). Although the ultimate objective of the program is to develop a kinetic model, the experimental results can also be used to determine, qualitatively, how each of the variables affects the removal of $SO_2$ and $NO_x$ and the generation rate of $NO_2$ in the product gas. Thus, one purpose of this report is to present the qualitative conclusions that can be drawn from the data.

## 1.2 Reaction Mechanisms:

To study the kinetics of this gas-solid reaction, we must know the reaction chemistry first. Two different reaction chemistries which have been proposed were included in the kinetic studies of this report. The one was developed by work supported by EPRI(6) and the other is work done by Solvay(12). These are described below.

### 1.2.1 Decomposition of sodium based dry sorbents to sodium carbonate.

In EPRI's work, the sodium carbonate must be made available to $SO_2$ in the flue gas stream by the injection of a sodium bearing compound which thermally decomposes to form sodium carbonate. To verify the decomposition of these sodium based dry sorbents which depends highly on temperature, a brief series of flow reactor tests were conducted to investigate the extent of decomposition of nahcolite, trona, and processed sodium sesquicarbonate in the dispersed phase without any flue gas being present.

At a temperature of 275°F, nahcolite exhibited very little decomposition at residence times up to 1.2 seconds; but at a temperature of 550°F, over 70 percent of the bicarbonate component of the nahcolite decomposed at residence times as low as 0.5 seconds. The trona materials exhibited a higher degree of decomposition at the lower temperature (275°F). Reviewing these resulting data suggests that the initial availability of carbonate in the trona coupled with the decomposition of the material at low temperature may explain the more rapid reaction with $SO_2$ compared to nahcolite.

Also, the decomposition of the sorbents resulting in the evolution of $H_2O$ and $CO_2$ can lead to an increase in the specific surface area of the reactive sorbent. Since the dry $SO_2$ removal process involves a gas solid reaction, the reaction rate and ultimate sorbent utilization are normally considered to be a function of the surface area which also explains why $SO_2$ is removed more rapidly in the presence of trona than in the presence of nahcolite. The postulated initial reactions for the dry sodium scrubbing process proposed by EPRI were:

Bicarbonate

$$2NaHCO_3 \;==>\; Na_2CO_3 + CO_2 + H_2O \qquad (1\text{-}1)$$

Sesquicarbonate

$$2[Na_2CO_3\text{-}NaHCO_3\text{-}2H_2O] \;==>\; 3Na_2CO_3 + 5H_2O + CO_2 \qquad (1\text{-}2)$$

### 1.2.2 Removal of $SO_2$ by dry sorbents

In Solvay's work, the IFP (Institute Francais du P'etrole) laboratory gives confirmation of the ability of sodium bicarbonate to remove simultaneously $SO_2$ and NOx in flue gas. They ascribed the abatement of $SO_2$ to the reaction between undecomposed dry sorbents and $SO_2$. The reaction describing sodium bicarbonate sulfation is as follows :

$$NaHCO_3 + SO_2 \;==>\; NaHSO_3 + CO_2 \qquad (1\text{-}3)$$

and sodium bisulfite later will dehydrate to the sodium pyrosulfite :

$$2NaHSO_3 \;==>\; Na_2S_2O_5 + H_2O \qquad (1\text{-}4)$$

EPRI proposed that $Na_2CO_3$ is the reactant which causes $SO_2$ reduction. The typical reaction between sodium carbonate and sulfur dioxide is as follows :

$$Na_2CO_3 + SO_2 + 1/2\ O_2 \ ==> \ Na_2SO_4 + CO_2 \qquad (1\text{-}5)$$

The formation of sodium sulfate, $Na_2SO_4$, or sulfite, $Na_2SO_3$ as the reaction product is strongly dependent on flue gas temperature if nitric oxide is not present in the test gas. Nitric oxide in the test gas, however, appears to not only change the $SO_2$ removal chemistry but also takes part itself in a complicated set of reactions which result in sodium nitrate formation and $NO_2$ production. The EPRI study proposed the following reaction for NO reduction in the presence of $SO_2$ and sodium with some undetermined intermediate steps:

$$NO + 1/2\ O_2 \ ==> \ NO_2 \qquad (1\text{-}6)$$

### 1.2.3 Removal of NO by dry sorbents

With the intermediate sodium pyrosulfite formation, Solvay has an alternate interpretation for nitric oxide reduction and sodium nitrate formation. They believe the NO reduction results from the sodium pyrosulfite nitration and sodium bisulfite nitration are described as follows:

Sodium pyrosulfite nitration

$$Na_2S_2O_5 + 2NO + O_2 \implies NaNO_2 + NaNO_3 + 2SO_2 \qquad (1\text{-}7)$$

Sodium bisulfite nitration

$$2NaHSO_3 + 2NO + O_2 \implies NaNO_2 + NaNO_3 + 2SO_2 + H_2O \qquad (1\text{-}8)$$

The stoichiometric ratio of NO to $SO_2$ in equation (1-7) has later been demonstrated in my experimental program which suggests that Equation (1-7) is in fact the reaction step and sodium pyrosulfite is the intermediate sulfur compound required for the removal of NO.

### 1.2.4 Formation and reduction of $NO_2$

Solvay did not discuss the formation and reduction of $NO_2$ in their work(12). However, from Equation (7) and Equation (8), $NO_2$ might be produced by decomposition of the relatively unstable sodium nitrite. This behavior has been observed in our laboratory.

In EPRI's work(6), it is believed that $NO_2$ formation occurs directly from NO and that $NO_x$ removal only occurs by the reaction of $NO_2$ with the sodium based dry sorbent. This reaction is described as follows:

$$Na_2CO_3 + 3NO_2 \implies 2NaNO_3 + NO + CO_2 \qquad (1\text{-}9)$$

### 1.2.5 Summery of mechanisms

For the simultaneous removal of $SO_2$ and $NO_x$ by sodium bicarbonate, the following are the possible mechanisms proposed by EPRI and by Solvay:

EPRI's mechanism

Decomposition of sodium bicarbonate

$$2NaHCO_3 \implies Na_2CO_3 + CO_2 + H_2O \qquad (1\text{-}1)$$

Sulfation of sodium carbonate

$$Na_2CO_3 + SO_2 + 1/2\ O_2 \implies Na_2SO_4 + CO_2 \qquad (1\text{-}5)$$

Oxidation of nitric oxide

$$NO + 1/2\ O_2 \implies NO_2 \qquad (1\text{-}6)$$

Nitration of sodium carbonate and removal of $NO_2$

$$Na_2CO_3 + 3NO_2 \implies 2NaNO_3 + NO + CO_2 \qquad (1\text{-}9)$$

Solvay's mechanism

Sulfation of sodium bicarbonate

$$NaHCO_3 + SO_2 \implies NaHSO_3 + CO_2 \qquad (1\text{-}3)$$

Dehydration of sodium bisulfite

$$2NaHSO_3 \implies Na_2S_2O_5 + H_2O \qquad (1\text{-}4)$$

Nitration of sodium pyrosulfite

$Na_2S_2O_5 + 2NO + O_2 ==> NaNO_2 + NaNO_3 + 2SO_2$ (1-7)

Nitration of sodium bisulfite

$2NaHSO_3 + 2NO + O_2 ==> NaNO_2 + NaNO_3 + 2SO_2 + H_2O$ (1-8)

The major difference between the two schemes is the manner in which NO reacts with the solid. In the EPRI scheme NO is first oxidized to $NO_2$ and the $NO_2$ reacts with the solid. In the Solvay scheme NO reacts directly with a reaction intermediate formed from the removal of $SO_2$. The significant difference using these different schemes will be discussed in Chapter V. Another difference is the reaction for the removal of $SO_2$, which reacts directly with the solid by the Solvay scheme and reacts with $Na_2CO_3$ formed after removal of $H_2O$ and $CO_2$ from $NaHCO_3$. This difference is of less significance since dehydration of the solid can occur either before or after the sulfation without there being a significant effect on the kinetics.

# CHAPTER II

# EXPERIMENTAL PROCEDURE

## 2.1 Reactor Configuration

A dry sorbent, bench scale, batch reactor was erected to conduct the experimental study. The objective of the experimental study was to obtain the intrinsic rate of the acid gas removal reactions by either sodium bicarbonate or sodium sesquicarbonate. The apparatus used in this investigation consists of $SO_2$ and NO feed units, a neutralization bottle containing 1M NaOH solution designed for trapping $SO_2$ and $NO_x$ acid gases, a background gas feed unit containing 3% oxygen and 97% nitrogen, a batch reactor with heating control unit, and a gas analysis system.

A batch reactor, designed and constructed for this study is shown in Figure 1. The basic components of the batch reactor system are a 12864 ml batch reactor to contain the reaction mixtures, a dry sorbent, a heating control unit to keep reaction temperature constant between 100 to 300°C, and a propeller type mixing unit to eliminate temperature and mass transfer gradients surrounding the dry sorbent particles.

The batch reactor is made of stainless steel with four fittings on the top cover. The first fitting, V2, a control valve with 1/2" opening, is designed for either gas or sorbent powder injection. The second fitting, V3, also a control valve with 1/4" opening, is designed for draining the unreacted acid gases to a neutralization bottle containing 1M

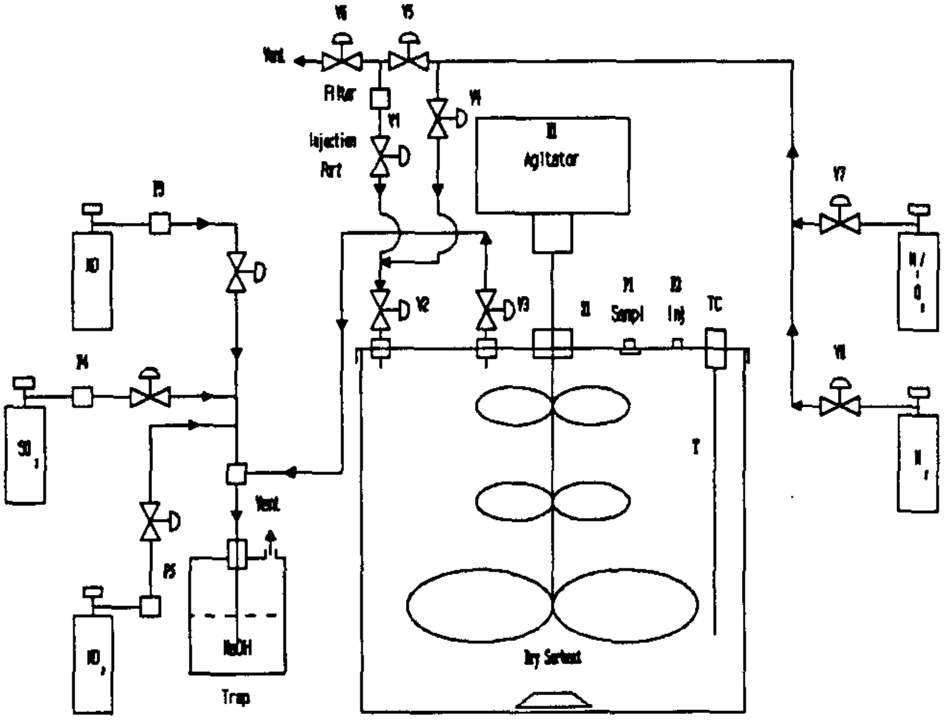


Figure 1. DRY SORBENT SCRUBBER SYSTEM

NaOH solution. The third fitting, P1, a sampling port with 1/2" opening, is a swagelock fitting equipped with a 9 millimeter diameter septum. The fourth fitting, P2, an injection port with 1/2" opening, is the same as the sampling port. Both sampling and injection ports are used for withdrawing the reacting gas mixtures and for injecting acid gases, $SO_2$ and NO.

A Haake Buchler stirring motor, M1, with a torque range from 55 to 60 in-lb is used to actuate a propeller type mixing device with the speed ranging from 0 to 700 rpm. The mixing device is composed of a 10" length x 1/4" diameter stainless steel stirring rod, two pairs of 3" long blades, and one pair of MixMor 7-1/2" propellers. The blades are tightened with screws on the stirring rod in different positions as shown in Figure 1. A teflon type Conax sealant is used to seal the rotating rod at ambient pressure in the reactor.

The major components in the heating control unit are a Watlow mica band heater with a size of 9" ID x 2" width and output power 1800 Watt, an Omega Series 920 temperature controller TC with an accuracy of 1% full scale, and an Omega type K thermocouple, T.

## 2.2 Analytical Techniques

Analytical techniques include analysis of $SO_2$ and analysis of $NO_x$ and NO. Conventionally, the extent of conversion in a gas-solid reaction is measured by recording the weight gain of the pellet with a thermal balance during the reaction. However, in the $SO_2$-$NaHCO_3$ or $NO_x$-$NaHCO_3$ system, the molecular weight difference between solid reactant $NaHCO_3$ and solid product either $Na_2SO_3$, or $NaNO_3$ is small and since formation of $Na_2SO_4$ and $NaNO_2$ can also occur, the weight change is not a measure of the extent of gaseous reaction. Use of a gas chromatograph makes it relatively easy to follow the reaction by observing the varying concentrations of gas reactants $SO_2$ and NO or $NO_x$.

### 2.2.1 Analysis of $SO_2$

The internal standard method was used to determine the concentrations of $SO_2$ accomplished by an Hewlett Packard model 5890 gas chromatograph equipped with a thermal conductivity detector. Initially, a 8' x 1/4" Supelco porapak Q glass column with particle size 80/100 at a temperature of 70°C separated air first, then carbon dioxide, water, and sulfur dioxide in order of retention times of about 0.31, 0.83, 3.97, and 8 minutes, respectively. Helium was used as a carrier gas. The operating conditions for the $SO_2$ analysis are stated in Table 1. The calibration curve is shown in Figure 2. The concentrations of $SO_2$ used for the calibration were determined by injecting a known amount of $SO_2$ into the reactor of known volume. The calibrated input volume of $SO_2$ was determined by a syringe and a stainless steel rod that was calibrated using measured water volumes. The calibration data are shown in Table 2. The sample size used in the gas chromatograph was also calibrated and the raw data are shown in Table 3. Later,

Table 1. Operation Conditions of Gas Chromatograph

| Parameters | Conditions |
|---|---|
| Column Temperature : | 70°C |
| Injector Temperature : | 70°C |
| Detector Temperature : | 100°C |
| Column Pressure : | 30 psig |
| Column Flow Rate : | 15 ml/min |
| Attenuation : | 0 |
| Zero : | 0 ± 0.01 mV |

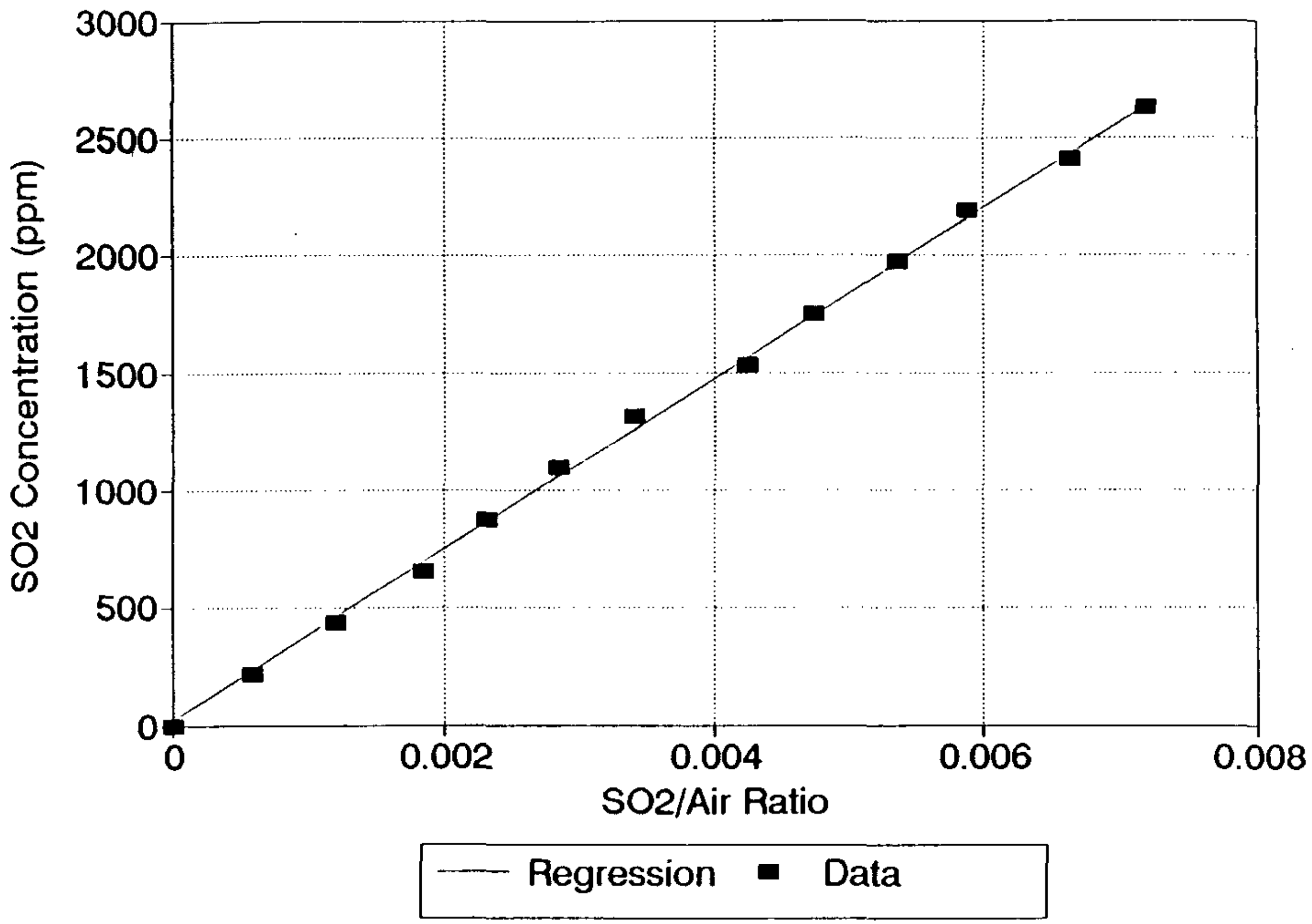


Figure 2. SO2 Calibration Curve Using GC Equipped with TCD

Table 2. Calibration for a constant input syringe

| No. | W1 (g) | W2 (g) | DW (g) | V (ml) |
|---|---|---|---|---|
| 1 | 13 | 15.8 | 2.8 | 2.804965 |
| 2 | 12.96 | 15.76 | 2.8 | 2.804965 |
| 3 | 12.76 | 15.58 | 2.82 | 2.825 |
| 4 | 12.92 | 15.72 | 2.8 | 2.804965 |
| 5 | 12.82 | 15.59 | 2.77 | 2.774912 |

* No : order of sampling bottle which is used to contain distilled water

W1: weight of bottle without water

W2: weight of bottle plus constant input of water

DW: net weight of a constant water input

V : volume of water estimated from DW with water density 0.99823 g/cc at 20°C

* The constant input volume is 2.80 ml

Standard Error = 4.86E-6 ml

Table 3. Calibration of a sample size for gas chromatograph

| No. | Bottle | + Water | Water | Inj. Vol. |
|---|---|---|---|---|
| | (g) | (g) | (g) | (ml) |
| 1 | 12.72 | 17.59 | 4.87 | 4.86138 |
| 2 | 12.9 | 17.77 | 4.87 | 4.86138 |
| 3 | 12.67 | 17.54 | 4.87 | 4.86138 |
| 4 | 12.86 | 17.74 | 4.88 | 4.871362 |
| 5 | 12.81 | 17.66 | 4.85 | 4.841416 |

* The standard error is 0.003599 ml

it is shown that this gas chromatographic procedure leads to errors in the $SO_2$ concentration due to the presence of $NO_x$ in the reaction mixture. The evidence of this phenomena obtained from blank tests will be discussed later.

### 2.2.2 Analysis of NO and $NO_x$

The Porapak Q glass collum used to determine $SO_2$ concentration with sample size greater than 50 ul was not able to separate NO from air due to the large amount of background gas, 97% nitrogen and 3% oxygen. The gas chromatographic (GC) determination of sulphur and nitrogen gases ($H_2S$, COS, $SO_2$, $NH_3$, $N_2O$, NO, $NO_2$) has previously been reported by many workers(7) with different detectors and stationary phases. From the early commercial availability of porous polymer beads (PPBs), these polymeric phases were considered a good choice for the determination of reactive gases, owing to their low polarity(8),(9) and good stability(10). Gianrico Castello and his coworker(7) performed a series of investigation on various Chromosorb Century Series porous polymer bead stationary phases for the simultaneous determination of sulphur and nitrogen gaseous compounds. According to their results, it seemed that we would be able to use Chromosorb 103 to separate our chemicals at low temperature, less than 30°C. A 10 feet long glass column with 2 millimeter inside diameter packed with 80/100 Chromosorb 103 polymer beads and a 30 feet stainless steel column with 0.085 inch inside diameter packed with Gas Chrom MP-1 suggested by Alltech Company were therefore used. Unfortunately, the adsorption and decomposition phenomena often indicated as the cause of the anomalous response of reactive gases on porous polymer columns were found to be a real problem for polar compounds. Reaction of nitrogen oxides with the polymer, resulting in sample disappearance, formation of decomposition products, yellowing of the polymer beads and changes in retention times of non-reactive compounds, after the injection of large reactive samples, was also observed in our testing. Reproducible data could not even be obtained at very low temperatures of 18°C where reactivity of nitrogen gases might be minimized.

After a significant unsuccessful effort in trying the simultaneous determination of $SO_2$ and $NO_x$ by gas chromatography, a chemiluminescent NO-$NO_x$ analyzer, model 44, developed by Thermo Electron Corporation was ultimately used to detect concentrations of NO and $NO_x$, while $SO_2$ were determined by the separate instrument, GC. The configuration of this analytical device and its flow diagram are shown on Figure 3, and Figure 4 respectively. A dry air gas is used to create ozone which later reacts with nitric oxide (NO) molecules in the gas phase. In the reaction a chemiluminescent decay of the resulting excited nitrogen dioxide ($NO_2$) molecules would produce characteristic light by which the concentration of NO is detected. The typical reactions are described as follows:

$$NO + O_3 = NO_2^* + O_2$$

$$NO_2^* = NO_2 + \text{light}$$

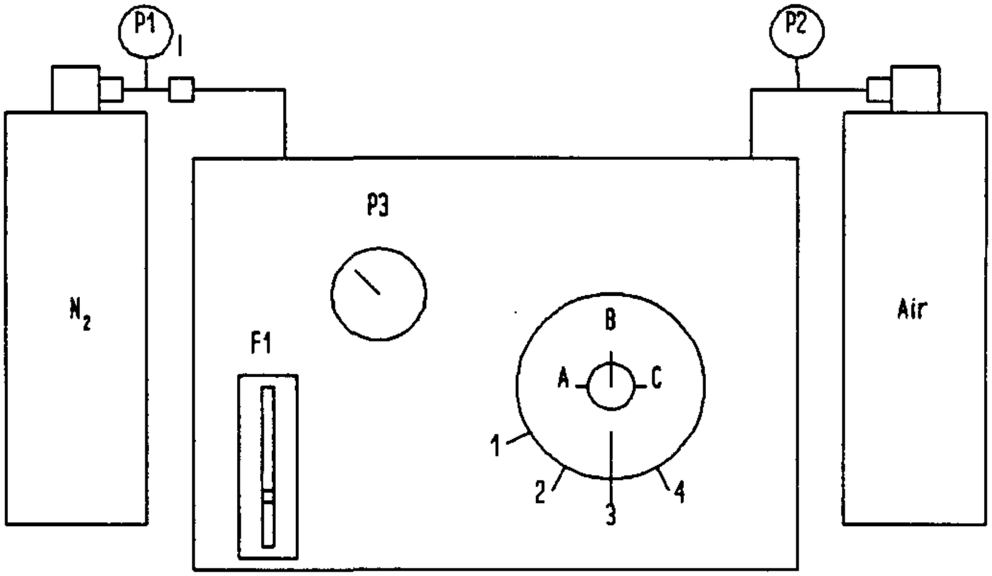


Figure 3. Chemiluminescent NO-NOx Analyzer

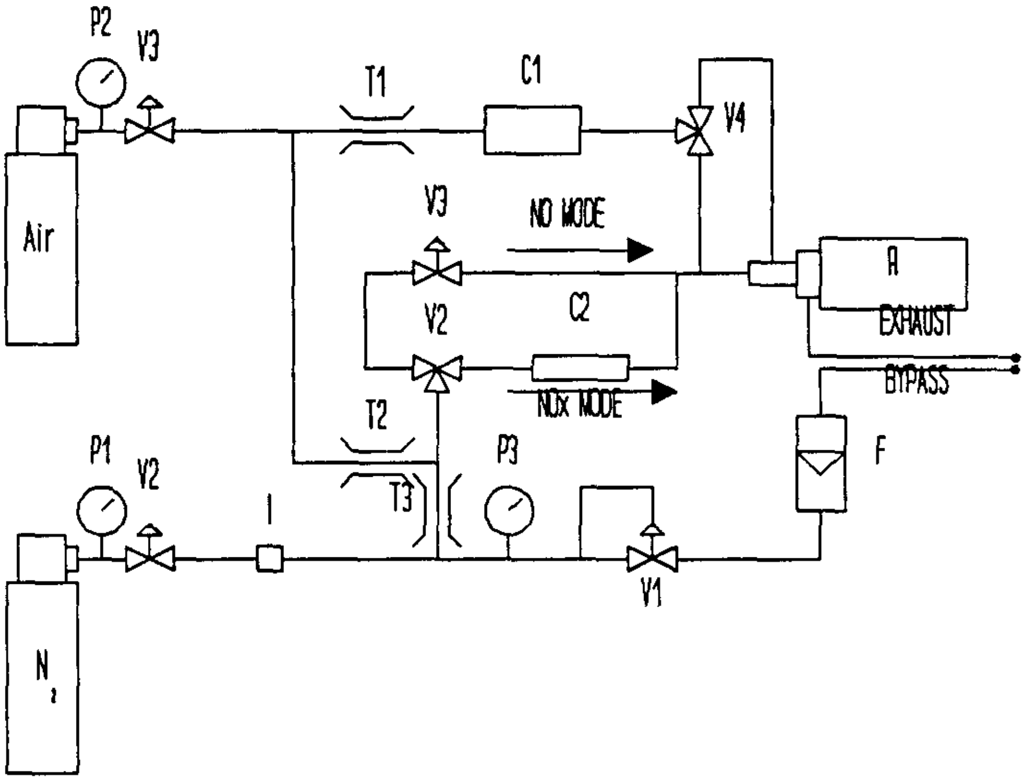


Figure 4. Flow Diagram for NO and NOx Analysis.

As we can see in Figure 4, a sample which includes a gas mixture of NO and $NO_x$ is introduced from injection port I. Industrial grade nitrogen is used as a carrier gas to carry the NO-$NO_x$ mixture to a reaction chamber, R, in which NO reacts with ozone gas from the top transport line as shown on the diagram. If we turn on the analyzer to $NO_x$ mode, then all $NO_2$ molecule would be converted to NO first in a NO converter, C2, then go to the reaction chamber; otherwise the gas goes directly to the reactor and only NO molecules are detected using the NO mode.

This instrument is normally used to analyze in situ dynamic sampling. If this is not the case, an alternative method is to inject the sample to a sampling bag and then pump it to the $NO_x$ analyzer. The reading obtained from the analyzer is exactly the value of the sample concentration. Neither of the above methods could be applied in our experiment due to the small total sample size, 12864 ml, and the likely loss or decomposition of samples while transferring from the reactor to the sampling bag. Another method, which later was proven to be reproducible for low concentrations of NO and $NO_x$, was used to analyze NO and $NO_x$ concentration in the samples.

A set of high concentration calibration curves ranging from 0 to 2500 ppm were obtained by the following procedure:

Step1. Calibrate a displaced volume I, which was later used to determine the concentrations of NO and $NO_x$ in the reactor, by drawing a constant volume of water using a 5 ml syringe and a stainless steel rod.

Step2. Calibrate another displaced volume II, which was later used to obtain a constant injection volume into the NO-$NO_x$ analyzer by drawing a constant volume of water using another stainless steel rod and a 5 ml syringe.

Step3. Heat the reactor to 260°F, open the valves V8, V4, V2, and V3; then flush it for twenty minutes with industrial grade compressed nitrogen gas. Keep the outlet flowing to the neutralization bottle just beneath the water level so that the pressure inside the reactor is about ambient.

Step4. Close all valves in the reactor system. Open the valve of another compressed industrial grade nitrogen at 10 psig to the NO-$NO_x$ analyzer, adjust the bypass stream pressure to 3 psig, and adjust the concentration range to a desired mode, B3.

Step5. Pull out a constant amount of NO gas at ambient temperature with the calibrated syringe, and inject it into the reactor. The calibration data for this syringe are shown in Table 4.

Step6. Pull out a constant amount of gas mixture at 260°F with the same calibrated syringe as described in step 5, then inject it into the NO-$NO_x$ analyzer.

Step7. Observe the highest reading, the index value of either NO or $NO_x$ from the analyzer, and record it.

Step8. Repeat the procedure from steps 5 to step 7 until reaching the high concentration limit.

Table 4. Calibration for a 2.8 ml constant input syringe.

| No. | W1 (g) | W2 (g) | DW (g) | V (ml) |
|---:|---:|---:|---:|---:|
| 1 | 13 | 15.8 | 2.8 | 2.804965 |
| 2 | 12.96 | 15.76 | 2.8 | 2.804965 |
| 3 | 12.76 | 15.58 | 2.82 | 2.825 |
| 4 | 12.92 | 15.72 | 2.8 | 2.804965 |
| 5 | 12.82 | 15.59 | 2.77 | 2.774912 |

Step9. Plot concentration determined from step 5 versus the reading index. The resultant plots are shown in Figure 5 and Figure 6.

Step10. Use the data with a linear relationship obtained from the results by regression using QPro computer software. The relation between the actual concentration and the index later was used to determine the concentration of reacting gas, NO or $NO_x$, in the reactor. The concentration of $NO_2$ can be determined by the difference in concentration between that of NO, and that of $NO_x$.

## 2.3 Preparation of dry sorbents

Sodium bicarbonate, sodium sesquicarbonate, and sodium sulfite are used to investigate the capability of removing acid gases from the mixture in the reactor. Sodium pyrosulfite, or sodium metabisulfite, is used to see if it is a intermediate in the reaction of sodium bicarbonate and the acid gases in the mixture. Acid gases and sorbents used in the experiments are listed in Table 5. The sorbent is first ground by a mortar, then separated using different sizes of sieves. The separated sorbents are then stored in the same desiccant jar, except the sodium pyrosulfite, which is active and might produce $SO_2$, and was stored in a separate desiccant.

For the sake of convenience to compare the results with each other, the doses of dry sorbents have been converted in terms of NSR (Normal Stoichiometric Ratio) which corresponds to the amount of $SO_2$ used in the reactions. $SO_2$ concentration of 1800 ppm has been chosen to be the reference with NSR equal to one for both sodium bicarbonate

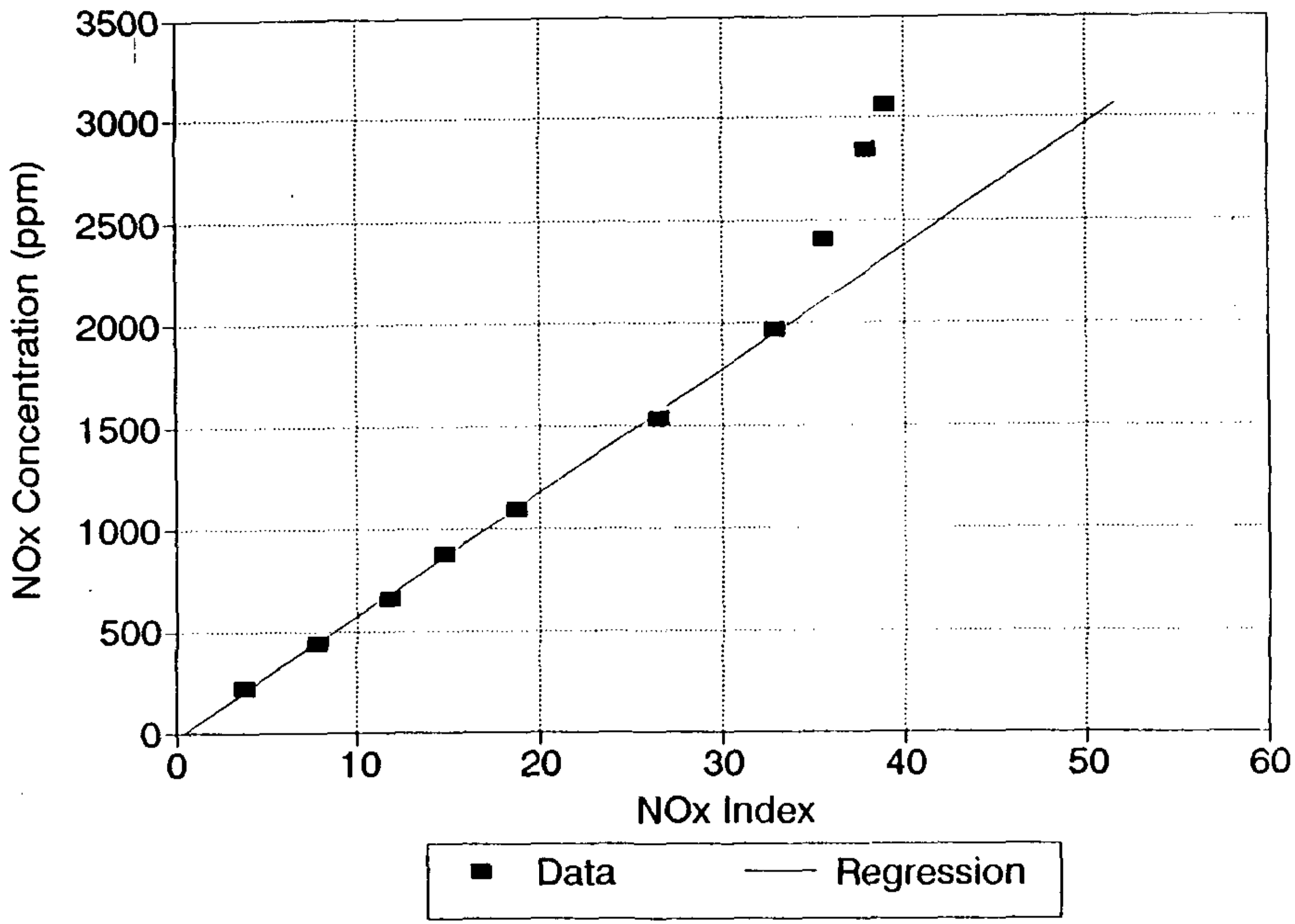


Figure 5. Calibration for NOx Concentration Using NOx Analyzer

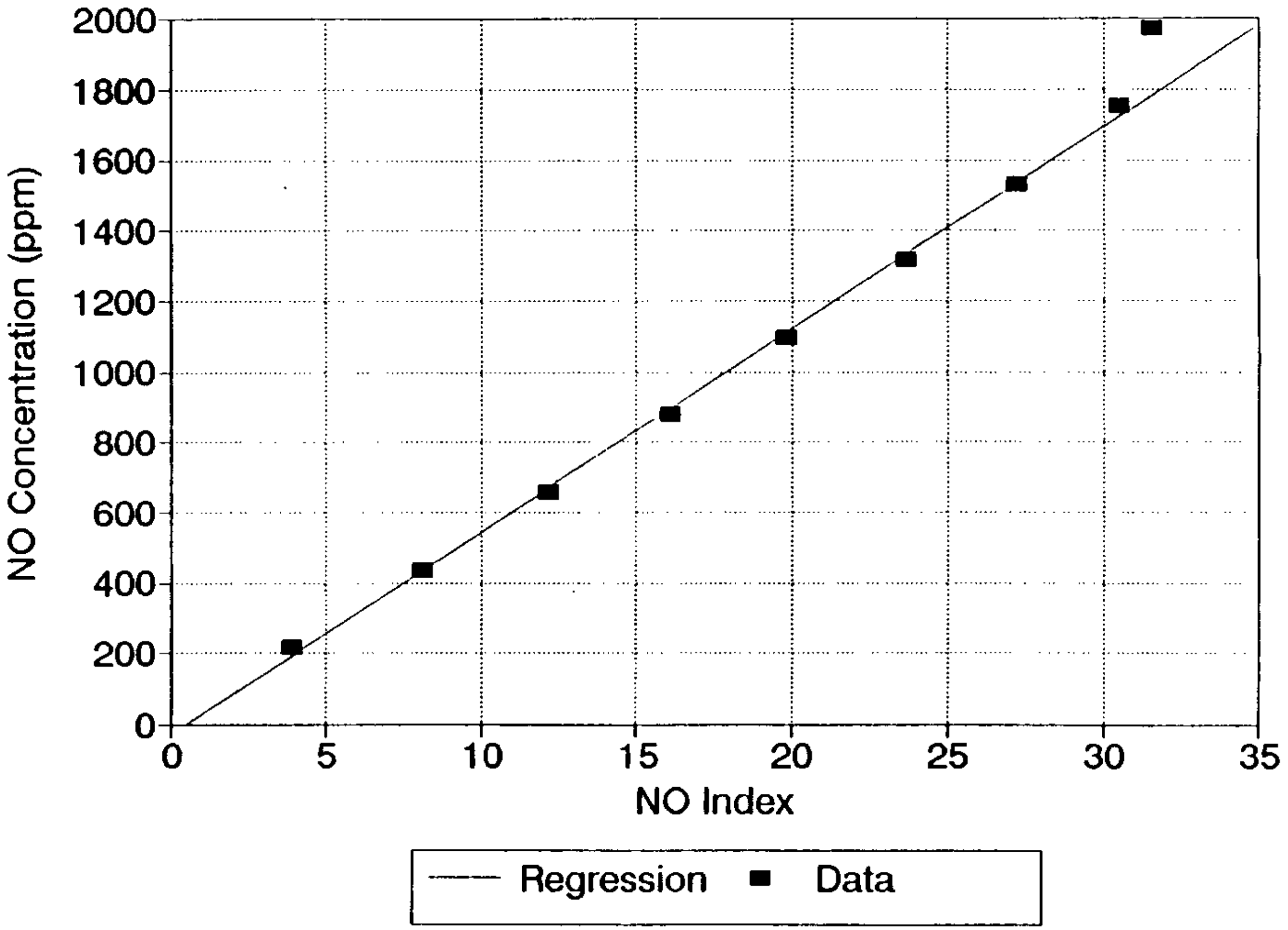


Figure 6. Calibration for NO Concentration Using NOx Analyzer

Table 5. List of chemicals

| Chemical | Formula | Company | Purity |
|---|---|---|---|
| Sodium Bicarbonate | $NaHCO_3$ | CMS | $99.7^+$% |
| Sodium Sesquicarbonate | $Na_2CO_3$-$NaHCO_3$-$2H_2O$ | B&D Chemical. | $99.0^+$% |
| Sodium Pyrosulfite | $Na_2S_2O_5$ | CMS | $97^+$% |
| Sodium Sulfite | $Na_2SO_3$ | CMS | 99% |
| Sulfur Dioxide | $SO_2$ | Aldrich Chemical. | $99.9^+$% |
| Nitric Oxide | NO | Matheson | $99^+$% |
| Nitrogen Dioxide | $NO_2$ | Aldrich Chemical | $99.5^+$% |
| Helium | He | Denver General Gas | 99.999% |
| Nitrogen | $N_2$ | Denver General Gas | 99.99% |
| Gas Mixture | 3% $O_2$ & 97% $N_2$ | Denver General Gas | Certified |

and sodium sesquicarbonate injection according to the Equation (1-1), Equation (1-2) and Equation (1-5). The typical doses of dry sorbents are calculated as follows :

<u>Reactor operating condition</u>

(1) V (Reactor volume) = 12864 ml = 12.864 L

(2) P (Pressure) = 1 atm.

(3) T (Temperature) = 260°F = 400°K

(4) Nt (Total mol of gas mixture in reactor)

$Nt = P\ V/R\ T = 0.392$ mol

where R is ideal gas law constant = 0.082 atm L/mol °K

(5) $N_A$ (Mol of $SO_2$ with concentration of 1800 ppm in the reactor)

$N_A = 1800E\text{-}6 * Nt = 0.706E\text{-}3$ mol

<u>For $NaHCO_3$</u> ($M_{NaHCO3}$ = 84.01 g/mol)

$2NaHCO_3 \implies Na_2CO_3 + CO_2 + H_2O$ (1-1)

$Na_2CO_3 + SO_2 + NO + O_2 \implies Na_2SO_4 + NO_2 + CO_2$ (1-6)

(1) NSR=3.37 (base case):

$N_{NaHCO3}$ (Mol required for NSR=3.37)

$= 2N_A * NSR = 4.76E\text{-}3$ mol

$W_{NaHCO3}$ (mass required for NSR=3.37)

$= N_{NaHCO3} * M_{NaHCO3} = 0.4$ g

(2) NSR=0.79 :

$W_{NaHCO3}$ (mass required for NSR=0.79)

$= 0.79/3.37 * [W_{NaHCO3}]_{NSR=3.37} * M_{NaHCO3} = 0.093$ g

For $2[Na_2CO_3\text{-}NaHCO_3\text{-}2H_2O]$ ($M_{Na2CO3\text{-}NaHCO3\text{-}2H2O} = 226.04$ g/mol)

$$2[Na_2CO_3\text{-}NaHCO_3\text{-}2H_2O] ==> 3Na_2CO_3 + 5H_2O + CO_2 \quad (1\text{-}2)$$

$$Na_2CO_3 + SO_2 + NO + O_2 ==> Na_2SO_4 + NO_2 + CO_2 \quad (1\text{-}6)$$

(1) NSR=3.38 (base case):

$N_{Na2CO3\text{-}NaHCO3\text{-}2H2O}$ (Mol required for NSR=3.38)

$= 2/3\ N_A * NSR = 4.76E\text{-}3$ mol

$W_{Na2CO3\text{-}NaHCO3\text{-}2H2O}$ (mass required for NSR=3.37)

$= N_{Na2CO3\text{-}NaHCO3\text{-}2H2O} * M_{Na2CO3\text{-}NaHCO3\text{-}2H2O} = 0.36$ g

(2) NSR=0.79 :

$W_{Na2CO3\text{-}NaHCO3\text{-}2H2O}$ (mass required for NSR=0.79)

$= 0.79/3.37 * [W_{Na2CO3\text{-}NaHCO3\text{-}2H2O}]_{NSR=3.38} * M_{NaHCO3} = 0.084$ g

## 2.4 Routine Operating Procedure

Before normal operation, the gas chromatograph, the NO-$NO_x$ analyzer, and the reactor system are set at the desired operating conditions, the motor is rotating, all valves are closed, and all fittings are tightened except V1. The procedure for routine operation is described as follows:

Step1. Remove about 5 ml of gas from the reactor and inject it to gas chromatograph to make sure the concentration of water is under 0.01%. If this is not the case then we need additional flushing by opening valves V7, V4, V2 and V3 using the background gas which is 3% oxygen and balance nitrogen.

Step2. Once the water level in the reactor is under 0.01%, close valves V7, V4, V2 and V3. Weigh a desired amount of sorbent powder, pour it into the 1/2" opening port V1, and securely tighten the fitting.

Step3. Open valve V7, V5, V6 and V1 and flush the solid powder at 5 psig to avoid water vapor, extra oxygen or carbon dioxide from being trapped in the sorbent.

Step4. Pour some distilled water into a beaker, strip it using industrial grade nitrogen gas for two minutes to reduce the carbon dioxide in the water, draw the desired amount of water using a 1 ml syringe, and then inject it into the reactor.

Step5. Use a 50 ml syringe to pull out 50 ml of $SO_2$ gas from sampling port P4, which is actually a swagelock fitting sealed with a septum. Vent the gas completely from the syringe and then draw another 50 ml $SO_2$ again. Push the gas out of the syringe slowly until the end of piston reaches the 20 ml mark. Inject this 20 ml $SO_2$ immediately into the reactor.

Step6. Pull out about a 5 ml gas sample from the reactor, inject it immediately into the gas chromatograph.

Step7. Wait for all peaks to elute from the GC, then check if the $SO_2$ peak is about the desired ratio. If not, then we need to repeat step 6 again; or else, follow step 5 to inject the NO gas into the reactor.

Step8. Pull out about a 5 ml gas sample from the reactor, inject it immediately into the gas chromatograph. Then pull out another two sample gases, one for NO analysis and the other for $NO_x$ analysis, and inject constant amounts of gases into the NO-$NO_x$ analyzer to obtain the NO and $NO_x$ index from the analyzer reading.

Step9. Duplicate NO and $NO_x$ sampling, then close the valves in the order of V6, V1, and V5.

Step10. Open the valve V2 and simultaneously close the same valve V2 and start the stop watch.

Step11. Start taking gas samples according to the arranged sampling schedule. A typical sampling schedule is listed in Table 6. In order to get as many samples as possible, $SO_2$ gas samples are stored and later injected into the GC when previous runs are completed. NO and $NO_x$ samples are injected into the NO-$NO_x$ analyzer immediately after they are removed from the reactor in increments of thirty second.

Step12. Use Qpro to convert the $SO_2$ to air ratio to $SO_2$ concentration, ppm, and NO and $NO_x$ index to NO and $NO_x$ concentration, ppm. Plot gas concentration, ppm,

Table 6. Typical sampling schedule

| Time (min) | $SO_2$ | NO | $NO_x$ |
|---|---|---|---|
| 0 | X | X | X |
| 0.0833 | X | | |
| 0.25 | X | | |
| 0.4166 | X | | |
| 0.5 | | | X |
| 0.9166 | X | | |
| 1.0 | | X | |
| 1.5 | | | X |
| 1.9166 | X | | |
| 2.0 | | X | |
| 2.5 | | | X |
| 2.9166 | X | | |
| 3.0 | | X | |
| 3.5 | | | X |
| 3.9166 | X | | |
| 4.0 | | X | |
| 4.5 | | | X |
| 4.9166 | X | | |
| 5.0 | | X | |
| 5.5 | | | X |
| 6.0 | X | | |
| 6.5 | | | X |
| 7.0 | X | | |

versus reaction time, min.

# CHAPTER III

## *DISCUSSION OF MODELS*

Postulated equations for simultaneous reaction of $SO_2$ and $NO_x$ from chapter one are used in this chapter to set up the kinetics models. There are two different schematic models; the one is from EPRI and the other is from Solvay. A good model needs to be able to represent the experimental data. The purpose of this chapter is to construct the rate laws for the four main compounds $SO_2$, NO, $NO_2$, and $Na_2CO_3$. The rate laws for the removal of the three gases are based on their concentrations in the continuous stirred batch reactor. The rate law for the removal of sodium carbonate is based on the changing radius of unreacted solid, which is based on the shrinking core model.

### 3.1 Model from EPRI's work

### 3.1.1 Simultaneous reduction of $SO_2$ and $NO_x$ by sodium bicarbonate

EPRI's mechanism for the simultaneous reduction of $SO_2$ and $NO_x$ is composed of four steps and described by Equation (1-1), Equation (1-5), Equation (1-6), and Equation (1-9) which have been discussed in Chapter one:

<u>Decomposition of sodium bicarbonate</u>

$$2NaHCO_3 \implies Na_2CO_3 + CO_2 + H_2O \qquad (1\text{-}1)$$

<u>Sulfation of sodium carbonate</u>

$$Na_2CO_3 + SO_2 + 1/2\ O_2 \implies Na_2SO_4 + CO_2 \qquad (1\text{-}5)$$

<u>Oxidation of nitric oxide</u>

$$NO + 1/2\ O_2 ==> NO_2 \qquad (1\text{-}6)$$

Nitration of sodium carbonate and removal of $NO_2$

$$Na_2CO_3 + 3NO_2 ==> 2NaNO_3 + NO + CO_2 \qquad (1\text{-}9)$$

The decomposition rate of sodium bicarbonate has been proven to be very fast(12) (about 20% decomposed at 275°F in 0.5 second and about 100% decomposed based on the carbon analysis at 350°F in 0.8 second in the absence of NO or $SO_2$). It seems that we can neglect the sodium bicarbonate decomposition step due to its fast rate compared with the other slower reactions.

EPRI's study suggests that the dependence of $SO_2$ removal on the concentration of NO is not significant while NO removal highly depends on the concentration of $SO_2$. So, Equations (1-5) and (1-6) might be rewritten as:

Removal of $SO_2$ by $Na_2CO_3$

$$Na_2CO_3 + SO_2 + 1/2\ O_2 ==> Na_2SO_4 + CO_2 \qquad (3\text{-}1)$$

Formation of $NO_2$

$$NO + 1/2\ O_2 \xrightarrow[Na_2CO_3]{SO_2} NO_2 \qquad (3\text{-}2)$$

Furthermore, to simplify the kinetic analysis we can write a simplified version of (1-9) as:

Reaction of $NO_2$

$$Na_2CO_3 + 2\ NO_2 + 1/2\ O_2 ==> 2\ NaNO_3 + CO_2 \qquad (3\text{-}3)$$

In the EPRI work the removal of $SO_2$ depends on the concentration of $SO_2$ and the normal stoichiometric ratio, NSR, used in the reaction which is equivalent to the amount of $Na_2CO_3$ injected. Either the $SO_2$ or the NO removal or the $NO_2$ formation does not highly depend on the concentration of oxygen due to the large excess amount of $O_2$ used, which was about 10%. In this report, the amount of $O_2$ used in each set of experiments is a constant of 3% which is still much greater than 1800 ppm or 0.18% of $SO_2$. So, when we construct the rate law the concentration of $O_2$ might be ascribed to the pseudo rate constant.

From Equation (3-1) and the above discussion, we can write the rate law for an intrinsic rate reaction of $SO_2$ as

$$R_A = - dC_A/dt = k_A\ C_A\ s \qquad (3\text{-}4)$$

where A : $SO_2$

$R_A$: removal rate of A, mol/cm$^3$ min

$C_A$: concentration of A, mol/cm$^3$

t : reaction time, minute

$\bar{k}_A$: rate constant of removing A, cm/min

s : total surface area per volume, mol/cm$^3$

From the definition, s could be expressed as

$$s = S/V = (4\ Pi\ R^2)\ N / V \qquad (3\text{-}5)$$

where

S : total surface area, $cm^2$

V : reactor volume, $cm^3$

Pi: constant, 3.14159

R : radius of solid particle, cm

N : total number of particles, ea

N could be estimated outside the reactor by assuming that the number of solid particles remained constant before and during the reaction:

$$N = W / (4/3\ Pi\ Ro^3)\ D \qquad (3\text{-}6)$$

where

W : weight of $NaHCO_3$ measured outside the reactor, g

Ro: mean radius of $NaHCO_3$ obtained outside the reactor, 0.0029 cm

D : density of $NaHCO_3$, 2.2 $g/cm^3$

Also, we can write the consumption rate of $Na_2CO_3$ from Equation (3-1)

$$R_{E0} = -\ dC_{E0}/dt = k_A\ C_A\ s \qquad (3\text{-}7)$$

where E : $Na_2CO_3$

0 : reaction contributed by Equation (3-1)

$R_{E0}$: removal rate of A due to reaction (3-1), $mol/cm^3$ min

$Na_2CO_3$, the concentrations of $SO_2$ and $O_2$. Since the concentration of $O_2$ is in large excess, we can again incorporate this term into the rate constant.

From Equation (3-1) and the above discussion, we can write the rate law for an intrinsic rate of reaction of $SO_2$ as

$$R_A = - dC_A/dt = k_A \, C_A \, s \qquad (3\text{-}3)$$

where A : $SO_2$

$R_A$: removal rate of A, mol/cm$^3$ min

$C_A$: concentration of A, mol/cm$^3$

t : reacting time, minute

$k_A$: rate constant of removing A, cm/min

s : total surface area of $Na_2CO_3$ per volume, mol/cm$^3$

As for the evaluation of s, we can still use Equation (3-5) and Equation (3-6).

To evaluate the consumption rate of sodium carbonate, we can use Equation (3-7),

$$R_{E0} = - dC_{E0}/dt = k_A \, C_A \, s \qquad (3\text{-}7)$$

where E : $Na_2CO_3$

0 : reaction contributed by Equation (3-1)

$R_{E0}$: removal rate of A due to reaction (3-1), mol/cm$^3$ min

$C_E$: mol of E per volum, mol/cm$_3$

To evaluate the derivative of $C_E$ with respect to reaction time t, we can just plug in

Equation (3-8) into Equation (3-7).

$$dC_E/dt = 1/V\ (dn_E/dt)$$

$$= 1/V\ (4\ Pi\ N\ R^2\ dR\ D/M) \qquad (3\text{-}8)$$

where M is the molecular weight of sodium bicarbonate.

For the NO removal step Equation (3-17) indicates that the removal of NO depends on the concentration of NO, the concentration of $O_2$, the concentration of $SO_2$, and the amount of $Na_2CO_3$ used in this reaction. Since the $O_2$ is in large excess; consequently, the rate expression can be written the same as Equation (3-9) as described in section 3.1.1 :

$$R_B = -\ dC_B/dt = k_B\ C_A\ C_B\ s \qquad (3\text{-}9)$$

where B : NO

$R_B$: removal rate of B, mol/cm$^3$ min

$C_B$: concentration of B, mol/cm$^3$

$k_B$: rate constant of removing B, cm/min

The definitions of t and s are the same as that for $SO_2$.

The reaction of $NaNO_2$ can significantly complicate the reaction kinetics, since it would be present in the reacted core of the solid and its disappearance would make the shrinking core model invalid. In order to simplify our kinetics and keep the shrinking core model in use, we can assume that the $NaNO_2$ is very reactive which implies that the reaction rates in Equation (3-18) and Equation (3-19) are very fast. Thus all of the solid reaction will still occur at the surface of the shrinking core. However, since the $NaNO_2$ can react to form either $NaNO_3$ or can generate $NO_2$ an additional stoichiometric constant x must be incorporated into the model to define the selectivity of the two reactions. To achieve this, Equation (3-18) with ratio x and Equation (3-19) with ratio 1-x are added to Equation (3-17) to account for the immediate disappearance of $NaNO_2$. The final form of these combined equations is:

$$(1-x/2)/2\ Na_2CO_3 + NO + 1/4\ O_2$$
$$==>\ (2-x)/2\ NaNO_3 + x/2\ NO_2 + (1-x/2)/2\ CO_2 \qquad (3\text{-}20)$$

From this final expression Equation (3-20), we can setup the $NO_2$ formation rate expression in terms of the removal rate of NO:

$$R_C = dC_C/dt = -x/2\ dC_B/dt = x/2\ k_B\ C_A\ C_B\ s \qquad (3\text{-}21)$$

where C : $NO_2$

x : undefined stoichiometric constant, which is between 0 and 1.

$\bar{R}_C$ : formation rate of C, $mol/cm^3$ min

$C_C$: concentration of C, $mol/cm^3$

$k_B$: rate constant of removal of B, cm/min

Also, we can write the consumption rate of $Na_2CO_3$ by this reaction, which is equivalent to the NO removal rate with a stoichiometric constant (1-x/2)/2, according to the Equation (3-9)

$$R_{E1} = - dC_{E1}/dt = (1-x/2)/2\ R_B$$
$$= (1-x/2)/2\ k_B\ C_A\ C_B\ s \qquad (3\text{-}22)$$

where E : $Na_2CO_3$

1 : reaction due to Equation (3-20)

$R_{E1}$: removal rate of E due to reaction (3-20), mol/$cm^3$ min

The overall consumption of the dry sorbent $Na_2CO_3$ is the contribution from the two reaction steps, Equation (3-1) and Equation (3-20). According to the stoichiometric ratio from these two equations, the overall consumption rate of sodium carbonate could be expressed as the summation of Equation (3-7) and Equation (3-22):

$$R_E = R_{E0} + R_{E1} = - dC_{E0}/dt - dC_{E1}/dt$$
$$= k_A\ C_A\ s + (1-x/2)/2\ k_B\ C_A\ C_B\ s \qquad (3\text{-}23)$$

Equation (3-23) can be expressed in term of the solid shrinking core radius by combining Equation (3-4) and Equation (3-7). The final form of (3-23) could be whiten as:

$$R_R = dR/dt = -0.5\ M/D * [k_A\ C_A + (1-x/2)/2\ k_B\ C_A\ C_B] \qquad (3\text{-}24)$$

The value 0.5 in Equation (3-24) is a stoichiometric conversion factor from sodium bicarbonate to sodium carbonate which can be obtained from Equation (1-1).

The kinetic variables of main interest in this study are the concentrations of $SO_2$, NO, and $NO_2$; and the radius of shrinking core of the dry sorbent R. Therefore, the following summary is made for these four variables.

Summary of rate expressions for the reaction using $NaHCO_3$

Removal rate of $SO_2$

$$R_A = - dC_A/dt = k_A C_A s \tag{3-3}$$

Removal rate of NO

$$R_B = - dC_B/dt = k_B C_A C_B s \tag{3-8}$$

Formation rate of $NO_2$

$$R_C = dC_C/dt = -x/2\ dC_B/dt = x/2\ k_B C_A C_B s \tag{3-21}$$

Shrinking rate of radius R

$$R_R = dR/dt = -0.5\ M/D * [k_A C_A + (1-x/2)/2\ k_B C_A C_B] \tag{3-24}$$

Evaluation of s and N

$$s = S/V = (4\ Pi\ R^2)\ N / V \tag{3-4}$$

$$N = W / (4/3\ Pi\ Ro^3)\ D \tag{3-5}$$

A similar analysis can be performed for sodium sesquicarbonate and as in the case of the EPRI model all of the equations remain the same with the exception of the equation for the radius of the shrinking core, where the stoichiometric coefficient of 0.5 must be replaced with 1.5 in switching from Equation (1-1) to Equation (1-2). The resulting equation is:

Shrinking rate of radius R

$$R_R = dR/dt = -1.5\ M/D * [k_A\ C_A + (1\text{-}x/2)/2\ k_B\ C_A\ C_B] \qquad (3\text{-}25)$$

where M and D now refer to the molecular weight and particle density for sodium sesqicarbonate.

### 3.3 Numerical solution for the reaction system

The above governing equations (Equations (3-3), (3-8), (3-11) and (3-15) for sodium bicarbonate and Equations (3-3), (3-8), (3-11), and (3-16) for sodium sesquicarbonate) represent a complete statement of the reaction system for the EPRI scheme. Similarly Equations (3-3), (3-8), (3-21) and (3-24) for sodium bicarbonate and Equations (3-3), (3-8), (3-21) and (3-25) represent a complete statement of the reaction system for the Solvay scheme. It is still impossible to solve any of the above simultaneous sets of equations analytically. There are several finite difference methods for solving these simultaneous first order initial value ordinary differential equations.(14) The first order Euler method and the second order modified Euler method are clearly inferior to the fourth order methods. The Runge-Kutta method is an excellent method; however, it requires four derivative function evaluation per step, compared to one for the Adams-Bashforth method and two for the Adams-Bashforth-Moulton method. The Runge-Kutta method and the Adams-Bashforth method both suffer from the lack of an efficient error control procedure. The Adams-Bashforth-Moulton method, which has a simple error control procedure, is the best compromise between accuracy and error control efficiency. Consequently, the Adams-Bashforth-Moulton method with a Runge-Kutta starting procedure is recommended for solving most first-order initial-value ordinary differential equations. This project therefore use this combined methods to solve the sets of simultaneous ordinary differential equations.

# CHAPTER IV

# EXPERIMENTAL RESULTS

From previous studies of $SO_2$ removal by Sodium Bicarbonate, $NaHCO_3$, conducted by Chang[11], we know that humidity plays an important role in this reaction system. Water content in the system $SO_2$-$NO_x$-dry sorbent is therefore likely to be an important parameter. Obviously, normalized stoichiometric ratio, NSR, which is the ratio of the amount of sorbent equivalent to the concentration of $SO_2$ to the concentration of $SO_2$ in the reaction system is also an important parameter. NSR is defined according to the following reactions described in the literature[6] in which the reaction stoichiometry is presented below:

<u>Sorbent decomposition :</u>

$$2\ NaHCO_3 \Rightarrow Na_2CO_3 + CO_2 + H_2O \qquad (1\text{-}1)$$

$$2[Na_2CO_3 \cdot NaHCO_3 \cdot 2H_2O] \Rightarrow 3Na_2CO_3 + 5H_2O + CO_2 \qquad (1\text{-}2)$$

<u>Removal of sulfur dioxide :</u>

$$SO_2 + Na_2CO_3 + 1/2\ O_2 \Rightarrow Na_2SO_4 + CO_2 \qquad (1\text{-}6)$$

Although both $SO_2$ and NO can react with either sodium bicarbonate or sodium sesquicarbonate, the established convention for defining NSR is to consider only the reactions involving $SO_2$.

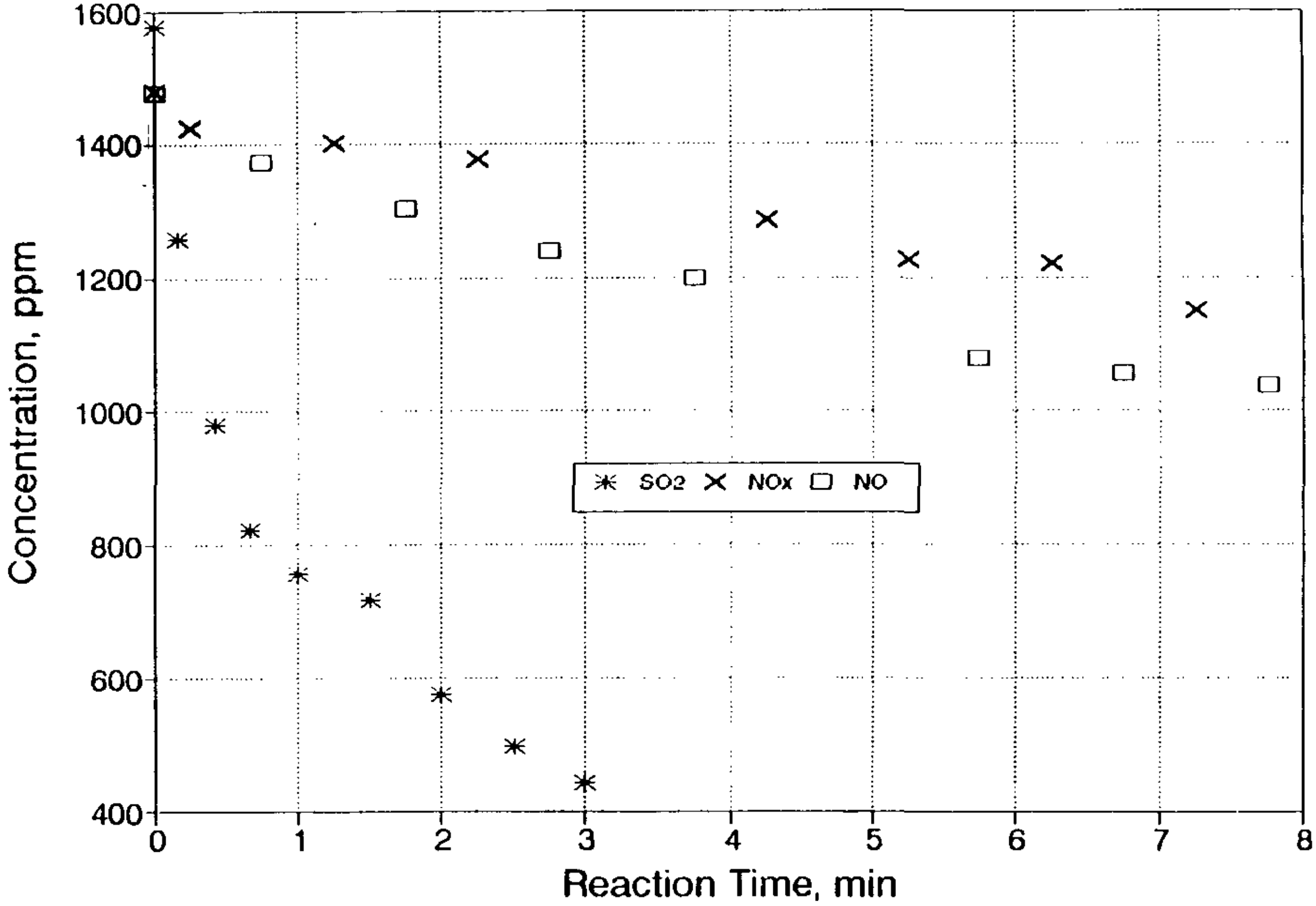
Besides water content and NSR, the stirring speed of the motor, the size of the sorbent particle, and reaction temperature were also considered as parameters in the $SO_2$-$NO_x$-sorbent reaction system. Furthermore, the initial ratio of $SO_2$/NO which has been considered to be a very important parameter in the literature[7,12] was also varied by considering lower concentrations of $SO_2$ and NO reacting with sodium sesquicarbonate to test this effect on $SO_2$ and $NO_x$ removal. The base case initial gas concentration of $SO_2$ and $NO_x$ for each run were set approximately to: $SO_2$ = 1800 ppm, NO = 1800 ppm. At these relatively high concentrations we would expect to see greater changes in component concentrations as the operating variables were varied. That is, the effects would be enhanced and more readily measured. In addition we generally set $O_2$ = 3% and $H_2O$ = 5% with the balance nitrogen. The typical particle size of sorbents used in these tests was 58 um which is the mean value of the particle size range from 53 to 63 um.

Typical results for an experimental run are presented in Table 7, and are illustrated graphically in Figure 7. This run was for a sodium bicarbonate sample at the typical operating conditions, NSR = 3.4 , and reactor temperature at 260°F, the approximate operating temperature of the Arapahoe 4 scrubbing system. As can be seen from the Figure, the $NO_2$ concentration must be determined as the difference between the

Table 7. Typical Results of $SO_2$ and $NO_x$ Removal by $NaHCO_3$ :

Date : 05-25-93
Sorbent : Sodium Bicarbonate
Water(%) : 5
Temp.(F) : 260
rpm : 700
NSR : 3
Size(um) : (53, 63)

| Time (min) | SO2/Air (Ratio) | SO2 (ppm) | NOx (Index) | NO (Index) | NOx (ppm) | NO (ppm) |
|---|---|---|---|---|---|---|
| 0 | 0.004274 | 1576.537 | 25.11 | 26.2 | 1480.523 | 1476.388 |
| 0.1667 | 0.003402 | 1259.431 | | | | |
| 0.25 | | | 24.2 | | 1425.894 | |
| 0.4167 | 0.002633 | 980.0017 | | | | |
| 0.6667 | 0.0022 | 822.4727 | | | | |
| 0.75 | | | | 24.4 | | 1372.868 |
| 1 | 0.002022 | 757.7006 | | | | |
| 1.25 | | | 23.8 | | 1401.882 | |
| 1.5 | 0.001912 | 717.6988 | | | | |
| 1.75 | | | | 23.2 | | 1303.855 |
| 2 | 0.001521 | 575.3917 | | | | |
| 2.25 | | | 23.4 | | 1377.869 | |
| 2.5 | 0.001304 | 496.5845 | | | | |
| 2.75 | | | | 22.1 | | 1240.593 |
| 3 | 0.001151 | 440.9603 | | | | |
| 3.75 | | | | 21.4 | | 1200.335 |
| 4.25 | | | 21.9 | | 1287.822 | |
| 5.25 | | | 20.9 | | 1227.791 | |
| 5.75 | | | | 19.3 | | 1079.562 |
| 6.25 | | | 20.8 | | 1221.788 | |
| 6.75 | | | | 18.9 | | 1056.558 |
| 7.25 | | | 19.6 | | 1149.751 | |
| 7.75 | | | | 18.6 | | 1039.305 |



NSR=3.4, Water=5%, 260F, 700 rpm, 53um< d <63um

Figure 7. Typical Result of SO2 and NOx Removal by Sodium Bicarbonate

interpolated concentrations of $NO_x$ and NO. From these results it appeared as though the $SO_2$ concentration decayed rapidly to zero. However, as will be discussed below, the $SO_2$ results are believed to be erroneously low. The remaining experimental results are presented as tables and graphs in the appendix.

In order to determine qualitatively the effects that the operating variables have on $NO_x$ reduction and, especially, $NO_2$ formation, the resultant data of the observed values of $SO_2$, NO, $NO_x$, and $NO_2$ at time zero, at 3 minutes for $SO_2$ and at 5 minutes for NO, $NO_x$, and $NO_2$ are tabulated from Table 8 through Table 17. These results were obtained by interpolating the graphs of the experimental results, presented in the appendix. A time of 5 minutes was selected for the nitrogen oxides, since by that time significant reaction had occurred. However, by that time the experimentally determined concentrations for $SO_2$ were essentially zero. Therefore, a shorter time, 3 minutes was selected for $SO_2$.

Symbols used in these tables are defined as follows:

- (A)o, (A)3, (A)5: concentration of chemical A at reaction time 0, 3 minute and 5 minute
- Chemical A could be $SO_2$, NO, $NO_2$ or $NO_x$
- d(A)5: the concentration difference of chemical A between reaction time 0 and 5 minutes.
- R%(A)3: removal % of chemical A at reaction time at 3 minute; i.e., [(A)o - (A)3] / (A)o*100%

* R%(A)5: removal % of chemical A at reaction time at 5 minute; i.e., [(A)o - (A)5] / (A)o*100%

The concentration of nitrogen dioxide is determined by the following relationship:

$[NO_2] = [NO_x] - [NO]$

## 4.1 Initial Studies

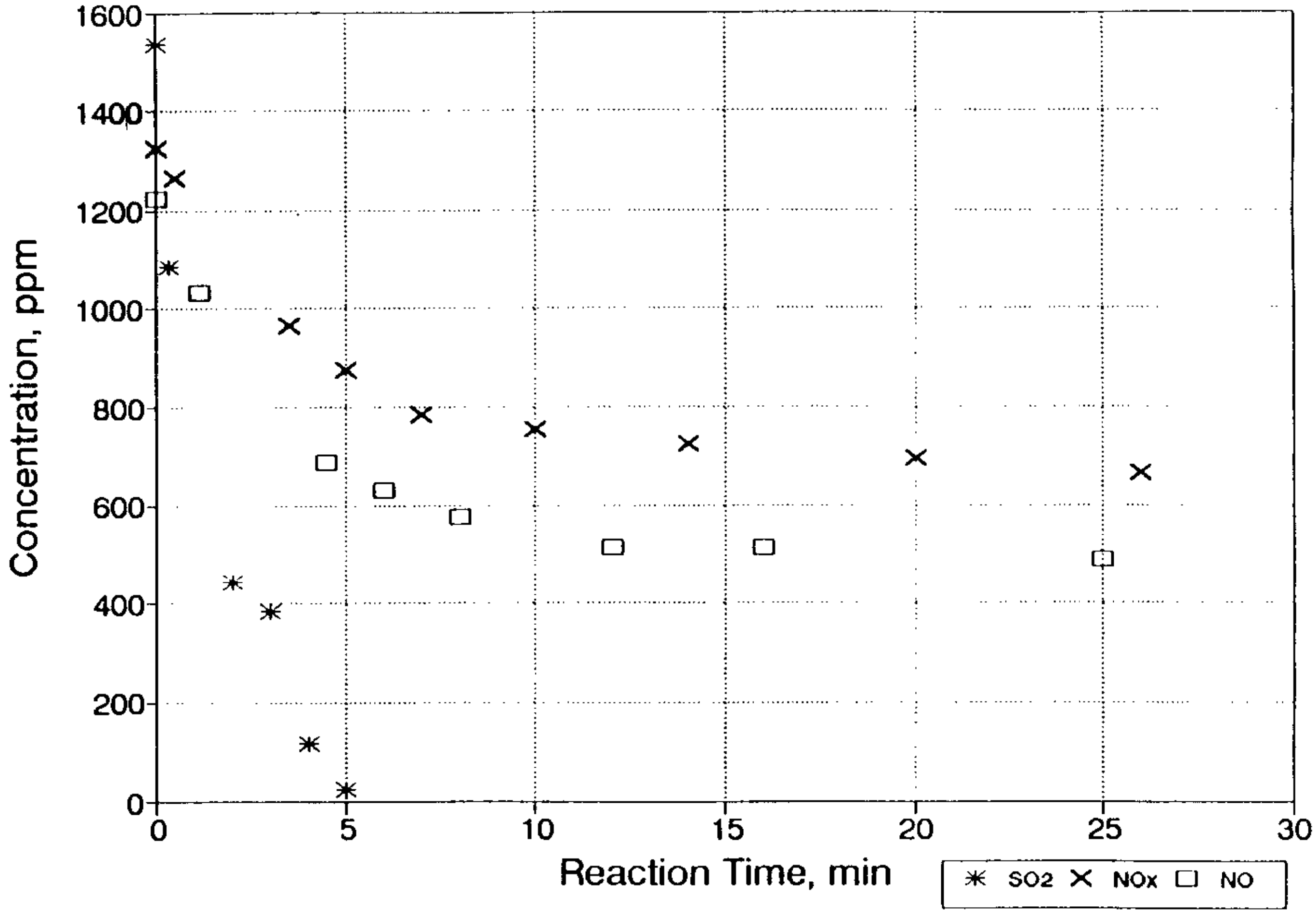
According to EPRI's Final Report[6] published on May 1990, $NO_x$ reduction potential depends on temperature and the amount of $SO_2$ presents in the system. The higher the $SO_2$ concentration presents in the system, the higher the $NO_x$ removal potential. They found that the optimum temperature for $NO_x$ removal appears to be approximately 350°F±75°F. Above this temperature region, NO oxidation to $NO_x$ and nitrate formation are impeded. Below the temperature band very little sorbent decomposition is possible, limiting $SO_2$ capture and subsequently the dependent $NO_x$ reaction. As for the $NO_x$ reduction mechanism, in their opinion, the NO and $NO_2$ oxidation process is heavily surface dependent which means oxidation of NO to $NO_2$ only occurs on the surface of the sodium sorbent and when $SO_2$ is actively being reacted with the sorbent. Five experimental runs therefore designed for investigating the effect of $SO_2$ on $NO_x$ reduction.

### 4.1.1 $NO_x$ Removal by Sodium Bicarbonate Enhanced by $SO_2$.

Three experimental runs were designed to see the effect of $SO_2$ on $NO_x$ removal by sodium bicarbonate. The first was $NO_x$ and $SO_2$ simultaneous removal by sodium bicarbonate with NSR=13.5, 3% water, mean particle size 58 um, at 300°F and 300 rpm. Result of this run has been plotted on Figure 8. It shows that in twenty minutes, $NO_x$ was reduced from 1324 ppm to 694 ppm which was about 630 ppm or 48% removal and $NO_2$ formed was increased from 100 ppm to 200 ppm.

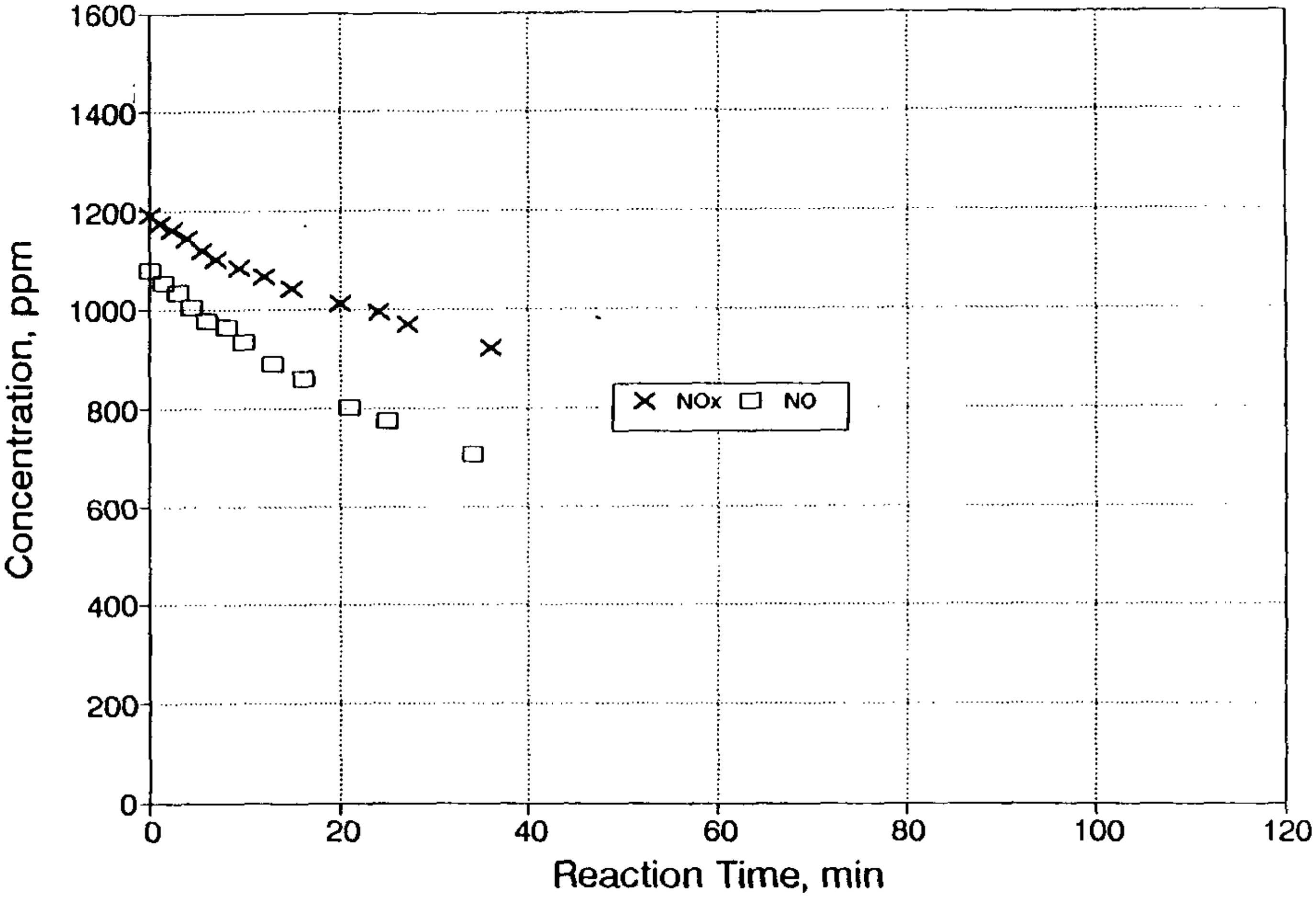
With the same operation condition, in the second run, we introduce $NO_x$ only with corresponding NSR value of 13.5. Results from this experimental run is shown in Figure 9. From the figure, we can see the $NO_x$ was removed less than that of the first run. The $NO_x$ was removed from about 1200 ppm to 1000 ppm with 200 ppm or 17% removal within twenty minutes. $NO_2$ concentration which is the difference between $NO_x$ and NO, was found to increase from 110 ppm to about 200 ppm at the end of twenty minutes.

The third run was operated as the same condition as the first run except that NOx was injected at twelve minutes at which the reaction of $SO_2$ was complete. Later we will show that the $SO_2$ concentrations measured in Figure 8 were too low due to their long sample storage time. At the end of this chapter we will also show that the twelve minute complete reaction time for $SO_2$ is approximately correct. Results from this experimental run are shown in Figure 10. As we can see in Figure 10, $NO_x$ was removed from about 1520 ppm to about 1200 ppm with about 320 ppm or 21% removal which was less than that of the first run, but slightly more than that in run two. At the end of twelve minute, only a little $SO_2$ was present in the reactor. $NO_x$ removal rate in this run is larger than



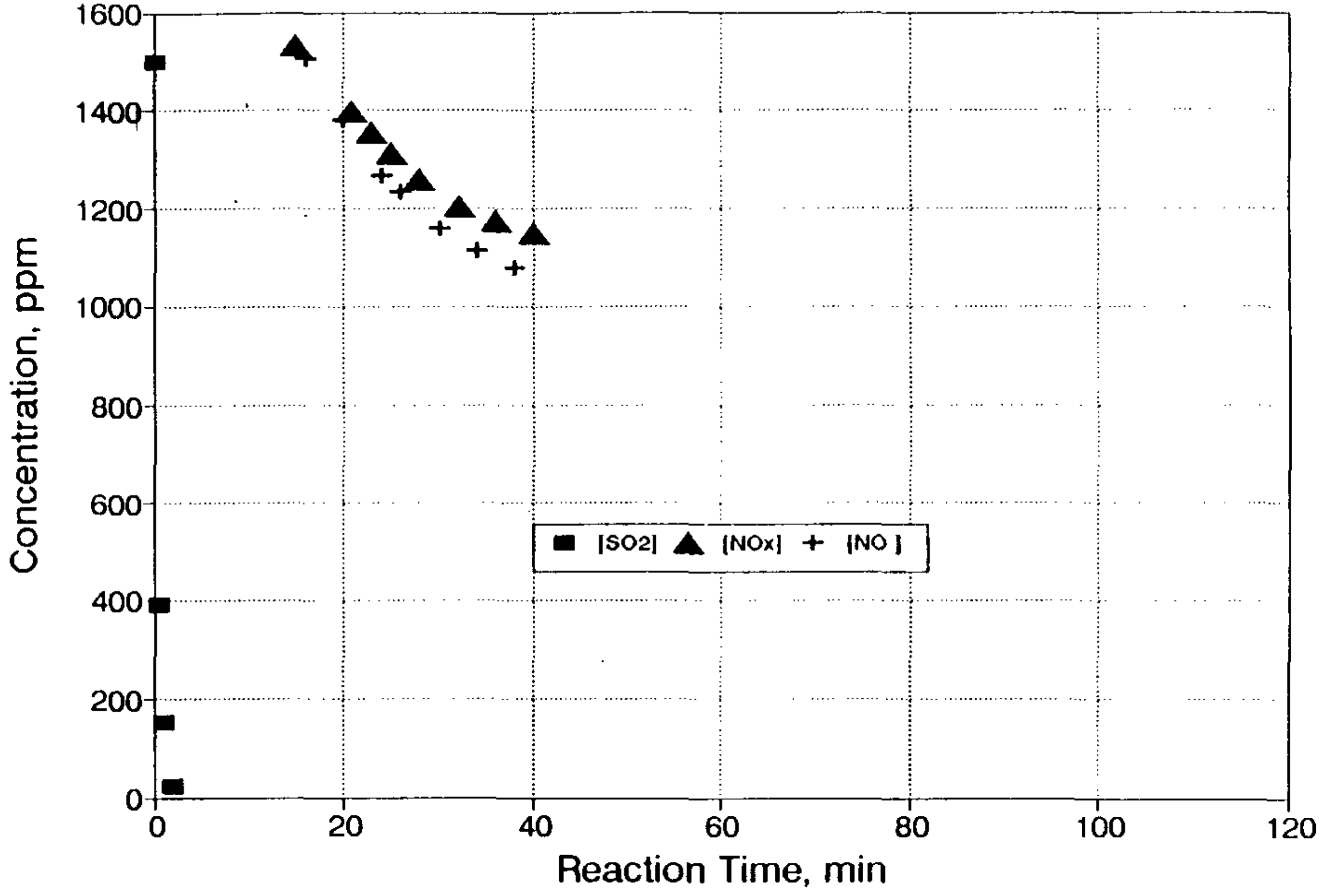
NSR=13.5, Water=3.5%, 300F, 300 rpm, 53um< d <63um

Figure 8. SO2 and NOx Simultaneous Removal by Sodium Bicarbonate



NSR=13.5, Water=3%, 300F, 300 rpm, 53um< d < 63um

Figure 9. NOx Removal by Sodium Bicarbonate



NSR=13.5, Water=3%, 300 F, 300 rpm, 53um< d <63um

Figure 10. NOx Removal by Sodium Bicarbonate After SO2 Completely Removed

that in run two because of the trace $SO_2$ present in the system. $NO_2$ formed increased from about 10 ppm to 20 ppm from the twelve minute to thirty two minutes. The $NO_2$ formation at the end of twenty minutes was found to be the least amount among these three runs.

### 4.1.2 $NO_2$ Formation enhanced by $SO_2$ in $NO_2$-NO-$O_2$ Gas Mixture.

Two experimental runs were conducted at 300°F and 300 rpm without any sorbent injection. Result from this set of runs was illustrated in Figure 11. $NO_x$ removed without $SO_2$ was from 1378 ppm to about 1250 ppm with about 128 ppm or 9% $NO_x$ removal at the end of forty minutes due to the system bleeding. $NO_2$ formation in this experimental run was from 5 ppm to 150 ppm within forty minutes. $NO_x$ removal with the presence of $SO_2$ was from 1342 ppm to 1080 ppm with about 157 ppm or 12 % removal. $NO_2$ formation in this experimental run was from 9 ppm to about 202 ppm which was slightly higher than that of the system without $SO_2$. It appears the $NO_2$ formation in this system is due to the oxidation of NO and $O_2$ in the gas phase.

## 4.2 Sodium Bicarbonate Injection

The typical operating conditions used in these tests were 300 rpm stirring speed, 300°F and NSR=13.5 for the earlier experiments, and 700 rpm, 260°F and NSR=3.4 for the rest of the tests. Sorbent dose, motor stirring speed, reaction temperature, and water content were used to test their effects on the removal of NO and $NO_x$, and the

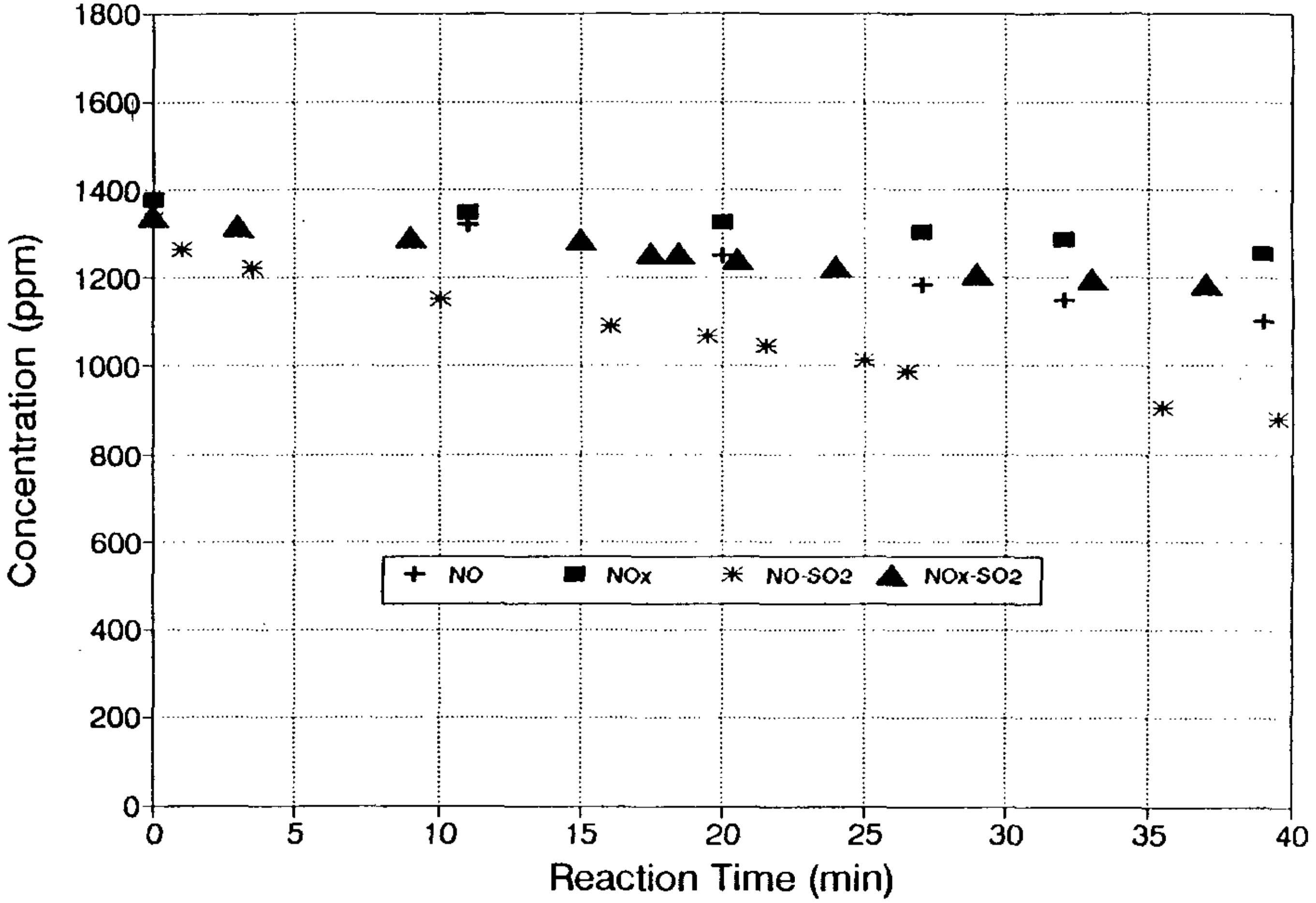


Figure 11. Comparison between the NOx System with SO2 and the NOx System without SO2

yield of $NO_2$ at the end of reaction.

### 4.2.1 Sorbent Dose Effect

Sorbent dose effect, or NSR effect, using sodium bicarbonate was investigated from four experimental runs, three base runs with NSR=3.4 and one run with NSR=0.6, under the typical operation conditions. As we can see from the resultant data tabulated in Table 8, the tests with NSR=3.4 have values of $NO_x$ removal around 13% which is greater than the 5% removal in the test with NSR=0.6 at 5 minutes. $NO_2$ formation is about 150 ppm for NSR =3.4 and for NSR=0.6, $NO_2$ formation is about 45 ppm. This is obviously what is expected, since a greater solids presence should result in a greater conversion.

### 4.2.2 Stirring Speed Effect

Resultant data from three base runs and one run with stirring speed 300 rpm were used to investigate the contribution of fluid velocity to the $SO_2$ and $NO_x$ removal. It seems higher $NO_x$ removal was obtained at lower stirring speed as we can see in Table 9. At the same time somewhat less $NO_2$ was formed. If mass transfer effects were important one would expect at least a lower conversion of $NO_x$. Thus, mass transfer effects are probably not important.

### 4.2.3 Temperature Effect

Three experimental runs, two at 300°F and the other at 240°F, illustrate the effect of temperature alone on $NO_x$ removal by sodium bicarbonate with the conditions of 7%

Table 8. NSR Effect on $SO_2$ and $NO_x$ Removal by Sodium Bicarbonate:

| Parameter | 08-08-93 | 05-25-93 | 05-31-93 | 08-07-93 |
|---|---|---|---|---|
| Sorbent | NaHCO3 | NaHCO3 | NaHCO3 | NaHCO3 |
| Water(%) | 5 | 5 | 5 | 5 |
| Temp.(F) | 260 | 260 | 260 | 260 |
| rpm | 700 | 700 | 700 | 700 |
| NSR | 3.4 | 3.4 | 3.4 | 0.6 |
| Size(um) | 53<d<63 | 53<d<63 | 53<d<63 | 53<d<63 |
| (SO2)o | 1617 | 1577 | 1478 | 1543 |
| (NOx)o | 1468 | 1480 | 1450 | 1432 |
| (NO )o | 1453 | 1476 | 1448 | 1430 |
| (NO2)o | 15 | 4 | 2 | 2 |
| (SO2)3 | 176 | 440 | 230 | 350 |
| (NOx)5 | 1284 | 1300 | 1255 | 1356 |
| (NO )5 | 1160 | 1120 | 1100 | 1309 |
| (NO2)5 | 124 | 180 | 155 | 47 |
| d(NO2)5 | 109 | 176 | 153 | 45 |
| R%(SO2)3 | 89 | 72 | 84 | 77 |
| R%(NOx)5 | 13 | 12 | 13 | 5 |

Table 9. Stirring Effect on $SO_2$ and $NO_x$ Removal by Sodium Bicarbonate:

| Parameter | 08-08-93 | 05-25-93 | 05-31-93 | 05-20-93 |
|---|---|---|---|---|
| Sorbent | NaHCO3 | NaHCO3 | NaHCO3 | NaHCO3 |
| Water(%) | 5 | 5 | 5 | 5 |
| Temp.(F) | 260 | 260 | 260 | 260 |
| rpm | 700 | 700 | 700 | 300 |
| NSR | 3.4 | 3.4 | 3.4 | 3.4 |
| Size(um) | 53<d<63 | 53<d<63 | 53<d<63 | 53<d<63 |
| (SO2)o | 1617 | 1577 | 1478 | 1610 |
| (NOx)o | 1468 | 1480 | 1450 | 1471 |
| (NO )o | 1453 | 1476 | 1448 | 1454 |
| (NO2)o | 15 | 4 | 2 | 15 |
| (SO2)3 | 176 | 440 | 230 | 189 |
| (NOx)5 | 1284 | 1300 | 1255 | 1215 |
| (NO )5 | 1160 | 1120 | 1100 | 1080 |
| (NO2)5 | 124 | 180 | 155 | 135 |
| d(NO2)5 | 109 | 176 | 153 | 120 |
| R%(SO2)3 | 89 | 72 | 84 | 88 |
| R%(NOx)5 | 13 | 12 | 13 | 17 |

water, 300 rpm stirring speed, and NSR=13.5. It is shown in Table 10 that there is not much difference in either reduction of $NO_x$ or formation of $NO_2$. Although one would expect a greater rate of reaction of $NO_x$ at higher temperature, $SO_2$, which is believed to be necessary for reaction of $NO_2$, is also more rapidly depleted.

### 4.2.4 Water Effect

The effects of water vapor concentration on $NO_x$ removal and $NO_2$ formation in the system of $NaHCO_3$-$SO_2$-NO can be determined by comparing the results of seven experimental runs ranging from 0% to 10% water. Results from these experiments are shown in Table 11. The most significant affect appears to be the very low conversion of $SO_2$ that occurs in the absence of moisture. It seems that systems with lower water contents yielded slightly higher $NO_x$ removal. As for the $NO_2$ formation, the $NO_2$ level is higher at water content about 3%. However, these latter effects were minor.

## 4.3 Sodium Sesquicarbonate Injection

The typical operating conditions used in these tests were 300 rpm stirring speed, 300°F and NSR=13.5 for the beginning of this phase, and 700 rpm, 260°F and NSR=3.4 for the rest of the tests. Sorbent doses, motor stirring speeds, reaction temperatures, and particle size were used to test their effects on the removal of NO and $NO_x$, and the yield of $NO_2$ at five minutes after reaction.

### 4.3.1 Sorbent Dose Effect

Sorbent dose effect, or NSR effect, using sodium sesquicarbonate was investigated

Table 10. Temperature Effect on $SO_2$ and $NO_x$ Removal by Sodium Bicarbonate:

| Parameter | 04-20-93 | 04-23-93 | 05-07-93 |
|---|---|---|---|
| Sorbent | NaHCO3 | NaHCO3 | NaHCO3 |
| Water(%) | 7 | 7 | 6.7 |
| Temp.(F) | 300 | 300 | 240 |
| rpm | 300 | 300 | 300 |
| NSR | 13.5 | 13.5 | 13.5 |
| Size(um) | 53<d<63 | 53<d<63 | 53<d<63 |
| (SO2)o | 1380 | 1504 | 1640 |
| (NOx)o | 1564 | 1564 | 1480 |
| (NO )o | 1522 | 1522 | 1480 |
| (NO2)o | 42 | 42 | 0 |
| (SO2)3 | 140 | 270 | 180 |
| (NOx)5 | 1120 | 1180 | 1120 |
| (NO )5 | 995 | 1035 | 1000 |
| (NO2)5 | 125 | 145 | 120 |
| d(NO2)5 | 83 | 103 | 120 |
| R%(SO2)3 | 90 | 82 | 89 |
| R%(NOx)5 | 28 | 25 | 24 |

Table 11. Water Effect on $SO_2$ and $NO_x$ Removal by Sodium Bicarbonate:

| Parameter | 04-21-93 | 04-27-93 | 04-16-93 | 04-27-93 | 04-20-93 | 04-23-93 | 04-30-93 |
|---|---|---|---|---|---|---|---|
| Sorbent | NaHCO3 | NaHCO3 | NaHCO3 | NaHCO3 | NaHCO3 | NaHCO3 | NaHCO3 |
| Water(%) | 0 | 2.9 | 3.5 | 3.5 | 7 | 7 | 10 |
| Temp.(F) | 300 | 300 | 300 | 300 | 300 | 300 | 300 |
| rpm | 300 | 300 | 300 | 300 | 300 | 300 | 300 |
| NSR | 13.5 | 13.5 | 13.5 | 13.5 | 13.5 | 13.5 | 13.5 |
| Size(um) | 53<d<63 | 53<d<63 | 53<d<63 | 53<d<63 | 53<d<63 | 53<d<63 | 53<d<63 |
| (SO2)o | 1381 | 1470 | 1384 | 1405 | 1380 | 1504 | 1547 |
| (NOx)o | 1504 | 1402 | 1383 | 1450 | 1564 | 1564 | 1474 |
| (NO )o | 1464 | 1387 | 1252 | 1440 | 1522 | 1522 | 1465 |
| (NO2)o | 40 | 15 | 131 | 10 | 42 | 42 | 9 |
| (SO2)3 | 724 | 313 | 270 | 200 | 140 | 270 | 111 |
| (NOx)5 | 1045 | 965 | 996 | 1020 | 1120 | 1180 | 1090 |
| (NO )5 | 900 | 792 | 804 | 850 | 995 | 1035 | 950 |
| (NO2)5 | 145 | 173 | 192 | 170 | 125 | 145 | 140 |
| d(NO2)5 | 105 | 158 | 61 | 160 | 83 | 103 | 131 |
| R%(SO2)3 | 48 | 79 | 80 | 86 | 90 | 82 | 93 |
| R%(NOx)5 | 31 | 31 | 28 | 30 | 28 | 25 | 26 |

by five experimental runs, one base runs with NSR=3.4, two runs with NSR=1.7, and two runs with NSR=0.85, under the typical operation conditions. As we can see from resultant data tabulated in Table 12, the tests with NSR=3.4 result in a value of $NO_x$ removal of 19% which is greater than the 13% removal in the test of sodium bicarbonate with the same operating and sorbent dose conditions. The $NO_2$ formation at 5 minute is about 120 ppm which is less than that of 150 ppm in the tests of sodium bicarbonate. As for sodium sesquicarbonate itself, the removal of $NO_x$ with NSR=1.7 and with NSR=0.85 at 5 minute are about 16% and 13% respectively. The $NO_2$ formation with NSR=1.7 and with NSR=0.85 at 5 minute are about 54 and 48 ppm respectively. The lower $NO_x$ removal results compared with those from EPRI[6] might be due to insufficient stirring speeds used in our experiments at which mass transfer effects can be important.

### 4.3.2 Sorbent Particle Size Effect

Three sizes of sorbent particles have been selected to study the effect on $NO_x$ removal and $NO_2$ formation. Experimental results were tabulated in Table 13. As we can see in Table 12, the $NO_x$ removal rate increases while we decrease the particle size. The $NO_x$ removal at 5 minutes after reaction for particle size 58, 29 and 24 um are 19%, 24% and 25% respectively, which implies that the $NO_x$ removal by sodium sesquicarbonate is proportional to the surface area. In this set of data, $NO_2$ formation seems lower for the result of particle size 24 um than for the other two sizes.

Table 12. Dose Effect on SO$_2$ and NO$_x$ Removal by Sodium Sesquicarbonate:

| Parameter | 06-18-93 | 06-22-93 | 06-21-93 | 06-17-93 | 05-27-93 |
|---|---|---|---|---|---|
| Sorbent | Sesq- | Sesq- | Sesq- | Sesq- | Sesq- |
| Water(%) | 5 | 5 | 5 | 5 | 5 |
| Temp.(F) | 260 | 260 | 260 | 260 | 260 |
| rpm | 700 | 700 | 700 | 700 | 700 |
| NSR | 0.85 | 0.85 | 1.7 | 1.7 | 3.4 |
| Size(um) | $53<d<63$ | $53<d<63$ | $53<d<63$ | $53<d<63$ | $53<d<63$ |
| (SO2)o | 1627 | 1795 | 1546 | 1620 | 1540 |
| (NOx)o | 1384 | 1498 | 1468 | 1384 | 1230 |
| (NO )o | 1338 | 1482 | 1465 | 1349 | 1206 |
| (NO2)o | 46 | 16 | 3 | 35 | 24 |
| (SO2)3 | 137 | 176 | 150 | 224 | 188 |
| (NOx)5 | 1210 | 1300 | 1230 | 1220 | 1000 |
| (NO )5 | 1131 | 1220 | 1154 | 1150 | 880 |
| (NO2)5 | 79 | 80 | 76 | 70 | 120 |
| d(NO2)5 | 33 | 64 | 73 | 35 | 96 |
| R%(SO2)3 | 92 | 90 | 90 | 86 | 88 |
| R%(NOx)5 | 13 | 13 | 16 | 12 | 19 |

Table 13. Sorbent Particle Size Effect on $SO_2$ and $NO_x$ Removal by Sodium Sesquicarbonate :

| Parameter | 05-27-93 | | 06-23-93 | | 06-23-93 |
|---|---|---|---|---|---|
| Sorbent | Sesq- | | Sesq- | | Sesq- |
| Water(%) | 5 | | 5 | | 5 |
| Temp.(F) | 260 | | 260 | | 260 |
| rpm | 700 | | 700 | | 700 |
| NSR | 3.4 | | 3.4 | | 3.4 |
| Size(um) | 53<d<63 | | 45<d<53 | | 15<d<32 |
| (SO2)o | 1540 | | 1752 | | 1744 |
| (NOx)o | 1230 | | 1424 | | 1474 |
| (NO )o | 1206 | | 1424 | | 1465 |
| (NO2)o | 24 | | 0 | | 9 |
| (SO2)3 | 188 | | 22.4 | | 180 |
| (NOx)5 | 1000 | | 1080 | | 1100 |
| (NO )5 | 880 | | 953 | | 1010 |
| (NO2)5 | 120 | | 127 | | 90 |
| d(NO2)5 | 96 | | 127 | | 81 |
| R%(SO2)3 | 88 | | 99 | | 90 |
| R%(NOx)5 | 19 | | 24 | | 25 |

### 4.3.3 Water Effect

The effect of humidity on $NO_x$ removal and $NO_2$ formation in the system of Sodium sesquicarbonate-$SO_2$-NO is also investigated by comparing three experimental runs ranging from 0% to 10% water. Experiments for 0% and 10% water lack $SO_2$ data. Results for these experiments are shown in Table 14. Water seemed to have very little effect on $NO_x$ removal. As for $NO_2$ formation, the $NO_2$ level is slightly higher at lower water content. $NO_2$ values were 145, 120 and 110 ppm for water content of 0%, 5% and 10% respectively.

### 4.3.4 Temperature Effects

Only two experimental runs with sorbent dose NSR=13.5 could be directly compared in this investigation, at 240°F and 300°F. The experiment at 300°F lacked $SO_2$ data. From Table 15, it is shown that lower reaction temperature results in lower $NO_x$ removal, 38% versus 45%, and lower $NO_2$ formation, 60 versus 120 ppm.

### 4.3.5 Low Concentrations $SO_2$ and $NO_x$

To investigate the removal of $SO_2$ and $NO_x$ at low initial concentrations ranging from 200 to 1100 ppm, the calibration data for both $SO_2$ and $NO_x$ had to be redone because a more sensitive method is required to observe the concentration differences from each other. The calibration procedure for $SO_2$ is the same as the one described in chapter 2 except that the $CO_2$ peak was combined with the air peak since trace amounts of $CO_2$ are negligible while compared with the huge amount of air. The retention time

Table 14. Water Effect on $SO_2$ and $NO_x$ Removal by Sodium Sesquicarbonate:

| Parameter | 07-22-93 | | 05-27-93 | | 07-22-93 |
|---|---|---|---|---|---|
| Sorbent | Sesq- | | Sesq- | | Sesq- |
| Water(%) | 0 | | 5 | | 10 |
| Temp.(F) | 260 | | 260 | | 260 |
| rpm | 700 | | 700 | | 700 |
| NSR | 3.4 | | 3.4 | | 3.4 |
| Size(um) | 53<d<63 | | 53<d<63 | | 53<d<63 |
| (SO2)o | - | | 1540 | | - |
| (NOx)o | 1474 | | 1230 | | 1461 |
| (NO )o | 1436 | | 1206 | | 1430 |
| (NO2)o | 38 | | 24 | | 31 |
| (SO2)3 | - | | 188 | | - |
| (NOx)5 | 1200 | | 1000 | | 1160 |
| (NO )5 | 1055 | | 880 | | 1050 |
| (NO2)5 | 145 | | 120 | | 110 |
| d(NO2)5 | 107 | | 96 | | 79 |
| R%(SO2)3 | - | | 88 | | - |
| R%(NOx)5 | 19 | | 19 | | 21 |

Table 15. Temperature Effect on $SO_2$ and $NO_x$ Removal by Sodium Sesquicarbonate:

| Parameter | 05-10-93 | | 05-03-93 |
|---|---|---|---|
| Sorbent | Sesq- | | Sesq- |
| Water(%) | 6.7 | | 3.5 |
| Temp.(F) | 240 | | 300 |
| rpm | 300 | | 300 |
| NSR | 13.5 | | 13.5 |
| Size(um) | 53<d<63 | | 53<d<63 |
| (SO2)o | 1530 | | |
| (NOx)o | 1550 | | 1550 |
| (NO )o | 1525 | | 1540 |
| (NO2)o | 25 | | 10 |
| (SO2)3 | 110 | | |
| (NOx)5 | 960 | | 860 |
| (NO )5 | 900 | | 740 |
| (NO2)5 | 60 | | 120 |
| d(NO2)5 | 35 | | 110 |
| R%(SO2)3 | 93 | | |
| R%(NOx)5 | 38 | | 45 |

for air, water and $SO_2$ were about 0.3, 1.4, and 2.5 minute respectively on which the internal standard method can still be applied. The calibration curves for $SO_2$, NO and $NO_x$ are shown in Figure 12, Figure 13, and Figure 14 respectively. The reliabilities of these calibration methods were investigated by conducting a blank test at low concentrations of $SO_2$, NO and $NO_x$.

The initial concentrations used in this investigation were 600 ppm for $SO_2$ and 550 ppm for NO. The sampling schedule for this blank test was identical to the typical one. The operation conditions also follow the normal operation condition, 260°F and 700 rpm, except the sorbent content was zero. The result of this investigation were plotted into Figure 15. It showed that there is no significant change for both NO and $NO_x$ concentration and only about a 50 ppm difference was detected for a reaction time of three minute.

Six experimental runs with different initial ratio of $SO_2$ to $NO_x$ were conducted at normal operating conditions with identical amount of sorbent injection (about 0.12 gram). This dose of sorbent is about an NSR=2 defined as initial amount of NO plus initial amount of $SO_2$. Data from these experiments is tabulated in Table 16 arranged from low initial concentration to high initial concentration for $SO_2$, and from high initial concentration to low initial concentration for NO. It is found in Table 16 that higher $SO_2$ to $NO_x$ ratio, or higher $SO_2$ and lower $NO_x$ concentration, results in lower $SO_2$ and higher $NO_x$ removal and also yields higher $NO_2$ formation. As we can see $SO_2$ removal

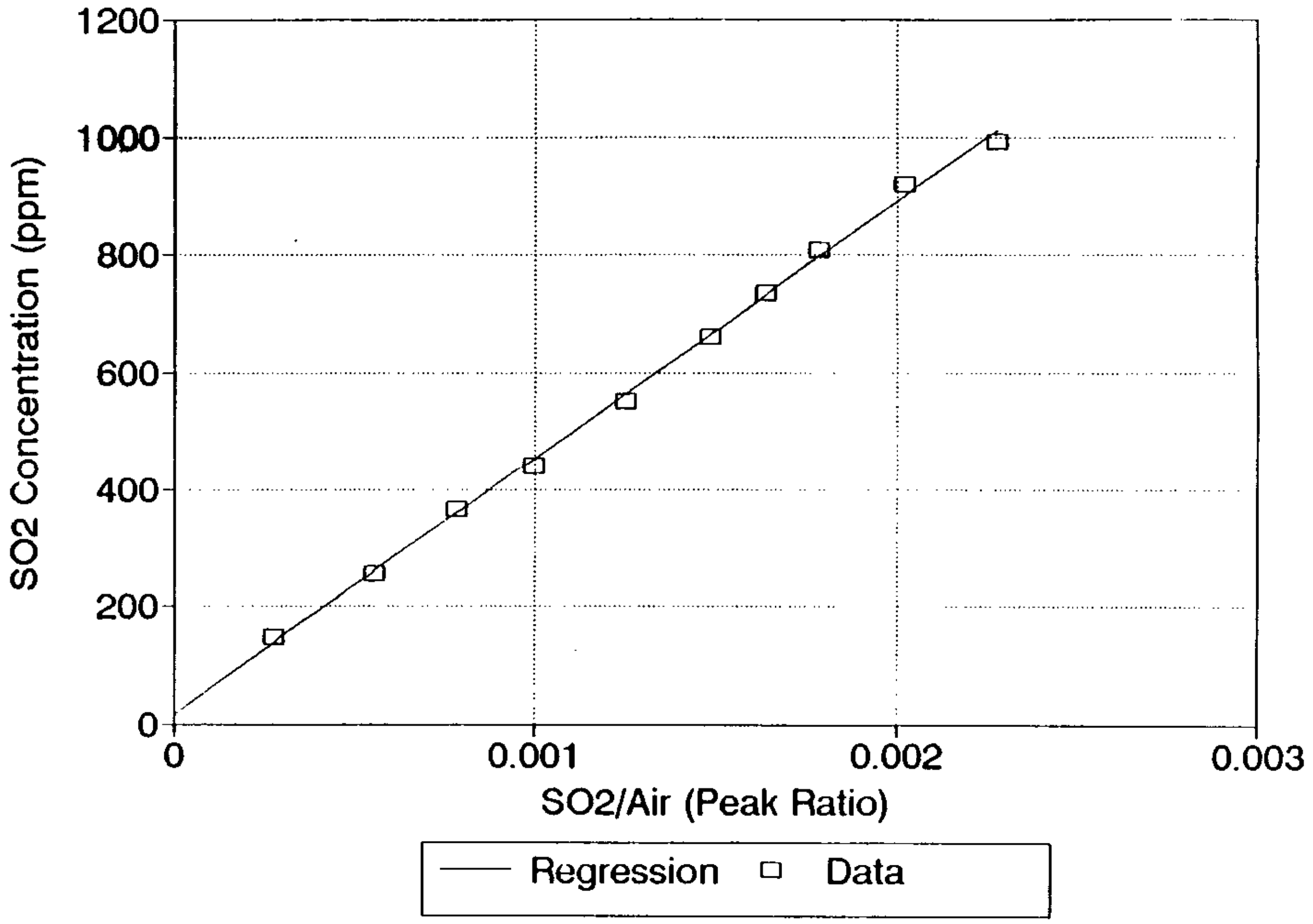


Figure 12. Calibration for Low Concentration SO2 Using GC Equipped with TCD

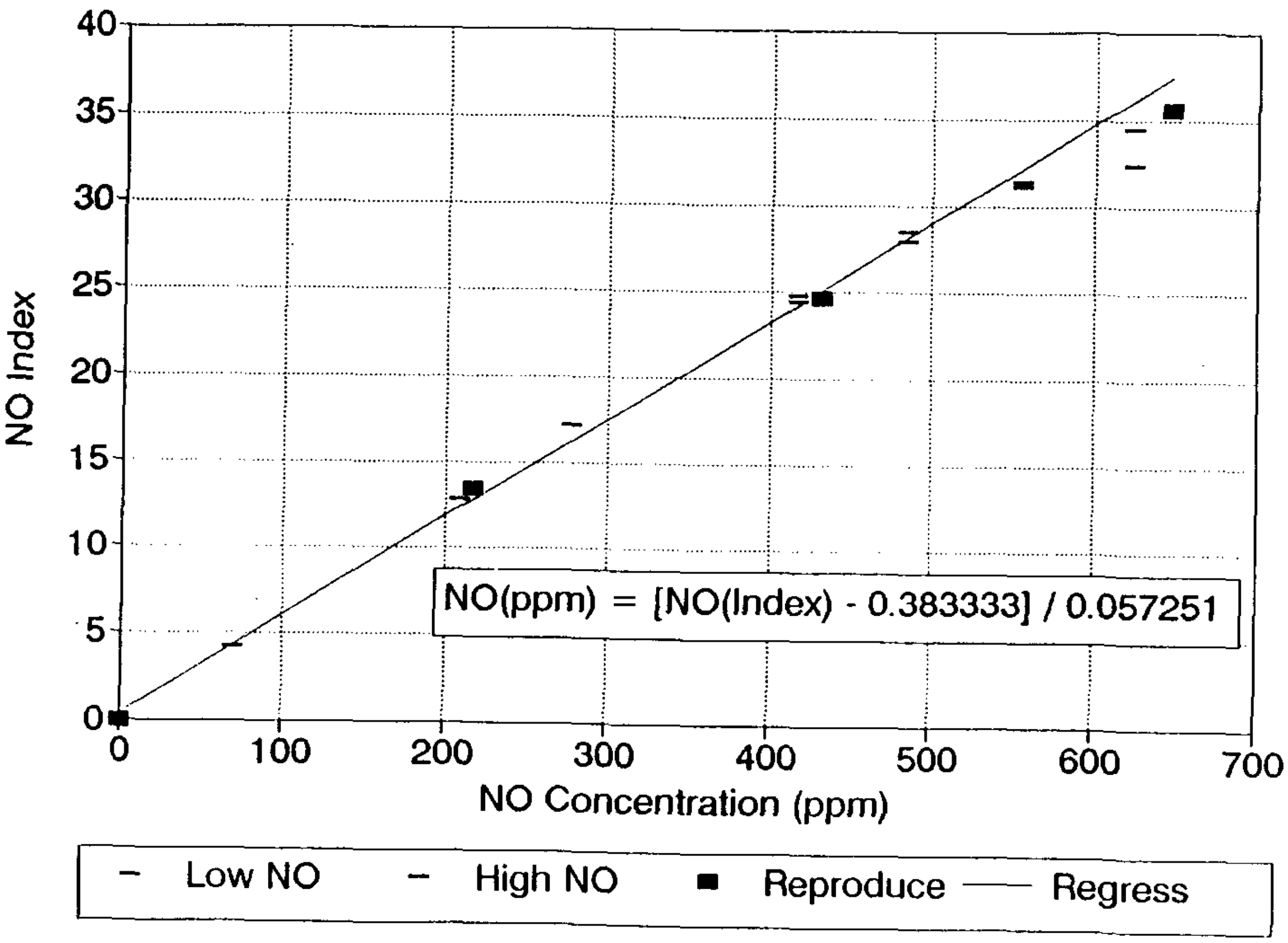


Figure 13. Calibration curve for low concentration NO

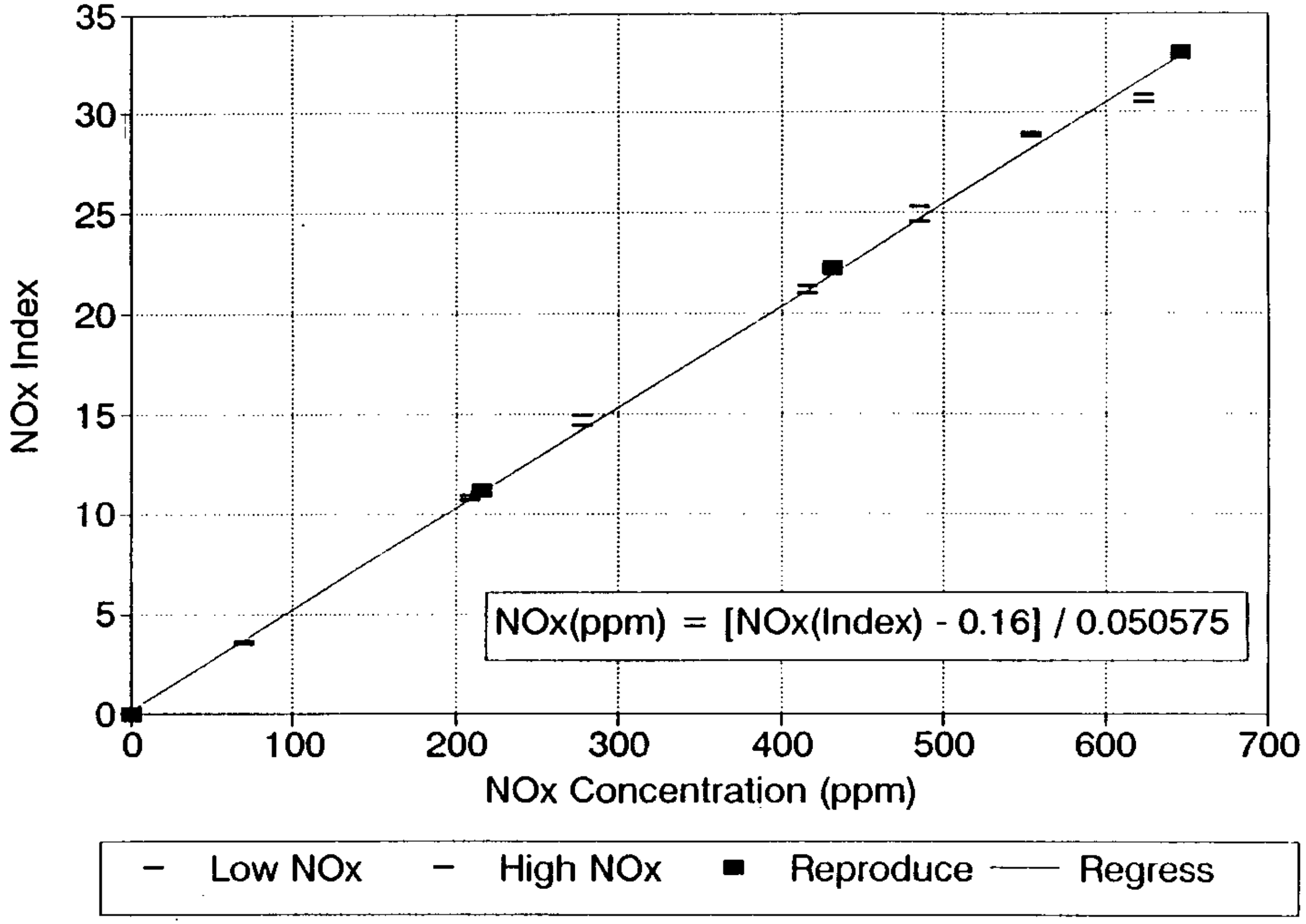
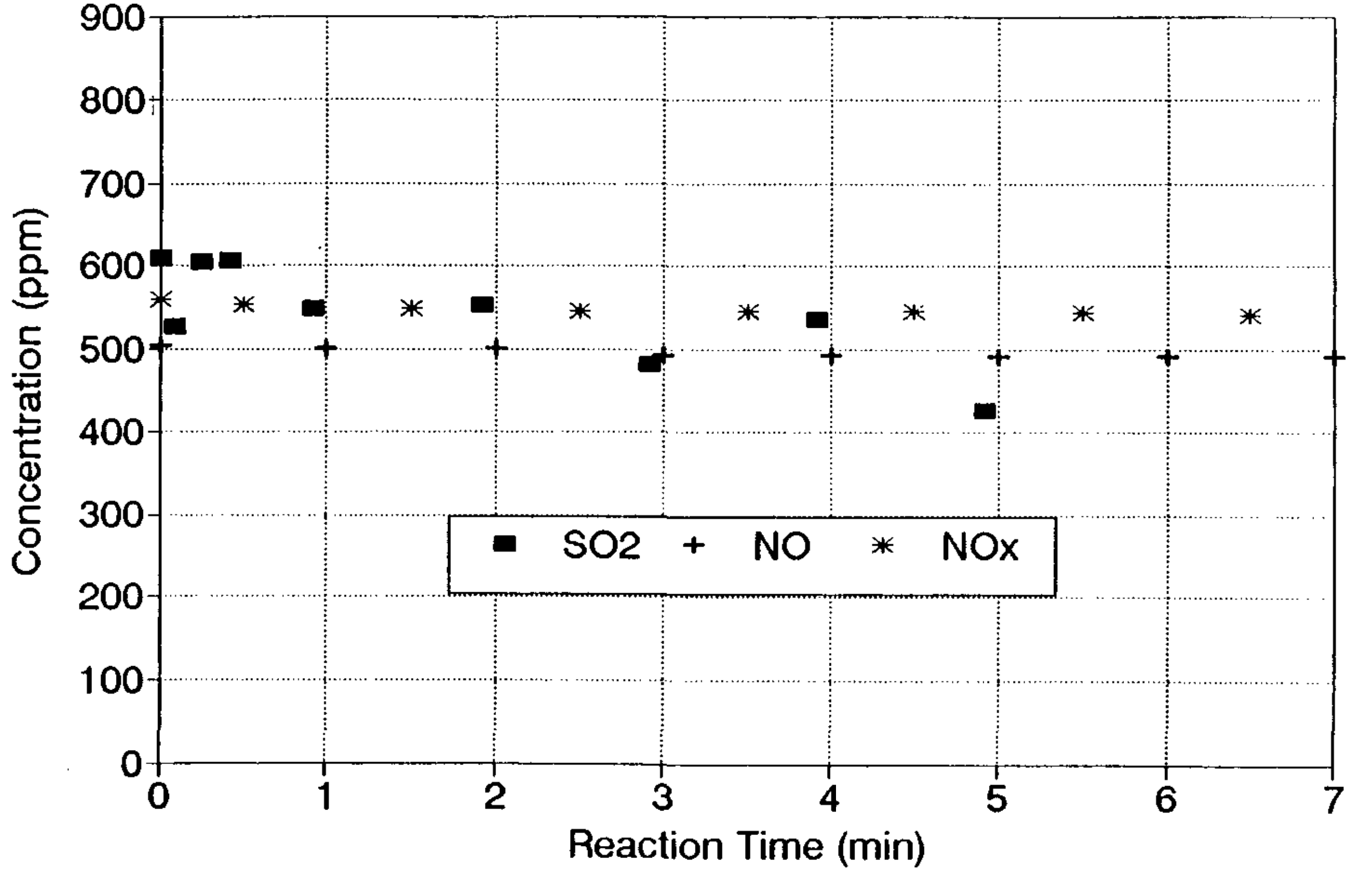


Figure 14. Calibration curve for low concentration NOx



700 rpm, 300 F without sorbent

Figure 15. Blank Test for Low Concentration NO, NOx, and SO2

Table 16. $SO_2$ and $NO_x$ Removal at Low Concentration by Sodium Sesquicarbonate:

| Parameter | 06-27-93 | 06-09-93 | 06-22-93 | 06-22-93 | 06-27-93 | 06-27-93 |
|---|---|---|---|---|---|---|
| Sorbent | Sesq- | Sesq- | Sesq- | Sesq- | Sesq- | Sesq- |
| Water(%) | 5 | 5 | 5 | 5 | 5 | 5 |
| Temp.(F) | 260 | 260 | 260 | 260 | 260 | 260 |
| rpm | 700 | 700 | 300 | 700 | 700 | 700 |
| NSR | 3.4 | 3.4 | 3.4 | 3.4 | 3.4 | 3.4 |
| Size(um) | 53<d <63 | 53<d <63 | 53<d <63 | 53<d <63 | 53<d <63 | 53<d <63 |
| (SO2)o | 220 | 295 | 379 | 464 | 785 | 871 |
| (NOx)o | 1084 | 850 | 785 | 585 | 289 | 252 |
| (NO )o | 1080 | 850 | 779 | 579 | 264 | 238 |
| (NO2)o | 4 | 0 | 6 | 6 | 25 | 14 |
| (SO2)3 | 88 | 75 | 140 | 145 | 450 | 530 |
| (NOx)5 | 975 | 720 | 667 | 492 | 200 | 182 |
| (NO )5 | 953 | 714 | 645 | 481 | 142 | 129 |
| (NO2)5 | 22 | 6 | 22 | 11 | 58 | 53 |
| d(NO2)5 | 18 | 6 | 16 | 5 | 33 | 39 |
| R%(SO2)3 | 80 | 75 | 63 | 69 | 43 | 39 |
| R%(NOx)5 | 10 | 15 | 15 | 16 | 31 | 28 |

decreases from 80% to about 39%, $NO_x$ removal increases from 10% to about 30%, and $NO_2$ formation increases from about 20 to 55 ppm when the $SO_2$ to $NO_x$ ratio increased from about 0.2 to 3.5. This phenomena also was observed in EPRI's[6] study as described in section seven. It should also be noted that $NO_2$ formation is considerably lower at these lower concentrations than for the high concentration runs.

### 4.4 Byproduct Identification

According to the work from J. Verlaeten[12] and his coworker in France, simultaneous reduction of $SO_2$ and $NO_x$ by sodium bicarbonate occurs by the following four steps:

Step 1. Sodium bicarbonate sulfation:

$$NaHCO_3 + SO_2 => NaHSO_3 + CO_2$$

Step 2. Sodium bisulfite dehydration:

$$2\ NaHSO_3 => Na_2S_2O_5 + H_2O$$

Step 3. Sodium pyrosulfite nitration:

$$Na_2S_2O_5 + 2\ NO + O_2 => NaNO_2 + NaNO_3 + 2\ SO_2$$

Step 4. Sodium bisulfite nitration:

$$2\ NaHSO_3 + 2\ NO + O_2 => NaNO_2 + NaNO_3 + 2\ SO_2 + H_2O$$

If the above reaction mechanism is right, then one mole of sodium pyrosulfite reacted with excess NO and oxygen should yield one mole of $NaNO_2$, one mole of $NaNO_3$, and

2 moles of $SO_2$. An experiment was therefore designed to determine if sodium pyrosulfite would in fact react with NO and, if it did, the stoichiometry for these chemicals. The quantities of material used for this experiment were 3000 ppm, 1500 ppm and 3 percent for sodium pyrosulfite, nitrogen oxide and oxygen respectively. Operating conditions in this experiment were 260°F, 700 rpm with water content 5%. As shown in Figure 16, $NO_x$ removal is approximately equal to the amount of $SO_2$ formation. Thus, it appears that sodium pyrosulfite may indeed be an intermediate in the removal of $NO_x$ by sodium based solids.

Qualitative and quantitative identification for both $NaNO_2$ and $NaNO_3$ were performed by the method of X-ray diffraction. Calibration curves made for $NaNO_2$ and $NaNO_3$ were not reproducible due to high reactivity and high water sensitivity of these two chemicals; so, no conclusion could be made at this point regarding the solids that are produced.

### 4.5 Chemical effect on the $NO_x$ removal and $NO_2$ formation

#### 4.5.1 The fate of $NO_x$ in the existence of sodium sulfite

According to the work from J. Verlaeten[12] sodium bisulfite would react with $NO_x$. An experiment therefore was designed to test if the $NO_x$ could also be removed by sodium sulfite. The NSR for this dry sorbent of 2, was based on the initial NO concentration. Resultant data have been tabulated and plotted in Table 17 and Figure 17.

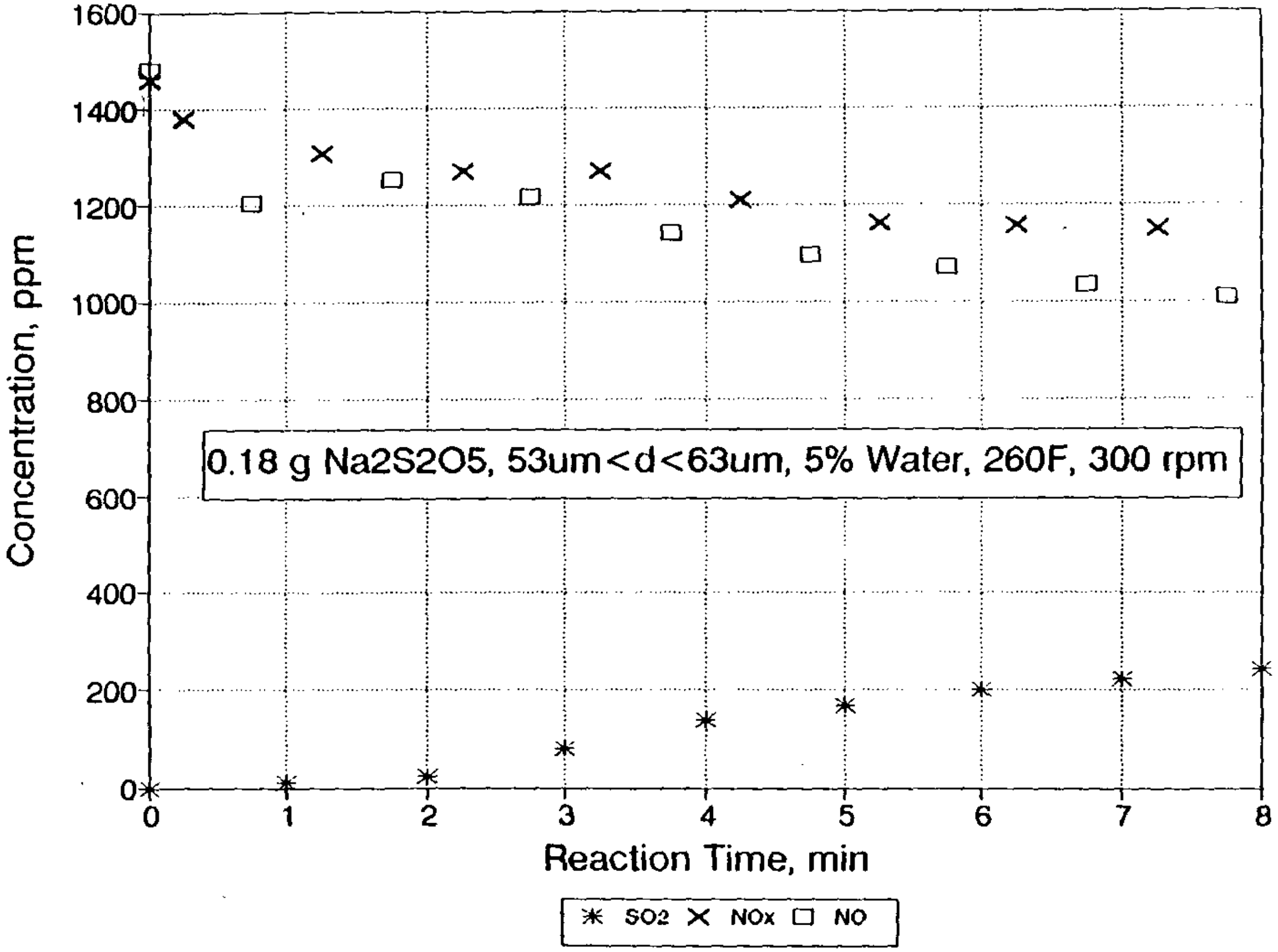


Figure 16. NOx Removal by Sodium Pyrosulfite

Table 17. $SO_2$ and $NO_x$ Removal by Three Chemicals :

| Parameter | 05-27-93 | 08-08-93 | 05-25-93 | 05-31-93 | 06-25-93 | 07-24-93 | 08-08-93 |
|---|---|---|---|---|---|---|---|
| Sorbent | Sesq- | Bic- | Bic- | Bic- | $Na_2SO_3$ | $Na_2SO_3$ | Blank |
| Water(%) | 5 | 5 | 5 | 5 | 5 | 5 | 5 |
| Temp.(F) | 260 | 260 | 260 | 260 | 260 | 260 | 260 |
| rpm | 700 | 700 | 700 | 700 | 700 | 700 | 700 |
| NSR | 3.4 | 3.4 | 3.4 | 3.4 | 2 | 2 | 0 |
| Size(um) | 53<d <63 | 53<d <63 | 53<d <63 | 53<d <63 | 53<d <63 | 53<d <63 | 0 |
| (SO2)o | 1540 | 1617 | 1577 | 1478 | 0 | 0 | 1538 |
| (NOx)o | 1230 | 1468 | 1480 | 1450 | 1439 | 1426 | 1424 |
| (NO )o | 1206 | 1453 | 1476 | 1448 | 1435 | 1425 | 1419 |
| (NO2)o | 24 | 15 | 4 | 2 | 4 | 1 | 5 |
| (SO2)3 | 188 | 176 | 440 | 230 | 0 | 0 | 280 |
| (NOx)5 | 1000 | 1284 | 1300 | 1255 | 1300 | 1296 | 1405 |
| (NO )5 | 880 | 1160 | 1120 | 1100 | 1281 | 1257 | 1384 |
| (NO2)5 | 120 | 124 | 180 | 155 | 19 | 39 | 21 |
| d(NO2)5 | 96 | 109 | 176 | 153 | 15 | 38 | 16 |
| R%(SO2)3 | 88 | 89 | 72 | 84 | 0 | 0 | 82 |
| R%(NOx)5 | 19 | 13 | 12 | 13 | 10 | 9 | 1 |

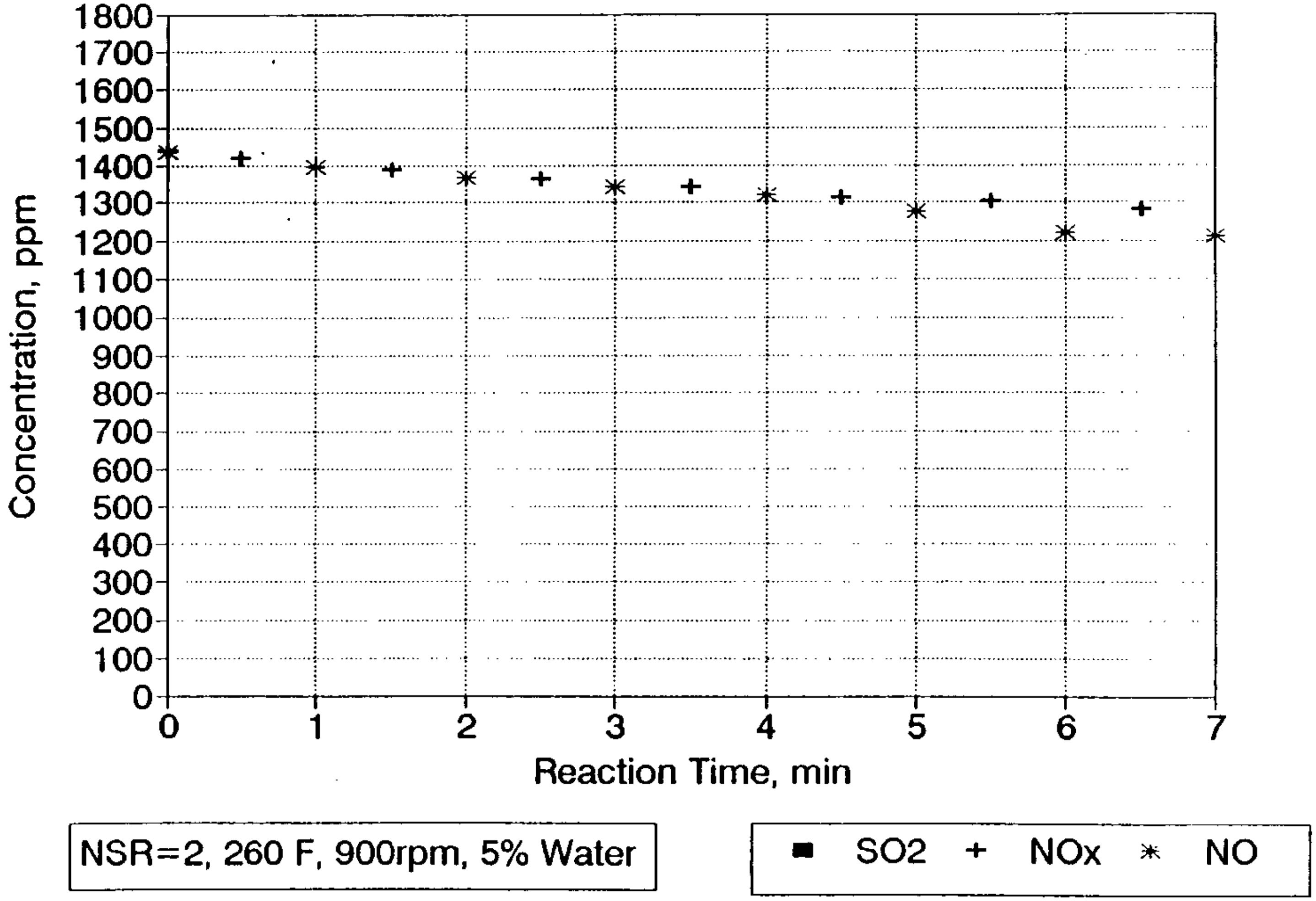
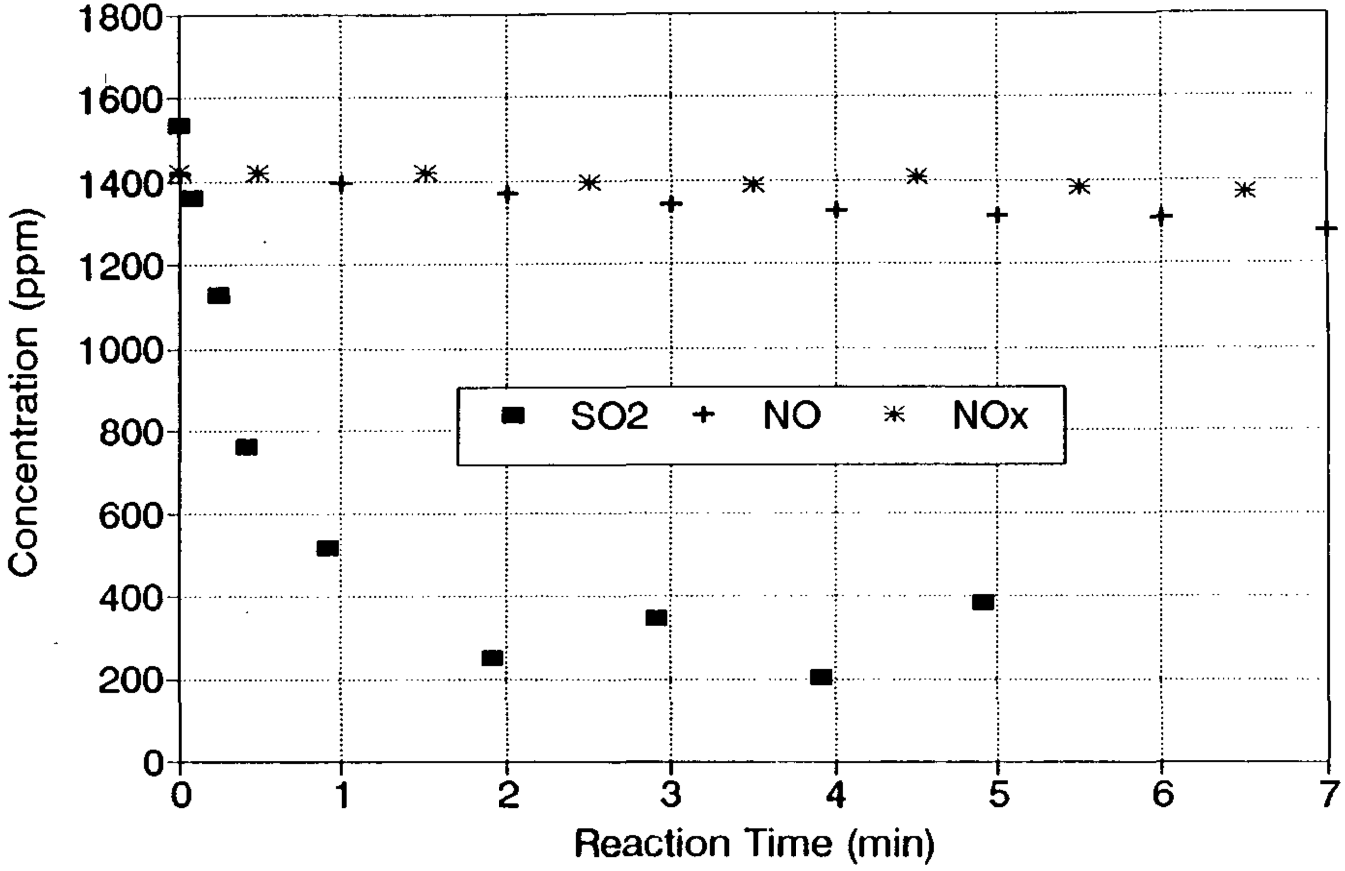


Figure 17. NOx Removed by Sodium Sulfite

No $SO_2$ was detected accompanying with the $NO_x$ removal. It shows that about 180 ppm $NO_x$, which was somewhat greater than the value from a blank test, has been removed. The blank test like the one that we have already discussed for low concentration was conducted at the same operation condition. Results from this test are shown in Figure 18 which indicats that only 20 ppm $NO_x$ was removed from the system during the reaction. According to the book, "Handbook of Fluid Sealing(15)", the loss of NO and $NO_x$ might be due to the rotation process. Direct contact of teflon sealant with therotating shaft will create friction which would wear out the surface of teflon and finally form a gap between teflon and the rotating shaft. However, the reduction in $SO_2$ is very significant and will be discussed below. We believe this reduction is due to our sampling procedure.

### 4.5.2 Comparison of three dry sorbents

Six experimental runs including three runs from sodium bicarbonate, one sodium sesquicarbonate and two for sodium sulfite can be compared to investigate the difference in the $NO_x$ removal efficiency between these three chemicals. The results from these data plus a blank at high concentration were tabulated in Table 17 which showed that sodium sesquicarbonate had the highest $NO_x$ removal efficiency among these three chemicals. The removal of $NO_x$ for sodium sesquicarbonate, sodium carbonate and sodium sulfite were 19%, 13% and 10% respectively. The removal of $NO_x$ by sodium sulfite was somewhat surprising. While compared with the result from the blank which



NSR=0, Water=5%, 260F, 700 rpm

Figure 18 . SO2 and NOx Reduction without Dry Sorbent

was 1% removal, the loss of $NO_x$ from the system should be negligible.

### 4.6 *Difficulties of high concentration $SO_2$ analysis*

As we can see from the blank run of Figure 18, there is quite a reduction in the $SO_2$ concentration which indicates that the $SO_2$ analytical method might be in error for these runs as discussed above. A more thorough study on this phenomena was therefore done by conducting a series of runs with stirring speed 700 rpm, water content 5%, and system temperature 260°F without adding any sorbent. Runs conducted were as follows:

Run 1. Blank test without $NO_x$

An experiment was designed to determine if there is a difference between the blank test with $SO_2$ and NO, and the blank test with $SO_2$ alone. This test demonstrated that without $NO_x$ there is not a large decrease in the $SO_2$ concentration, and the analytical method for $SO_2$ is still valid. The $SO_2$ decrease may be due to $SO_2$ diffusion from the syringe to the environment through the needle. The result has been plotted in Figure 19.

Run 2. Blank test without $SO_2$

An experiment was designed to find out if there is a difference between the blank test with $SO_2$ and NO, and the blank test with NO alone. This test demonstrated that without $SO_2$, the result for both NO and $NO_x$ is close to the one with $SO_2$. The $NO_x$ decrease is mainly due to the bleeding from the reactor to the environment

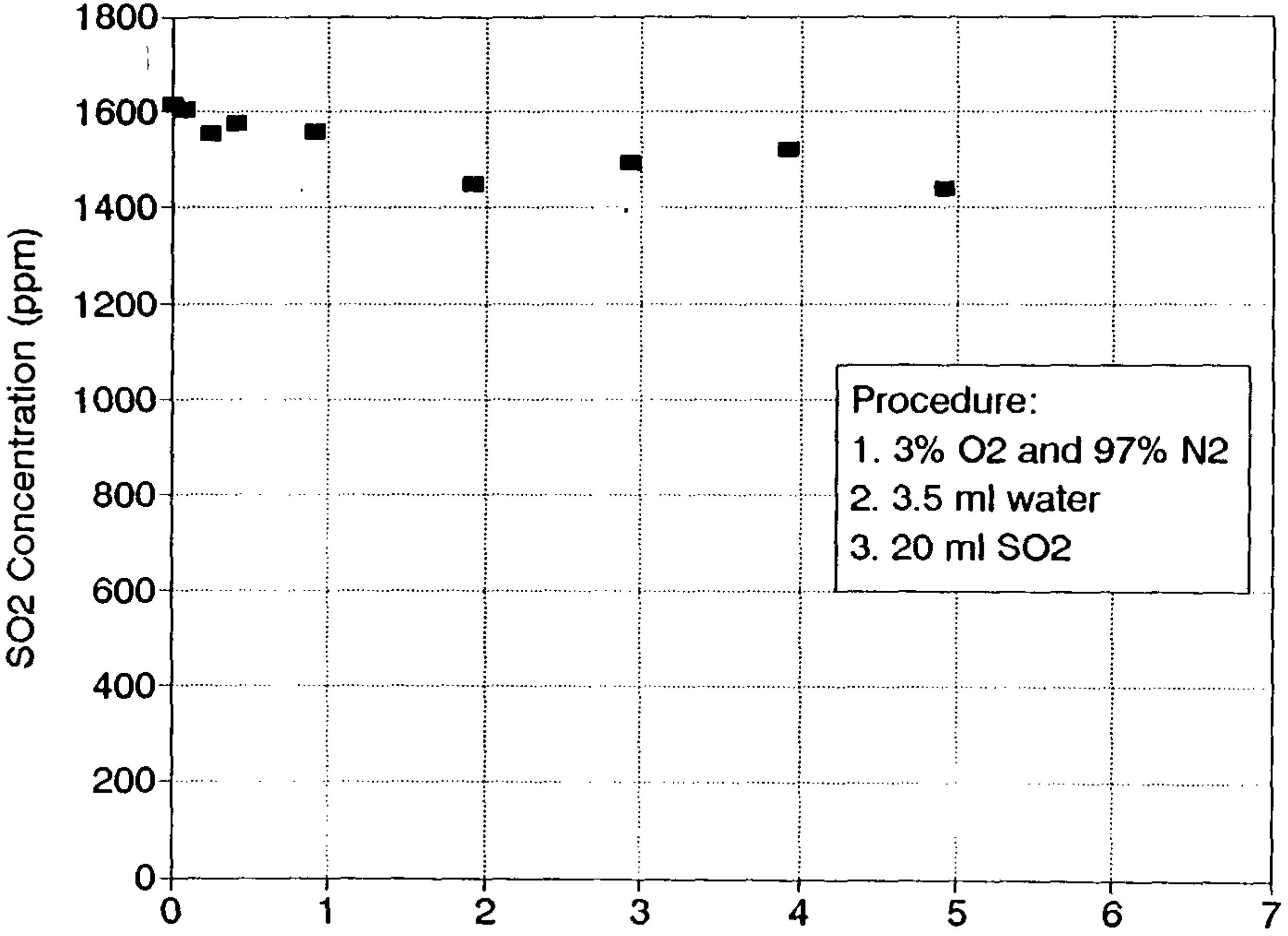


Figure 19. Blank Test without NOx

through the stirring process. The result has been plotted in Figure 20.

Run 3. Blank test with $SO_2$ and $NO_x$ using direct injection

Another blank test was designed to determine if there is a difference if we shorten the sample waiting time. To speed up the $SO_2$ analysis procedure, a new calibration curve based on the method used for low $SO_2$ concentration was obtained and presented in Figure 21 for this blank test. This test demonstrated that by directly injecting the $SO_2$ sample into the gas chromatograph immediately after removal from the reactor (as was done at zero two and five minutes), the resultant values for $SO_2$ concentrations detected by GC are close to the initial values. While those concentrations determined from other $SO_2$ samples which were put aside while waiting for the GC to finish other analyses were significantly lower in concentration. Results for NO and $NO_x$ are similar to the one with $SO_2$ which was shown in Figure 19 and the one without $SO_2$ which was shown in Figure 20. The results from this test have been plotted in Figure 22.

The analytical procedure which was used in our high concentration analysis for $SO_2$ required about 8.5 minutes for the GC to finish a run. Normally, we determined eight samples for each experiment which took about sixty eight minutes to finish the GC $SO_2$ analysis. During the waiting time for GC analysis, something was happening to the $SO_2$ in the presence of $NO_x$ at room temperature as we can see from Figure 18, 19, 20 and 22. Thus, we believe that the low $SO_2$ concentrations obtained during the earlier runs

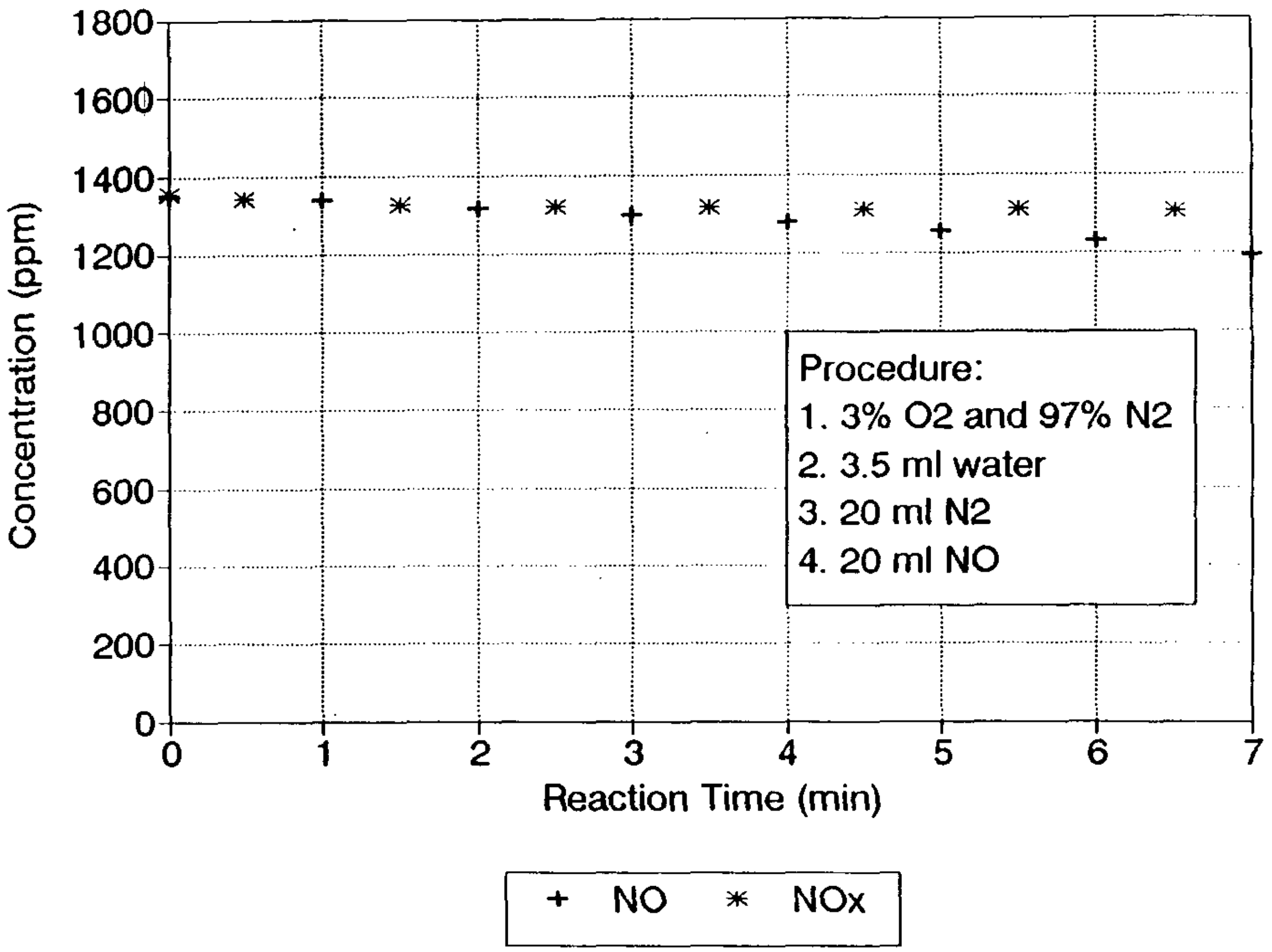


Figure 20. Blank Test without SO2

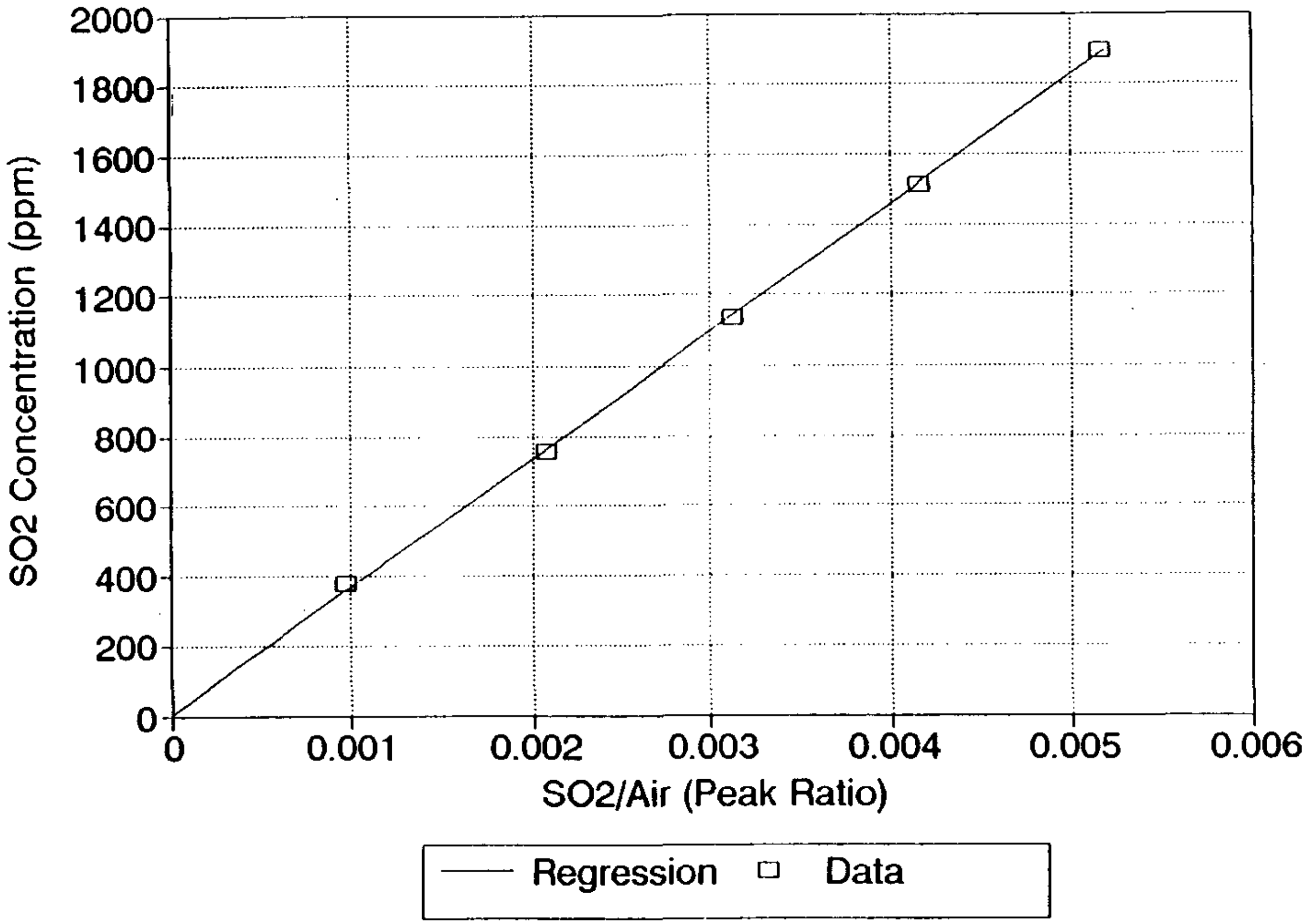


Figure 21. Calibration for High Concentration SO2 Using GC Equipped with TCD

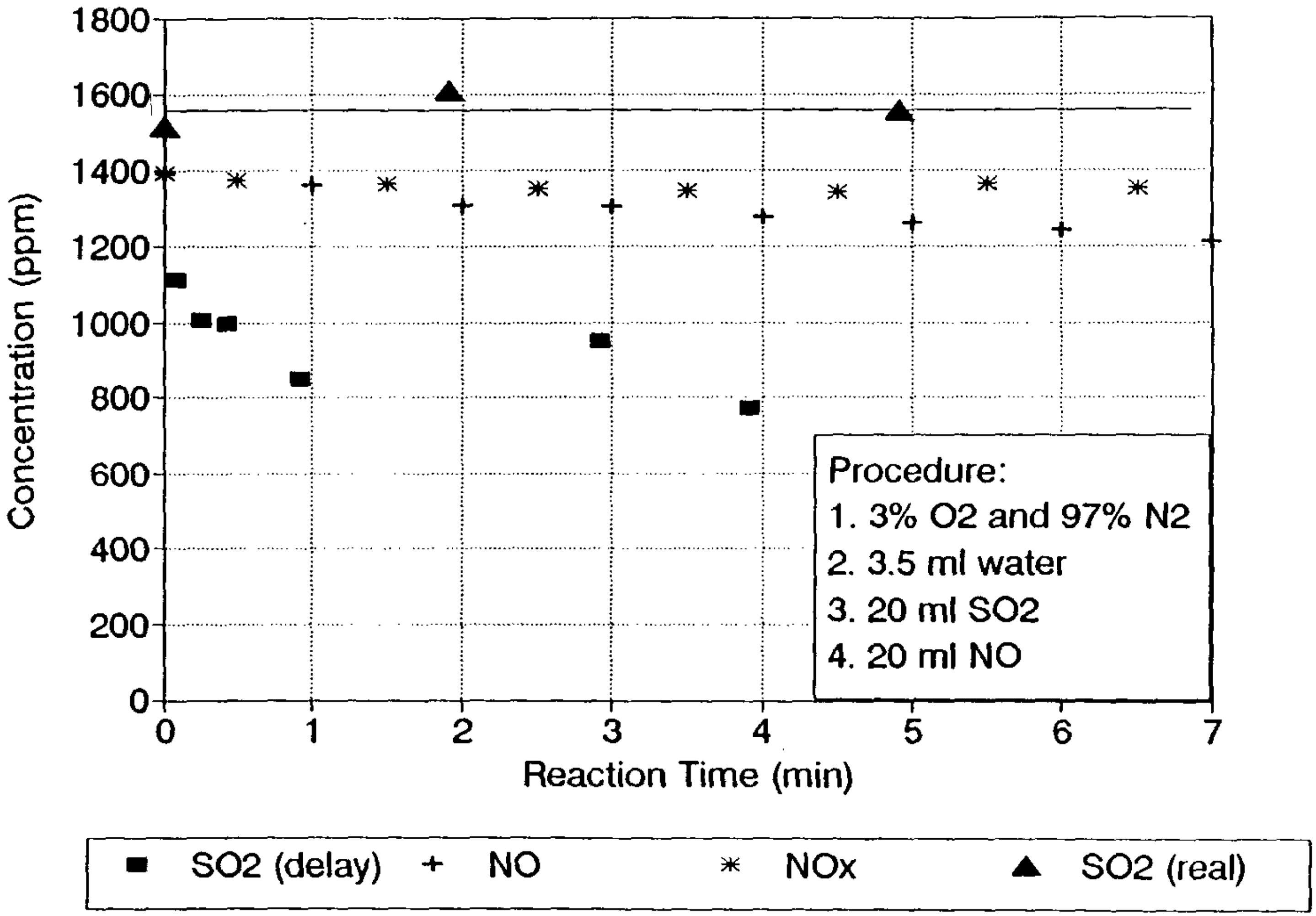


Figure 22. Blank Test with / without Sample Storage

were in error.

### 4.7 Real time analysis for the reaction of flue gas and dry sorbents

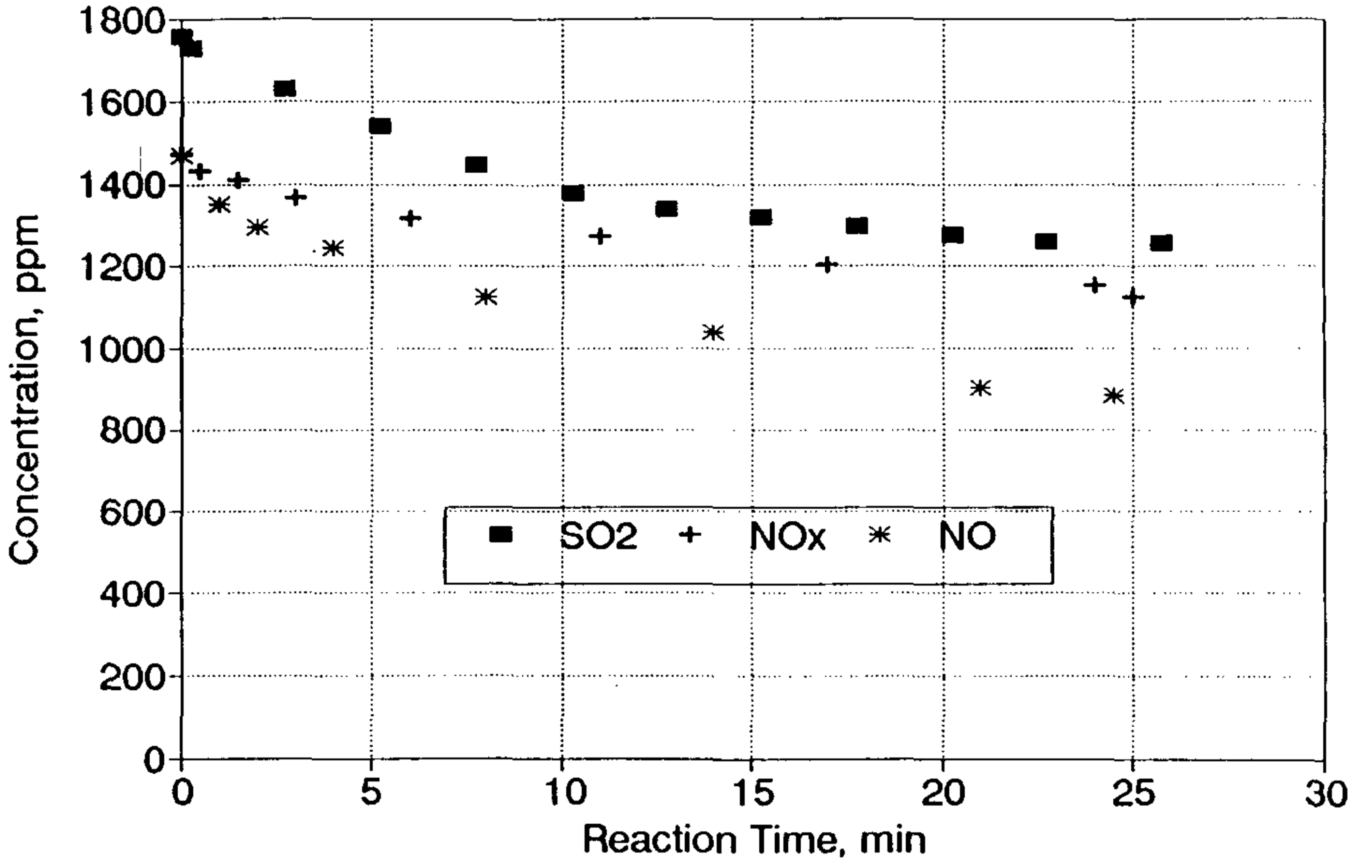
With the new calibration method for $SO_2$ based on the calibration curve, Figure 21, the determination of $SO_2$ concentration by GC was speeded up. Three reaction runs of flue gas with sodium bicarbonate and two experimental runs for sodium sesquicarbonate were obtained to set up the basic reaction runs for each dry sorbent without any sample storage. Two additional blank runs based on this analytical method were also presented at the end of this chapter.

#### 4.7.1 Real time analysis for the reaction of flue gas and sodium bicarbonate

With the new calibration method for $SO_2$ based on the calibration curve, three reaction runs of flue gas in the dry scrubber system using sodium bicarbonate, one with NSR=0.85, another with NSR=3.4 and the other with NSR=13.5, were obtained to set up the basic runs for the sodium sesquicarbonate under the normal operation condition with 700 rpm stirring speed, 58 um mean particle size, 5% water content at temperature of 300°F for NSR=13.5 and 260°F for the rest. Raw data for this study were tabulated and plotted in Table 18 and Figure 23 for the case of NSR=0.85; Table 19 and Figure 24 for the case of NSR=3.4; and Table 20 and Figure 25 for the case of NSR=13.5 respectively. The dry scrubber system with sodium bicarbonate injection with NSR=0.85 was found to be capable of removing $SO_2$ from 1758 ppm to 1270 ppm and

Table 18. Raw Data for $SO_2$ and $NO_x$ Removal by Sodium Bicarbonate with NSR=0.85 :

| Time | SO2/Air | SO2 | NOx | NO | NOx | NO |
|---|---|---|---|---|---|---|
| (min) | (Ratio) | (ppm) | (Index) | (Index) | (ppm) | (ppm) |
| 0 | 0.004819 | 1758.467 | 25 | 26.1 | 1473.919 | 1470.637 |
| 0.25 | 0.004744 | 1731.227 | | | | |
| 0.5 | | | 24.3 | | 1431.897 | |
| 1 | | | | 24 | | 1349.864 |
| 1.5 | | | 23.9 | | 1407.885 | |
| 2 | | | | 23 | | 1292.353 |
| 2.75 | 0.004461 | 1628.402 | | | | |
| 3 | | | 23.2 | | 1365.863 | |
| 4 | | | | 22.2 | | 1246.344 |
| 5.25 | 0.00422 | 1540.655 | | | | |
| 6 | | | 22.4 | | 1317.838 | |
| 7.75 | 0.00396 | 1446.109 | | | | |
| 8 | | | | 20.1 | | 1125.571 |
| 10.25 | 0.003775 | 1378.948 | | | | |
| 11 | | | 21.6 | | 1269.813 | |
| 12.75 | 0.00367 | 1340.655 | | | | |
| 14 | | | | 18.6 | | 1039.305 |
| 15.25 | 0.00361 | 1318.836 | | | | |
| 17 | | | 20.5 | | 1203.779 | |
| 17.75 | 0.00355 | 1297.018 | | | | |
| 20.25 | 0.00349 | 1275.2 | | | | |
| 21 | | | | 16.2 | | 901.2784 |
| 22.75 | 0.003445 | 1258.711 | | | | |
| 24 | | | 19.7 | | 1155.754 | |
| 24.5 | | | | 15.9 | | 884.0251 |
| 25 | | | 19.2 | | 1125.738 | |
| 25.75 | 0.00344 | 1257.018 | | | | |

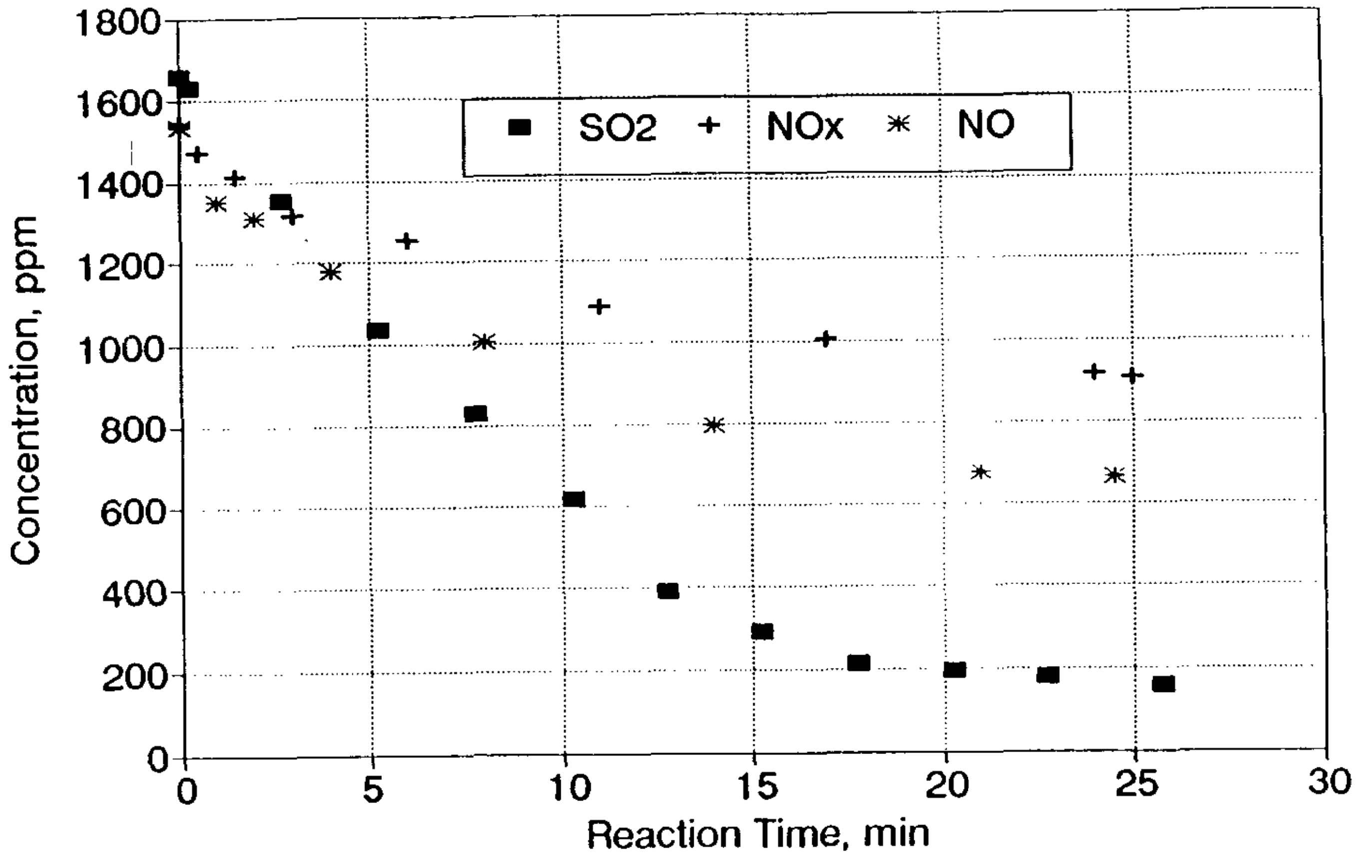


NSR=0.85, 260 F, 700rpm, 5% Water, 53um< d <63um

Figure 23. SO2 and NOx Removed by Sodium Bicarbonate

Table 19. Raw Data for $SO_2$ and $NO_x$ Removal by Sodium Bicarbonate with NSR=3.4 :

| Time (min) | SO2/Air (Ratio) | SO2 (ppm) | NOx (Index) | NO (Index) | NOx (ppm) | NO (ppm) |
|---|---|---|---|---|---|---|
| 0 | 0.004526 | 1652.04 | 24.9 | 26.2 | 1467.916 | 1476.388 |
| 0.25 | 0.004526 | 1652.04 | | | | |
| 0.5 | | | 24.5 | | 1443.904 | |
| 1 | | | | 24.6 | | 1384.37 |
| 1.5 | | | 23.8 | | 1401.882 | |
| 2 | | | | 24 | | 1349.864 |
| 2.75 | 0.003467 | 1266.887 | | | | |
| 3 | | | 23.1 | | 1359.86 | |
| 4 | | | | 21.4 | | 1200.335 |
| 5.25 | 0.002785 | 1018.684 | | | | |
| 6 | | | 21.3 | | 1251.804 | |
| 7.75 | 0.002115 | 775.0761 | | | | |
| 8 | | | | 17.5 | | 976.0426 |
| 10.25 | 0.001505 | 553.2198 | | | | |
| 11 | | | 17.4 | | 1017.682 | |
| 12.75 | 0.001233 | 454.2929 | | | | |
| 14 | | | | 14 | | 774.7544 |
| 15.25 | 0.000834 | 309.4106 | | | | |
| 17 | | | 15.4 | | 897.6195 | |
| 17.75 | 0.000569 | 212.9872 | | | | |
| 20.25 | 0.000478 | 179.7919 | | | | |
| 21 | | | | 12 | | 659.7325 |
| 22.75 | 0.000335 | 128.0145 | | | | |
| 24 | | | 14.8 | | 861.6007 | |
| 24.5 | | | | 11 | | 602.2216 |
| 25 | | | 14.5 | | 843.5914 | |
| 25.75 | 0.000254 | 98.53301 | | | | |

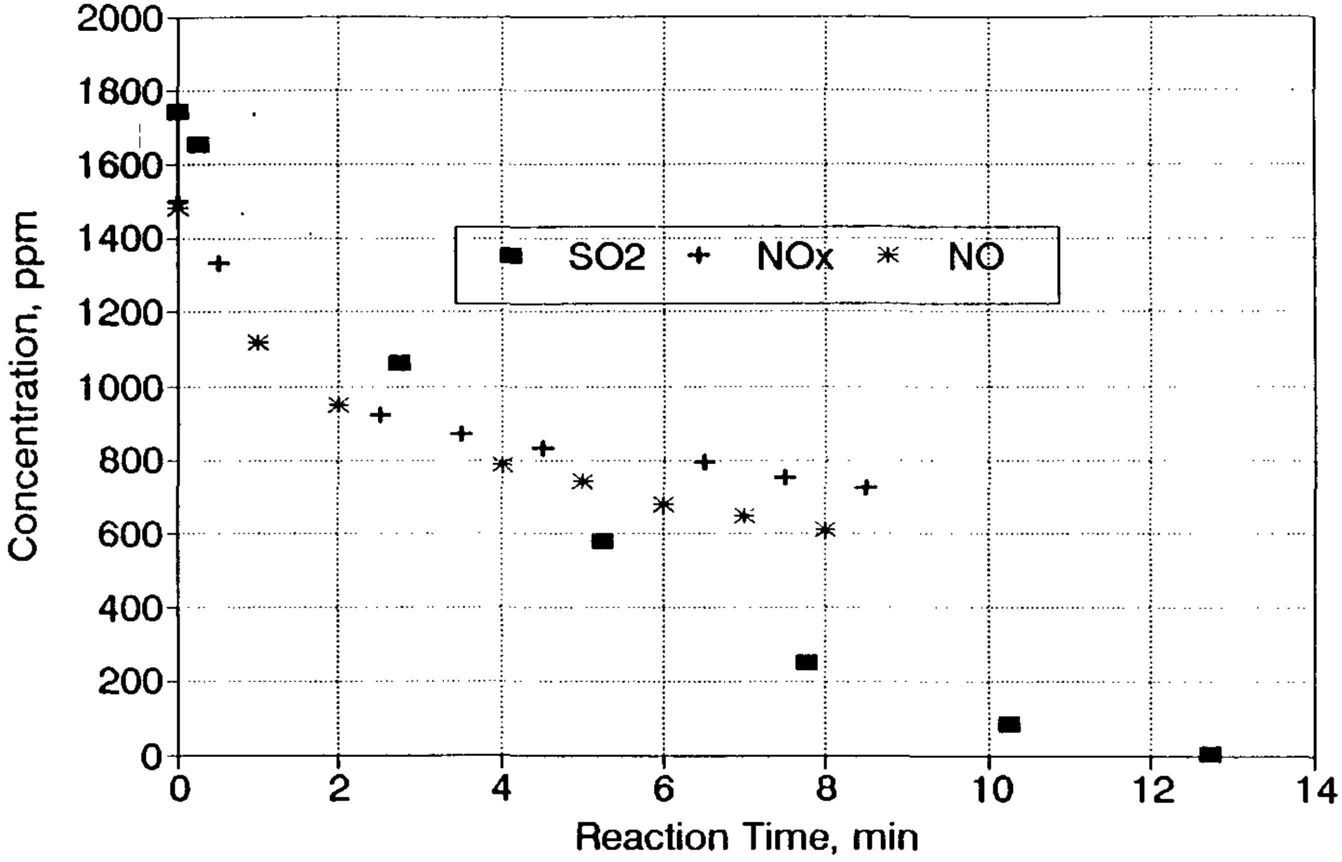


NSR=3.4, 260 F, 700rpm, 5% Water, 53um< d <63um

Figure 24. SO2 and NOx Removed by Sodium Bicarbonate

Table 20. Raw Data for $SO_2$ and $NO_x$ Removal by Sodium Bicarbonate with NSR=13.5 :

| Time (min) | SO2/Air (Ratio) | SO2 (ppm) | NOx (Index) | NO (Index) | NOx (ppm) | NO (ppm) |
|---|---|---|---|---|---|---|
| 0 | 0.004783 | 1745.432 | 25.4 | 26.3 | 1497.932 | 1482.139 |
| 0.25 | 0.004526 | 1652.04 | | | | |
| 0.5 | | | 22.7 | | 1335.847 | |
| 1 | | | | 20 | | 1119.82 |
| 2 | | | | 17 | | 947.2872 |
| 2.5 | | | 15.8 | | 921.6319 | |
| 2.75 | 0.002912 | 1065.018 | | | | |
| 3.5 | | | 14.9 | | 867.6039 | |
| 4 | | | | 14.2 | | 786.2566 |
| 4.5 | | | 14.3 | | 831.5851 | |
| 5 | | | | 13.4 | | 740.2478 |
| 5.25 | 0.001575 | 578.8172 | | | | |
| 6 | | | | 12.3 | | 676.9858 |
| 6.5 | | | 13.7 | | 795.5664 | |
| 7 | | | | 11.8 | | 648.2303 |
| 7.5 | | | 13 | | 753.5445 | |
| 7.75 | 0.000671 | 250.0586 | | | | |
| 8 | | | | 11.2 | | 613.7238 |
| 8.5 | | | 12.5 | | 723.5289 | |
| 10.25 | 0.000212 | 83.29007 | | | | |
| 12.75 | 0 | 6.109091 | | | | |



NSR=13.5, 300 F, 300rpm, 5% Water, 53um< d <63um

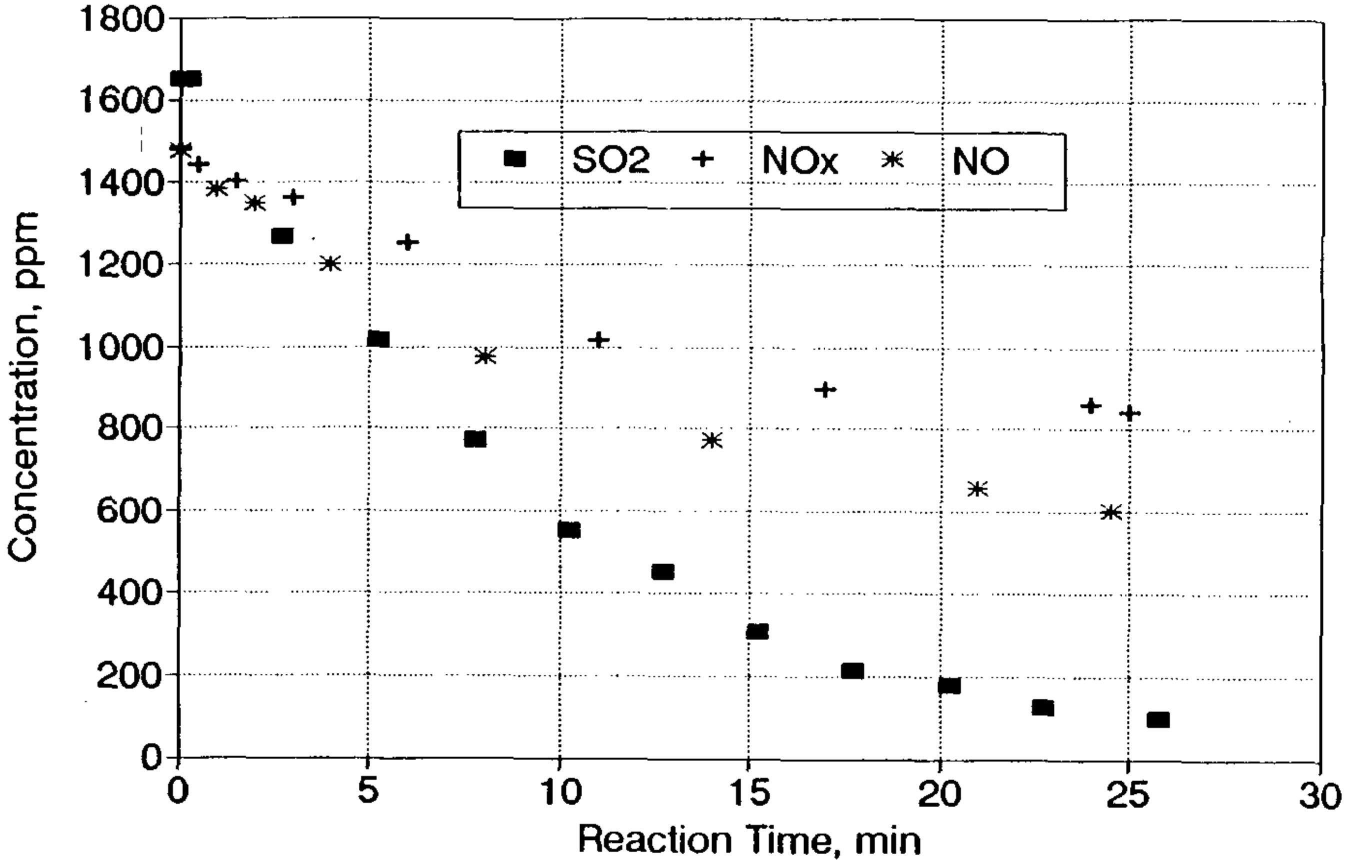
Figure 25. SO2 and NOx Simultaneous Removed by Sodium Bicarbonate

$NO_x$ from 1474 ppm to 1180 ppm within twenty minutes, or about 488 ppm or 28% $SO_2$ removal, 290 ppm or 20% $NO_x$ removal, and there was about 260 ppm $NO_2$ formed at the end of twenty minutes. As for NSR=3.4, after 25 minutes from concentration of $SO_2$ and $NO_x$ initial concentrations of about 1650 ppm, over 94% removal for $SO_2$ occurred, and 50% removal for $NO_x$, and with the formation of 200 ppm $NO_2$. In the case of NSR=13.5 at 300°F, this dry scrubber system was found to require 15 minutes to remove $SO_2$ from 1750 ppm to under detectable limits and to remove $NO_x$ from about 1500 to 750 ppm at 8 minutes and produce an $NO_2$ yield at 8 minutes of about 140 ppm. An additional run was also done to duplicate the run with NSR=3.4. It showed that we can duplicate the run with NSR=3.4 very well. The results of this experimental run are shown in Figure 26.

It is very important to look at how the $SO_2$ and the $NO_x$ removal occurred in Figure 23 through Figure 25. It seems that the reaction of $SO_2$ and the reaction of $NO_x$ all followed first order reaction kinetics. It also implies that for sodium bicarbonate, the removal of the flue gases highly depends on the solid present. If we fixed the particle size, then the reaction rate depends on the amount of sodium bicarbonate we used.

### 4.7.2 Real time analysis for the reaction of flue gas and sodium sesquicarbonate

With the new calibration method for $SO_2$ based on the calibration curve, Figure 21, two complete reaction runs of flue gases in the dry scrubber system using sodium sesquicarbonate, one with NSR=0.85 and the other with NSR=3.4, were conducted to



NSR=3.4, 260 F, 700rpm, 5% Water

Figure 26. SO2 and NOx Removed by Sodium Bicarbonate

set up the basic runs for the sodium sesquicarbonate under the typical operation condition with 700 rpm stirring speed, 58 um mean particle size, 5% water content at 260°F. Raw data for this study were tabulated and plotted in Table 21 and Figure 27 for the case of NSR=0.85; Table 22 and Figure 28 for the case of NSR=3.4 respectively. The dry scrubber system with sodium bicarbonate injection with NSR=0.85 was found to be capable of removing $SO_2$ from 1726 ppm to 1285 ppm and $NO_x$ from 1492 ppm to 1185 ppm within twenty minutes. This is about 441 ppm or 26% $SO_2$ removal, 307 ppm or 21% $NO_x$ removal, and there was about 230 ppm $NO_2$ formed at the end of twenty minute. As for NSR=3.4, it was found to require 20 minutes to remove $SO_2$ and $NO_x$ from initial concentrations of 1508 ppm and 1534 ppm to the concentration of 150 ppm and 930 ppm at the end of twenty minute. The removal of $SO_2$ is about 1358 ppm or 90%, and about 604 ppm or 39% removal for $NO_x$. The $NO_2$ yield at the end of twenty minutes was about 230 ppm. The reduction of flue gases by sodium sesquicarbonate is similar to that of sodium bicarbonate. It seems that the initial rate of the flue gases reduction by sodium sesquicarbonate is faster than that by sodium bicarbonate. It might be due to the different chemical structure of sodium sesquicarbonate.

In order to duplicate the above results, three additional runs at NSR=3.4 and one additional run at NSR=0.85 were also done under the same operational conditions. Results for these four runs, shown in Figure 29 through Figure 32, were consistent with the previous two runs. The reduction rates of $SO_2$, NO and $NO_x$ at NSR=0.85 slows

Table 21. Raw Data for $SO_2$ and $NO_x$ Removal by Sodium Sesquicarbonate with NSR=0.85:

| Time (min) | SO2/Air (Ratio) | SO2 (ppm) | NOx (Index) | NO (Index) | NOx (ppm) | NO (ppm) |
|---|---|---|---|---|---|---|
| 0 | 0.004728 | 1725.517 | 25.3 | 26.4 | 1491.929 | 1487.89 |
| 0.25 | 0.004439 | 1620.329 | | | | |
| 0.5 | | | 24.8 | | 1461.913 | |
| 1 | | | | 24 | | 1349.864 |
| 1.5 | | | 23.5 | | 1383.872 | |
| 2 | | | | 22.9 | | 1286.602 |
| 2.75 | 0.004186 | 1528.297 | | | | |
| 3 | | | 23.2 | | 1365.863 | |
| 4 | | | | 22.2 | | 1246.344 |
| 5.25 | 0.003924 | 1433.181 | | | | |
| 6 | | | 21.3 | | 1251.804 | |
| 7.75 | | | | | | |
| 8 | | | | 20.1 | | 1125.571 |
| 10.25 | 0.003678 | 1343.537 | | | | |
| 11 | | | 20.9 | | 1227.791 | |
| 12.75 | 0.00363 | 1326.151 | | | | |
| 14 | | | | 18.9 | | 1056.558 |
| 15.25 | 0.003616 | 1320.908 | | | | |
| 17 | | | 20.4 | | 1197.776 | |
| 17.75 | 0.00354 | 1293.54 | | | | |
| 20.25 | 0.003524 | 1287.445 | | | | |
| 21 | | | | 17 | | 947.2872 |
| 22.75 | 0.003492 | 1275.983 | | | | |
| 24 | | | 19.8 | | 1161.757 | |
| 24.5 | | | | 16.2 | | 901.2784 |
| 25 | | | 19.3 | | 1131.741 | |

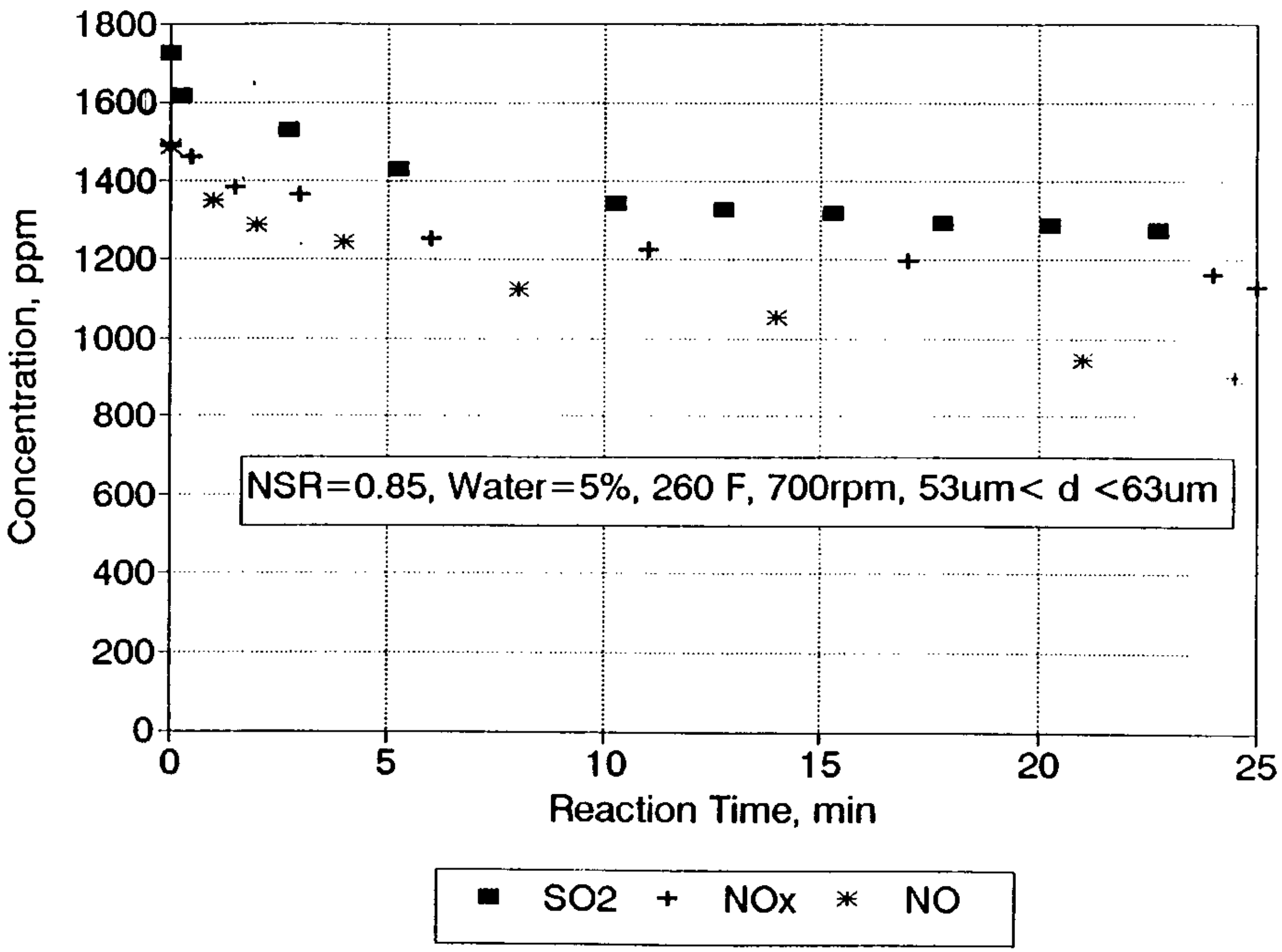


Figure 27. SO2 and NOx Removal by Sodium Sesquicarbonate

Table 22. Raw Data for $SO_2$ and $NO_x$ Removal by Sodium Sesquicarbonate with NSR=3.4 :

| Time | SO2/Air | SO2 | NOx | NO | NOx | NO |
|---|---|---|---|---|---|---|
| (min) | (Ratio) | (ppm) | (Index) | (Index) | (ppm) | (ppm) |
| 0 | 0.004129 | 1507.547 | 26 | 26.4 | 1533.95 | 1487.89 |
| 1 |  |  | 24.6 |  | 1449.907 |  |
| 2 |  |  |  | 22.2 |  | 1246.344 |
| 3 | 0.002325 | 851.4231 |  |  |  |  |
| 4 |  |  | 20.9 |  | 1227.791 |  |
| 5 |  |  |  | 18.3 |  | 1022.051 |
| 6 | 0.001724 | 633.1955 |  |  |  |  |
| 7 |  |  | 19.9 |  | 1167.76 |  |
| 8 |  |  |  | 16.8 |  | 935.785 |
| 9 | 0.001401 | 515.4968 |  |  |  |  |
| 10 |  |  | 18.9 |  | 1107.729 |  |
| 11 |  |  |  | 15.8 |  | 878.274 |
| 12 | 0.001143 | 421.9122 |  |  |  |  |
| 15 | 0.000967 | 357.7891 |  |  |  |  |
| 16 |  |  | 17.1 |  | 999.6725 |  |
| 17 |  |  |  | 14.6 |  | 809.2609 |
| 18 | 0.000784 | 291.1866 |  |  |  |  |
| 21 | 0.00066 | 245.9431 |  |  |  |  |
| 22 |  |  | 16.5 |  | 963.6538 |  |
| 23 |  |  |  | 13.1 |  | 722.9945 |
| 24 | 0.000375 | 142.529 |  |  |  |  |
| 27 | 0.000435 | 164.3607 |  |  |  |  |
| 28 |  |  | 15.5 |  | 903.6226 |  |
| 29 |  |  |  | 12 |  | 659.7325 |
| 30 | 0.000324 | 124.0352 |  |  |  |  |

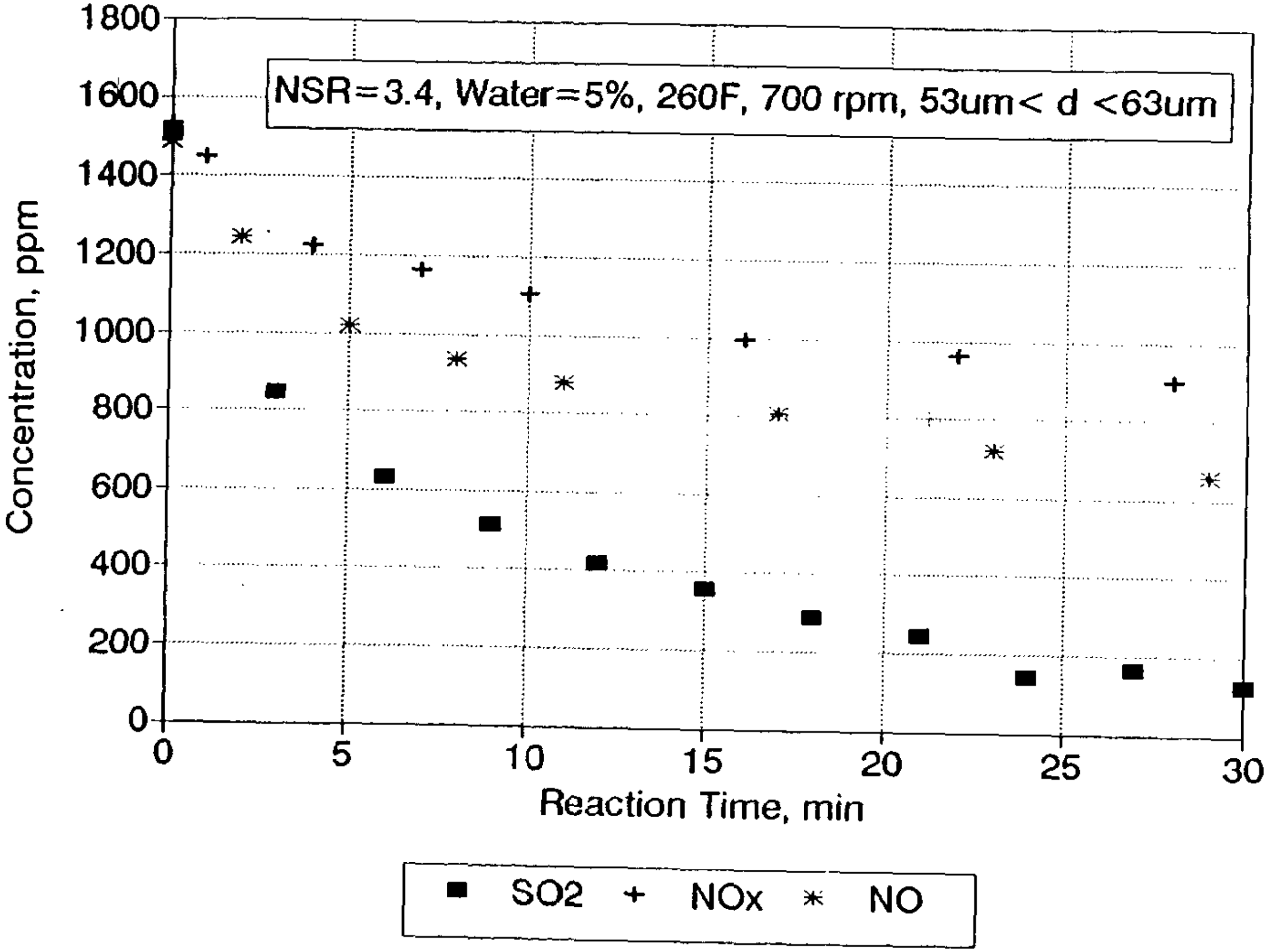


Figure 28. SO2 and NOx Removal by Sodium Sesquicarbonate

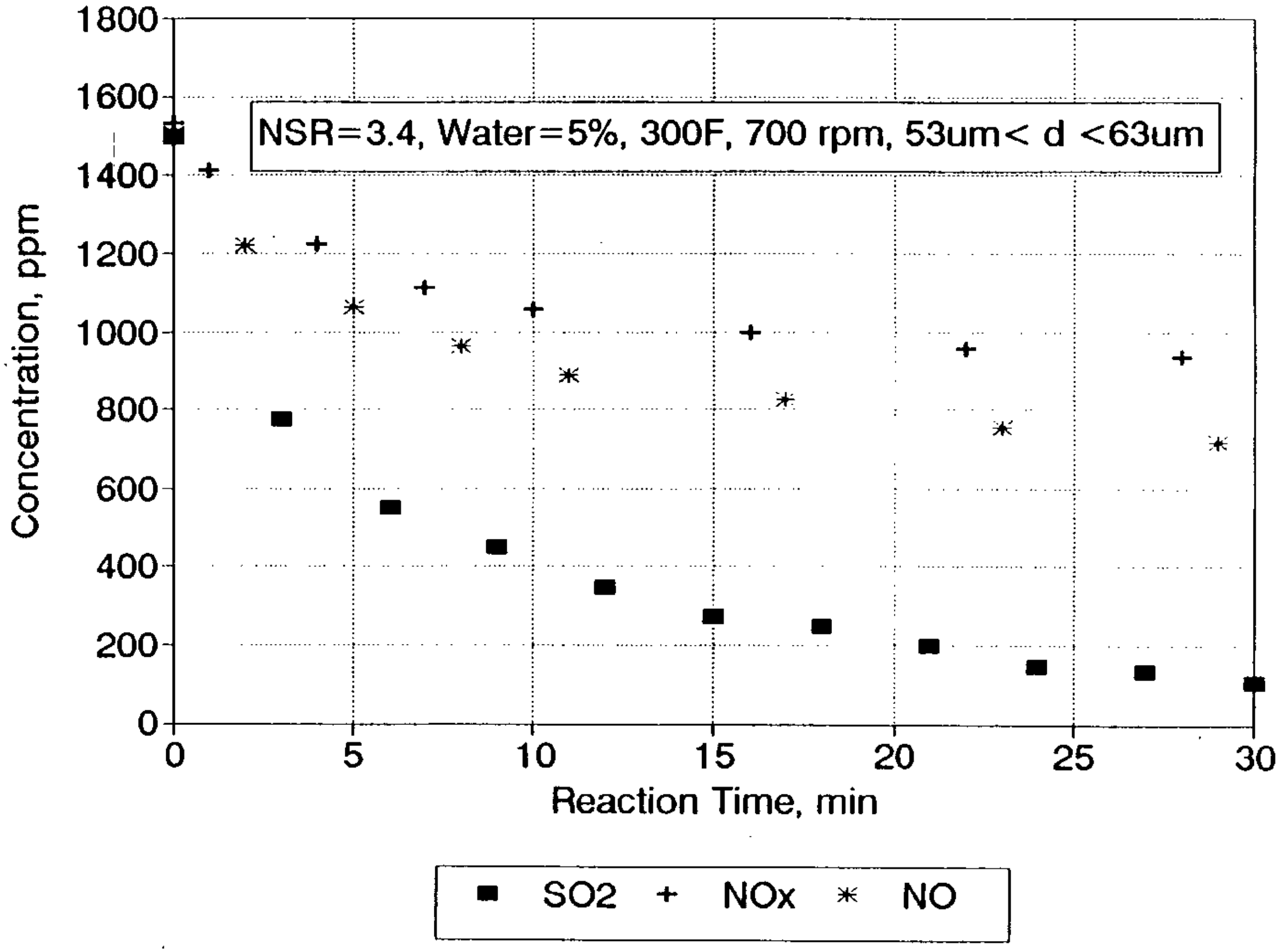


Figure 29. SO2 and NOx Removal by Sodium Sesquicarbonate

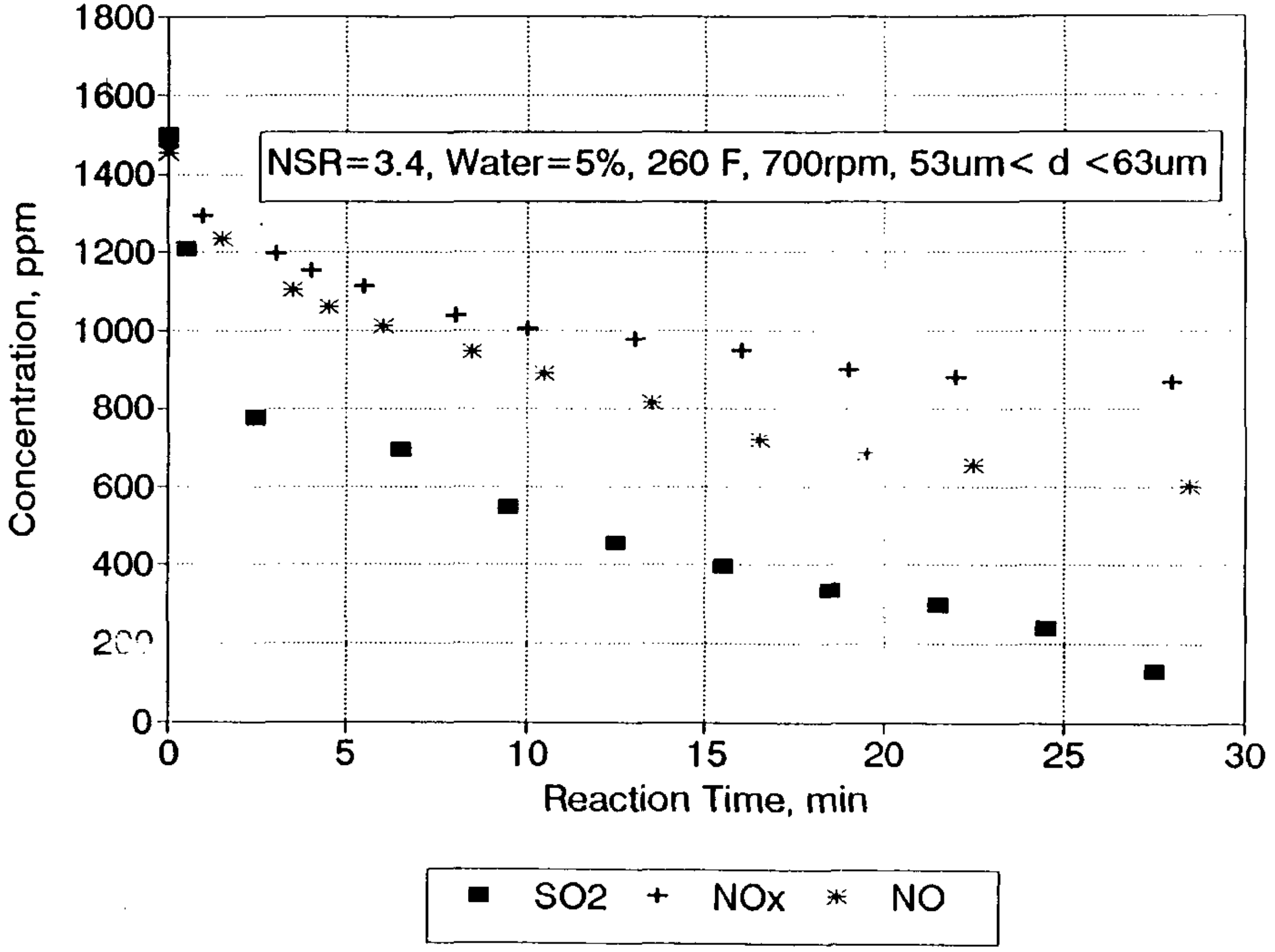


Figure 30. SO2 and NOx Removal by Sodium Sesquicarbonate

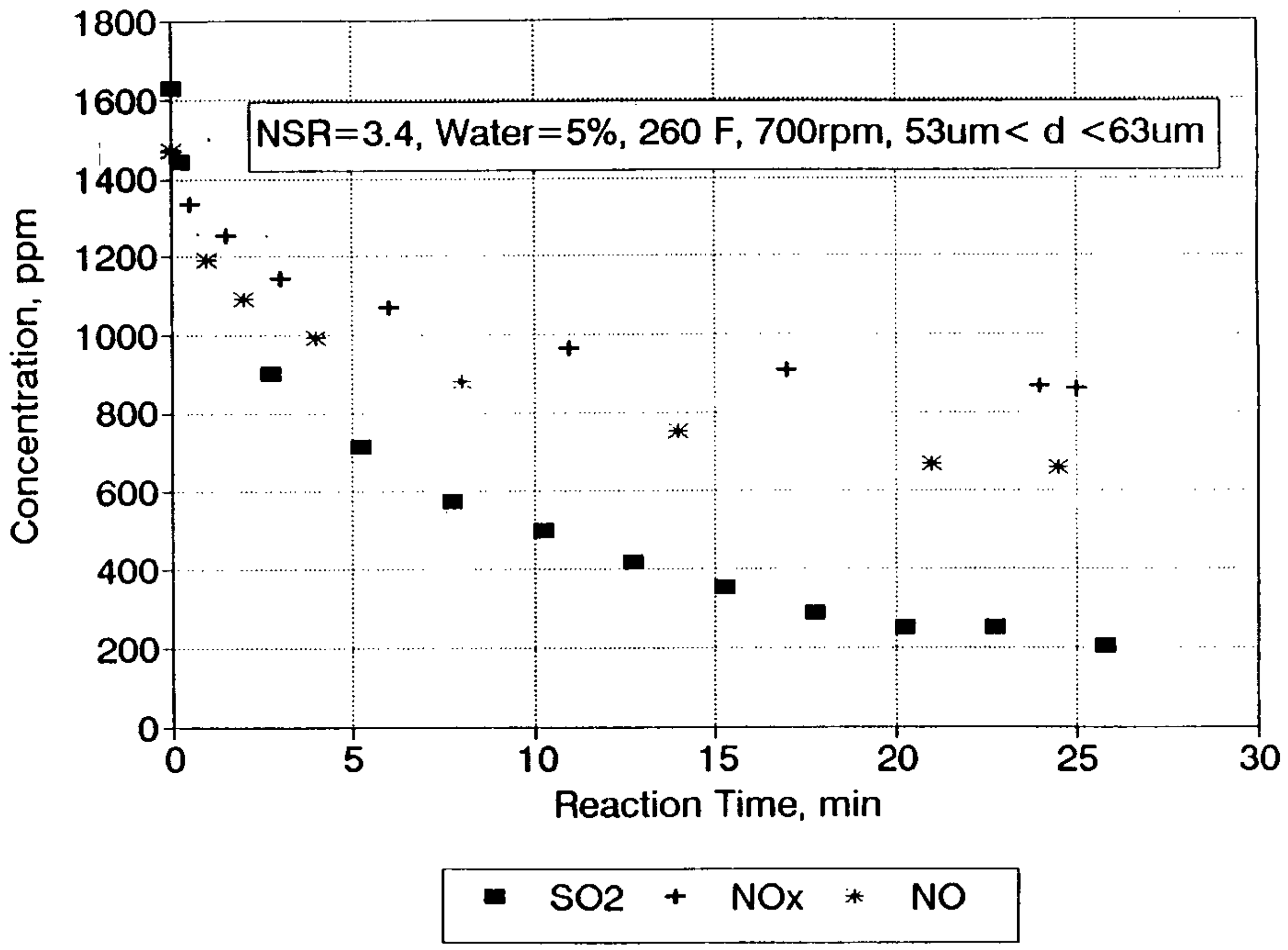


Figure 31. SO2 and NOx Removal by Sodium Sesquicarbonate

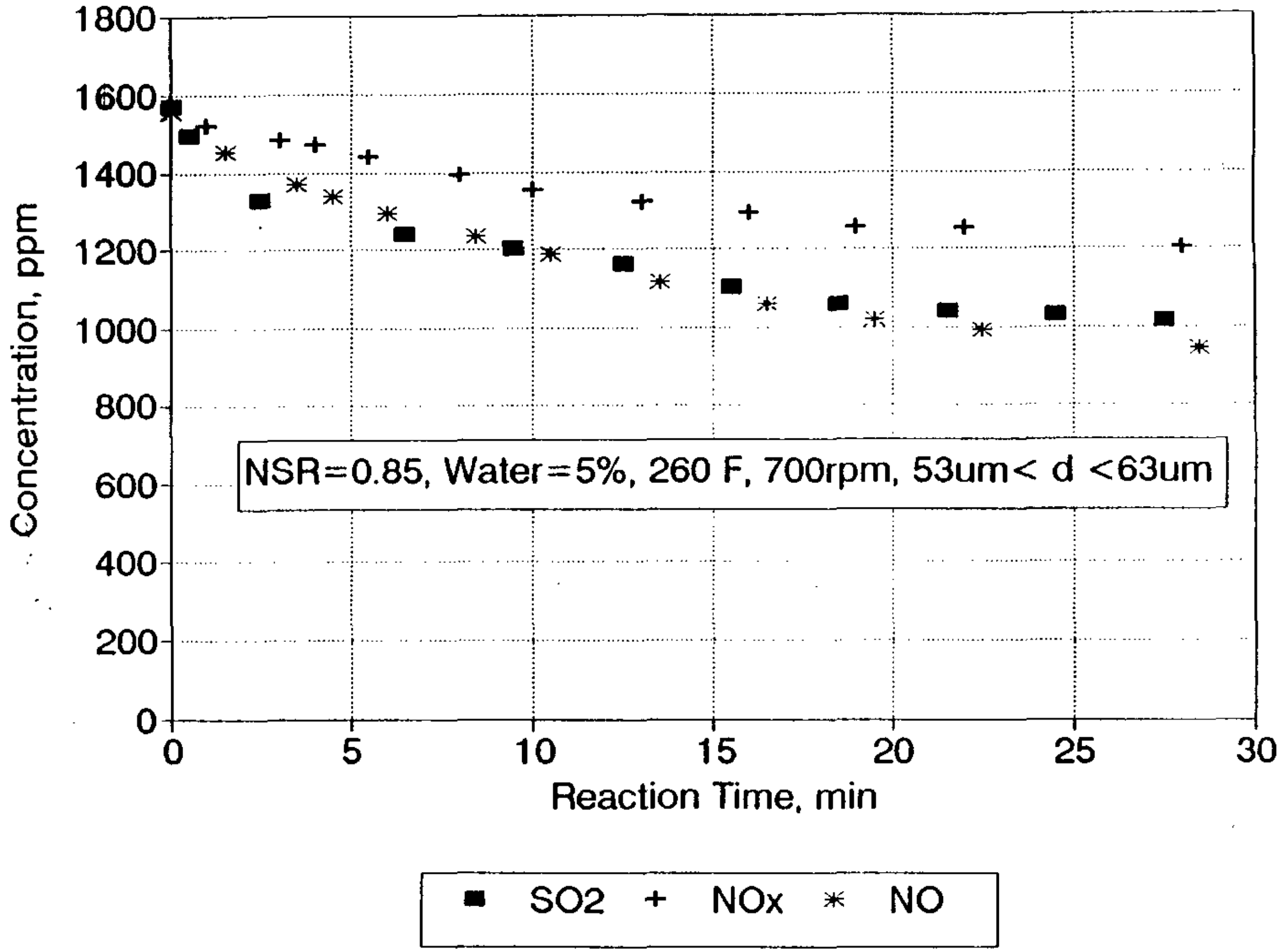


Figure 32. SO2 and NOx Removal by Sodium Sesquicarbonate

down after fifteen minutes. On the other hand, the reduction rates of $SO_2$, NO and $NO_x$ at NSR=3.4 slows down after twenty five minutes.

# CHAPTER V

# MODEL RESULTS

The Adams-Bashforth-Moulton method with a Runge-Kutta starting procedure is recommended for solving most first-order initial-value ordinary differential equations(14). This project therefore uses this combined method to solve sets of ordinary differential equations. An experimental data set for simultaneous removal of $NO_x$ and $SO_2$ by $NaHCO_3$ with an NSR equal to 13.5 was initially used to verify the two models described in Chapter three. The experimental data were first corrected for the bleeding rate of the system. The corrected data were then used to evaluate rate constants and the selectivity constant by the initial rate approach. The gas concentration results of the computer simulation are then compared with the experimental results and the radius of the unreacted $Na_2CO_3$ is predicted from the model.

## 5.1 Experimental data correction for the bleeding rate of the system

In some cases, chemical bleeding from a shaft rotating system is not unusual. Corrections are often made for this system bleeding by assuming a constant bleeding rate which is described in the book "Fluid Sealant Handbook" published by McGraw Hill Book Company(13). Two experiments were therefore conducted to investigate the bleeding rates at two sets of operating conditions; one was at 300°F with a stirring speed of 300 rpm and the other was for the remaining runs at 260°F with a stirring speed of 700 rpm.

5.1.1 Correction for the case of NSR equal to 13.5 at 300°F

An experiment was conducted with initial concentrations of about 1600 ppm $SO_2$ and NO, 3% $O_2$, and 5% water without any dry sorbent injected under the operating conditions of 300°F and a stirring speed of 300 rpm. The results of this experimental run are shown in Table 23. From the blank test presented in chapter four, which was shown in Figure 22, we know that the concentration change of $SO_2$ is not significant and could be ignored compare to the total change in $SO_2$ concentration. Such is not the case for NO and $NO_2$ which are the constituents of $NO_x$, since the change in concentration of these components is not very large. Consequently, we used the reduction in the $NO_x$ copncentration during the blank run to correct the experimental data. The resulting data from Table 23 are illustrated in Figure 33. From this figure, it seems we can use a linear relationship to represent concentration change versus reaction time. A regression technique was therefore used to obtain the constant bleeding rate which is the X coefficient shown in Table 24. The value of the bleeding rate is 4.79 ppm per minute which was then used to obtain the corrected concentration of $NO_x$ and the concentration of NO by simply adding 4.79 ppm per minute to the experimental data. Data from Table 20 were therefore corrected by this bleeding rate and are shown in Table 25 and Figure 34.

Table 23. Bleeding Rate Study at rpm=300

Date : 11-09-93
Sorbent : None
Water(%) : 5

Temp.(F) : 300
rpm : 300
NSR : 0
Size(um) : 0

| Time (min) | SO2/Air (Ratio) | SO2 (ppm) | NOx (Index) | NO (Index) | NOx (ppm) | NO (ppm) |
|---|---|---|---|---|---|---|
| 0 | 0.004338 | 1599.887 | 27.2 | 28 | 1605.988 | 1579.907 |
| 0.5 | 0.004703 | 1732.512 | | | | |
| 1 | | | 27.2 | | 1605.988 | |
| 1.5 | | | | 27.4 | | 1545.401 |
| 2.5 | | | 27.2 | | 1605.988 | |
| 3 | | | | 27.2 | | 1533.899 |
| 3.5 | 0.004739 | 1745.78 | | | | |
| 4 | | | 27 | | 1593.982 | |
| 4.5 | | | | 27 | | 1522.396 |
| 5.5 | | | 26.9 | | 1587.978 | |
| 6 | | | | 26.3 | | 1482.139 |
| 7 | | | 26.9 | | 1587.978 | |
| 8 | | | | 25.8 | | 1453.383 |
| 9.5 | | | 26.6 | | 1569.969 | |
| 10 | | | | 25 | | 1407.375 |
| 11 | 0.004802 | 1768.532 | | | | |
| 12 | | | 26.4 | | 1557.963 | |
| 13 | | | | 24.5 | | 1378.619 |
| 15 | | | 26 | | 1533.95 | |
| 16 | | | | 23.6 | | 1326.859 |
| 18 | 0.00425 | 1567.998 | | | | |
| 20 | | | 25 | | 1473.919 | |
| 21 | | | | 22.5 | | 1263.597 |
| 27 | | | 24 | | 1413.888 | |
| 29 | | | | 20 | | 1119.82 |
| 30 | 0.004632 | 1706.78 | | | | |

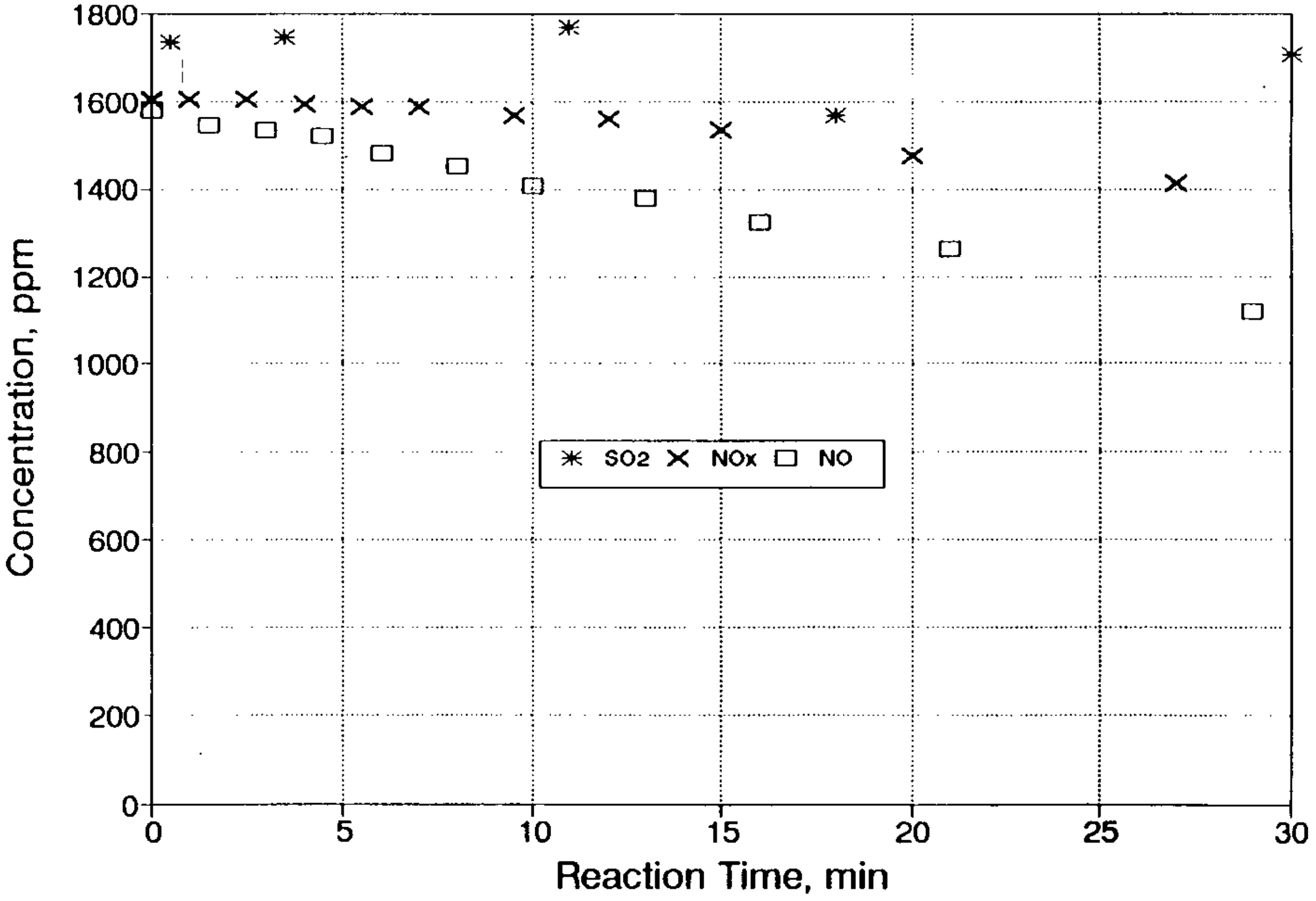


Figure 33. SO2 and NOx Decrease Adding no Dry Sorbents

Table 24. Regression on the Results of Bleeding Rate Study (300 rpm)

| Time (min) | SO2 (ppm) | Time (min) | NOx (ppm) | Time (min) | NO (ppm) |
|---|---|---|---|---|---|
| 0 | 1599.887 | 0 | 1605.988 | 0 | 1579.907 |
| 0.5 | 1732.512 | 1 | 1605.988 | 1.5 | 1545.401 |
| 3.5 | 1745.78 | 2.5 | 1605.988 | 3 | 1533.899 |
| 11 | 1768.532 | 4 | 1593.982 | 4.5 | 1522.396 |
| 18 | 1567.998 | 5.5 | 1587.978 | 6 | 1482.139 |
| 30 | 1706.78 | 7 | 1587.978 | 8 | 1453.383 |
|  |  | 9.5 | 1569.969 |  |  |
|  |  | 12 | 1557.963 |  |  |
|  |  | 15 | 1533.95 |  |  |

```
NOx     Regression Output:
Constant                1613.351
Std Err of Y Est         5.548794
R Squared               0.956523
No. of Observations            9
Degrees of Freedom             7

X Coefficient(s)  -4.78542
Std Err of Coef.  0.385616
```

(NOx) = 1613.351 - 4.785424 * t

Tabel 25. Corrected Concentrations for Three Gases (300 rpm) :

| | Corrected Data | | | |
|---|---|---|---|---|
| Time (min) | (SO2) (ppm) | (NOx) (ppm) | (NO) (ppm) | (NO2) (ppm) |
| 0 | 1745.432 | 1497.932 | 1482.139 | 15.79285 |
| 0.25 | 1652.04 | | | |
| 0.5 | | 1338.24 | | |
| 1 | | | 1124.605 | 27 |
| 2 | | | 956.858 | 43.142 |
| 2.5 | | 933.5955 | | |
| 2.75 | 1065.018 | | | |
| 3.5 | | 884.3528 | | |
| 4 | | | 805.3983 | 67 |
| 4.5 | | 853.1195 | | |
| 5 | | | 764.1749 | 82 |
| 5.25 | 578.8172 | | | |
| 6 | | | 705.6983 | 102.3551 |
| 6.5 | | 826.6717 | | |
| 7 | | | 681.7283 | 107.7069 |
| 7.5 | | 789.4352 | | |
| 7.75 | 250.0586 | | | |
| 8 | | | 652.0072 | 137.4281 |
| 8.5 | | 764.205 | | |
| 10.25 | 83.29007 | | | |
| 12.75 | 6.109091 | | | |

Initial Rate of $SO_2$ = -373.566 ppm/min =-1.1E-08 mol/(min)(ml)
Initial Rate of $NO_x$ = -319.383 ppm/min =-9.2E-09 mol/(min)(ml)
Initial Rate of NO = -357.533 ppm/min = -1E-08 mol/(min)(ml)
Initial Rate of $NO_2$ = 38.15027 ppm/min = 1.1E-09 mol/(min)(ml)

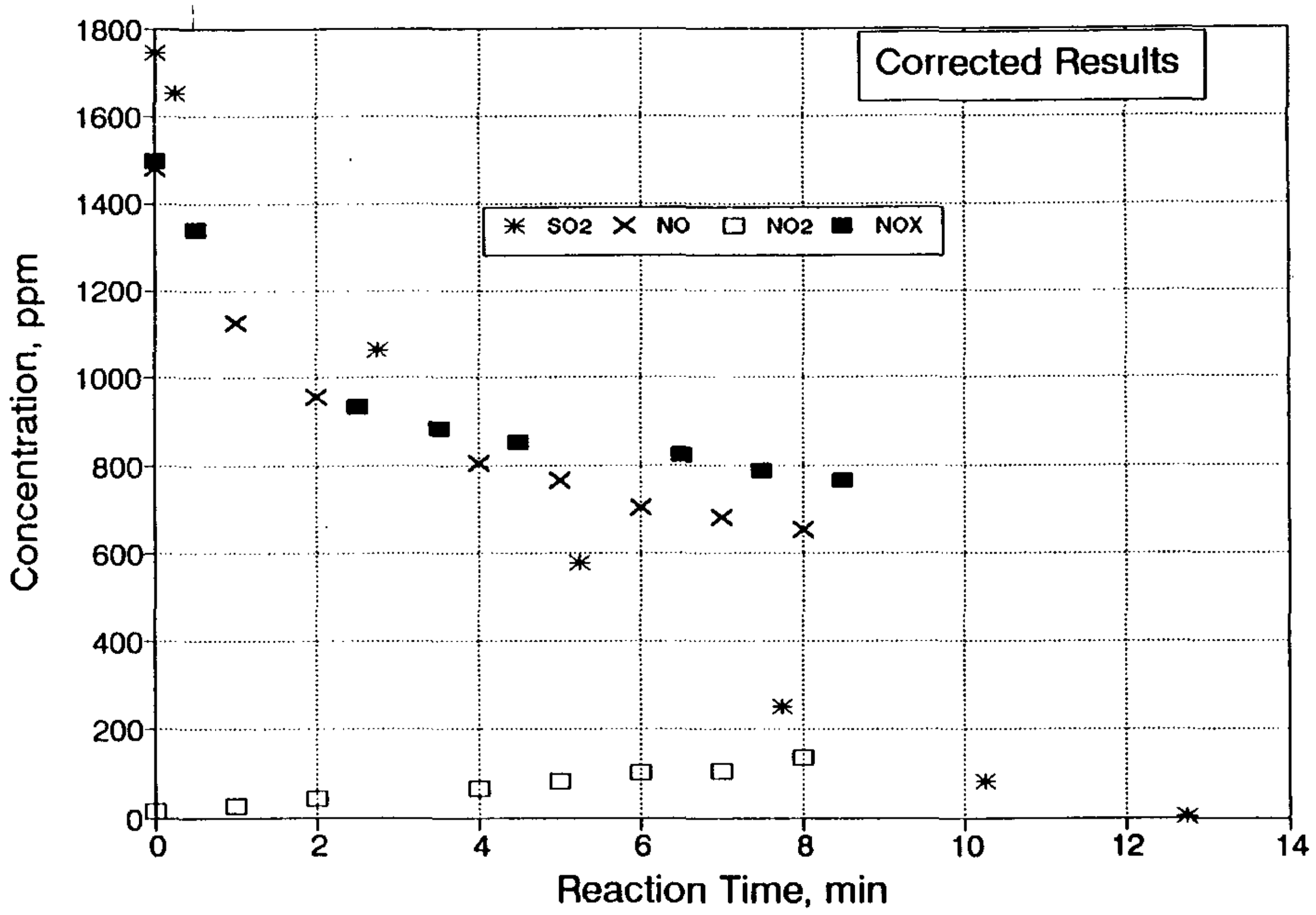


Figure 34. SO2 and NOx Simultaneous Reaction by Sodium Bicarbonate

### 5.1.2 Correction for the remaining cases

Another experiment was conducted with initial concentration of about 1600 ppm $SO_2$ and 1400 ppm $NO_x$, 3% $O_2$, and 5% water without no dry sorbent injected under the operating conditions of 260°F and stirring speed of 700 rpm. The result of this experimental run is the blank test already reported in chapter four and shown in Figure 22. Again, the concentration change of $SO_2$ is not significant and could be ignored and consequently, we only use the bleeding rate of the $NO_x$ to correct the experimental data for these cases. Raw data from Figure 22 are shown in Table 26. After performing the regression on the data taken from Table 26, we obtain the constant bleeding rate at 7.4 ppm per minute which is the X coefficient shown in Table 27. To demonstrate the effect of the system bleeding at 700 rpm and 260°F on the experimental results, the results taken from Figure 28 was used as an example. The corrected results were shown in Table 28 and Figure 35.

## 5.2 Experimental curve fitting by EPRI's model

Rate laws proposed by EPRI, which are given in Chapter 3.1 were applied to simulate the resulting data. The experimental results is for the $SO_2$-$NO_x$-$NaHCO_3$ reaction system with normal stoichiometric ratio equal to 13.5 at 300°F stirred at 300 rpm. Results of this experiment have been shown in Table 20 and Figure 25.

Table 26. Bleeding Rate Study at rpm=700

| | | | |
|---|---|---|---|
| Date | 08-08-93 | Temp.(F) | 260 |
| Sorbent | Nil | rpm | 700 |
| Water(%) | 0 | NSR | 0 |
| | | Size(um) | 0 |

| Time (min) | SO2/N2 (Ratio) | SO2/N2 (ppm) | NO (Index) | NOx (Index) | NO (ppm) | NOx (ppm) |
|---|---|---|---|---|---|---|
| 0 | 0.004166 | 1537.532 | 25.2 | 24.2 | 1418.877 | 1425.894 |
| 0.083333 | 0.003676 | 1359.344 | | | | |
| 0.25 | 0.003042 | 1128.767 | | | | |
| 0.416667 | 0.002038 | 763.5321 | | | | |
| 0.5 | | | | 24.1 | | 1419.891 |
| 0.916667 | 0.001363 | 518.0101 | | | | |
| 1 | | | 24.8 | | 1395.872 | |
| 1.5 | | | | 24.1 | | 1419.891 |
| 1.916667 | 0.000628 | 250.7347 | | | | |
| 2 | | | 24.4 | | 1372.868 | |
| 2.5 | | | | 23.7 | | 1395.879 |
| 2.916667 | 0.000897 | 348.5613 | | | | |
| 3 | | | 23.9 | | 1344.113 | |
| 3.5 | | | | 23.6 | | 1389.875 |
| 3.916667 | 0.000499 | 204.0983 | | | | |
| 4 | | | 23.6 | | 1326.859 | |
| 4.5 | | | | 23.9 | | 1407.885 |
| 4.916667 | 0.000999 | 385.7238 | | | | |
| 5 | | | 23.4 | | 1315.357 | |
| 5.5 | | | | 23.5 | | 1383.872 |
| 6 | | | 23.3 | | 1309.606 | |
| 6.5 | | | | 23.3 | | 1371.866 |
| 7 | | | 22.8 | | 1280.851 | |

Table 27. Results of Bleeding Rate (rpm = 700) :

| Time (min) | NOx (ppm) | (NOx)sim (ppm) |
|---|---|---|
| 0 | 1425.894 | 1424.673 |
| 0.5 | 1419.891 | 1420.952 |
| 1.5 | 1419.891 | 1413.51 |
| 2.5 | 1395.879 | 1406.068 |
| 3.5 | 1389.875 | 1398.626 |
| 4.5 | 1407.885 | 1391.183 |
| 5.5 | 1383.872 | 1383.741 |
| 6.5 | 1371.866 | 1376.299 |

Regression Output:

| | |
|---|---|
| Constant | 1424.673 |
| Std Err of Y Est | 9.330284 |
| R Squared | 0.804136 |
| No. of Observations | 8 |
| Degrees of Freedom | 6 |

| | |
|---|---|
| X Coefficient(s) | -7.44213 |
| Std Err of Coef. | 1.499458 |

BLEEDING RATE = 7.44 ppm/min

Table 28. Bleeding Rate Study on the SO2-NOx-[NaHCO3-Na2CO3-2H2O] Reaction System

| RAW DATA | | | | CORRECTED DATA | |
|---|---|---|---|---|---|
| Time (min) | SO2 (ppm) | NOx (ppm) | NO (ppm) | NOx (ppm) | NO (ppm) |
| 0 | 1507.547 | 1533.95 | 1487.89 | 1533.95 | 1487.89 |
| 1 | | 1449.907 | | 1457.307 | |
| 2 | | | 1246.344 | | 1261.144 |
| 3 | 851.4231 | | | | |
| 4 | | 1227.791 | | 1257.391 | |
| 5 | | | 1022.051 | | 1059.051 |
| 6 | 633.1955 | | | | |
| 7 | | 1167.76 | | 1219.56 | |
| 8 | | | 935.785 | | 994.985 |
| 9 | 515.4968 | | | | |
| 10 | | 1107.729 | | 1181.729 | |
| 11 | | | 878.274 | | 959.674 |
| 12 | 421.9122 | | | | |
| 15 | 357.7891 | | | | |
| 16 | | 999.6725 | | 1118.073 | |
| 17 | | | 809.2609 | | 935.0609 |
| 18 | 291.1866 | | | | |
| 21 | 245.9431 | | | | |
| 22 | | 963.6538 | | 1126.454 | |
| 23 | | | 722.9945 | | 893.1945 |
| 24 | 142.529 | | | | |
| 27 | 164.3607 | | | | |
| 28 | | 903.6226 | | 1110.823 | |
| 29 | | | 659.7325 | | 874.3325 |
| 30 | 124.0352 | | | | |

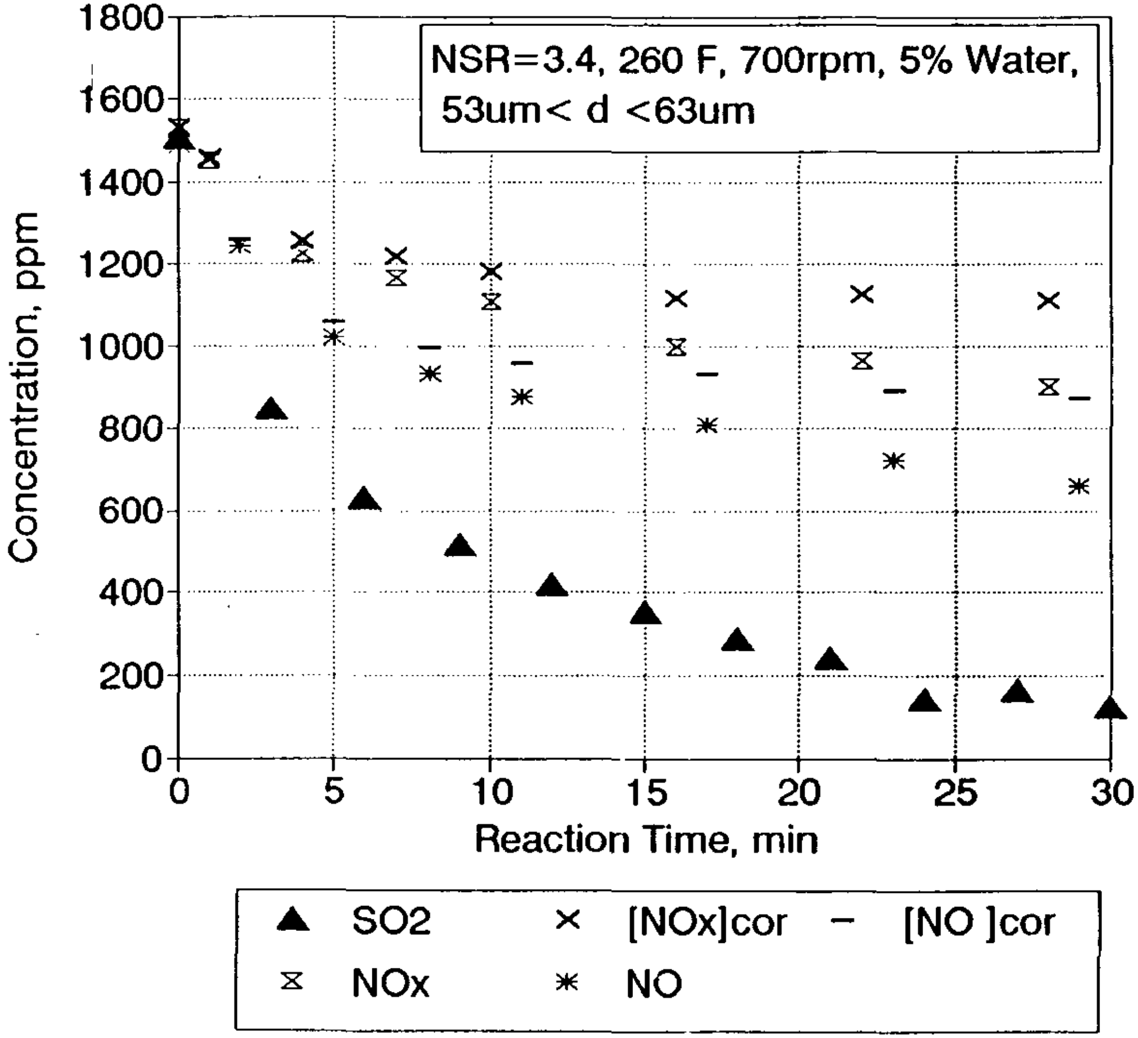


Figure 35. Correction of SO2 and NOx Removal by Sodium Sesquicarbonate

This model was found to be poor in describing the $NO_2$ formation as will be shown below. The complete set of simultaneous ordinary differential equations describing the model were presented in chapter 3.

### 5.2.1 Simplified rate expressions for EPRI's model

Since the total surface area per volume of $Na_2CO_3$ is proportional to the square of the shrinking core radius which is described in Equation (3-5), Equation (3-4), Equation (3-9) and Equation (3-12) can be expressed in terms of radius. In the reaction system, system temperature and pressure are assumed to be constant; so, the only variables needed to describe the complete reaction system are the concentrations of $SO_2$, NO and $NO_2$, and the radius of unreacted $Na_2CO_3$.

For the case of NSR=13.5, the amount of $NaHCO_3$ with a density of 2.2 g/cm$^3$ injected was 1.6 grams and the mean radius of particles is 0.0029 cm. From Equation (3-6), we can obtain the total number of $NaHCO_3$ particles used in this experiment: N=7.12E6 ea. So, the group parameter 4 Pi N/V in Equation (3-5) is 6954.22 ea/cm$^3$. Consequently, equations (3-4), (3-9), and (3-12) can be rewritten as follows:

Removal rate of $SO_2$

$$R_A = R_A(C_A, R) = dC_A/dt = - 6954.22\ k_A\ C_A\ R^2 \qquad (5\text{-}1)$$

Removal rate of NO

$R_B = R_B(C_A, C_B, R) = dC_B/dt = - 6954.22\ k_B\ C_A\ C_B\ R^2$ (5-2)

Formation rate of $NO_2$

$R_C = R_C(C_A, C_B, C_C, R) = dC_C/dt = R_{C1} - R_{C2}$

$= 6954.22\ (k_B\ C_A\ C_B - k_C\ C_C)\ R^2$ (5-3)

For the consumption rate of $Na_2CO_3$, the value of the group constant 0.5 M/D in Equation (3-15) is 20.92; therefore, Equation (3-15) can be written as:

Shrinking rate of radius R

$R_R = R_R(C_A, C_C) = dR/dt$

$= -41.84\ [k_A\ C_A + 1/2\ k_C\ C_C]$ (5-4)

5.2.2 Evaluations of rate constants for EPRI's model

The use of the differential method of data analysis to determine reaction orders and specific reaction rates is clearly one of the easiest, since it requires only one experiment(15). Inspecting our model, the determination of reaction order is not required because we assumed first order for all chemicals. However, we can not use the differential method to estimate the rate constants due to the difficulties in determining the changing core radius vs reaction time. The same problem occurs for the integral method and the method of half life time. So, the method of initial rates, which only requires information at the initial condition, seems to be the best way to determine the reaction rate constants. Information required to determine the rate constants using the initial rate approach are initial concentrations of $SO_2$, NO, and $NO_2$; the initial radius of $NaHCO_3$; and the initial rates of $SO_2$, NO, and $NO_2$. The concentration of $NO_2$ can be obtained from the concentration difference of $NO_x$ and NO. The initial radius can be obtained from the mean radius of unreacted $NaHCO_3$ particles which is about 0.0028 cm; i.e., R=0.0028 cm. The initial rates for gases can be roughly estimated by the two point method. With the initial concentrations of gases, the initial radius of $NaHCO_3$, and the initial estimated reaction rate for each gas chemical, the specific reaction rates could then be calculated from Equation (5-1) through Equation (5-4). The best curves of concentration versus time for determining the initial rates are obtained by naked eyeball such that the modeled points do not deviate significantly from the average of the data points. After the best curves are located, the values of rate constant used in the model are determined.

The units of gas concentration, ppm, can be converted to units of mol/cm$^3$ by simply applying the ideal gas law. From Table 20, the concentration of $SO_2$, or $C_A$, is 1745.43 ppm, or 5.04E-8 mol/cm$^3$; the concentration of NO, or $C_B$, is 1482.14 ppm, or 4.28E-8 mol/cm$^3$; and the concentration of $NO_2$, or $C_C$, which is the concentration difference between NO and $NO_x$ (1497.93 -1482.14) ppm is 15.79 ppm, or 4.56E-10 mol/cm$^3$.

Also, the units of initial rates, ppm/min, which is directly obtained from the resulting data can be converted to the units of mol/cm$^3$ min using the ideal gas law. The final initial rates are listed below:

$R_A$ = -373.57 ppm/min = -1.08E-8 mol/cm$^3$ min

$R_B$ = -357.53 ppm/min = -1.03E-8 mol/cm$^3$ min

$R_C$ = 38.15 ppm/min = 1.10E-9 mol/cm$^3$ min

Plugging these initial values, $C_A$, $C_B$, $C_C$, R, $R_A$, $R_B$, and $R_C$ into Equation (5-1), Equation (5-2) and Equation (5-3), rate constants $k_A$, $k_B$ and $k_C$ can be obtained. The values of rate constants $k_A$, $k_B$ and $k_C$ are 3.66 cm/min, 8.18E7 cm$^4$/min mol and 345.78 cm/min respectively.

### 5.2.3 Kinetics modeling by computer programming

Once the rate constants have been obtained, the one point fourth order Runge-Kutta method is applied on the simultaneous ordinary equations from Equation (5-1) through Equation (5-4) to evaluate the first three points with time difference 0.0005 minute; and then, these three points together with initial values of $C_A$, $C_B$, $C_C$, and R are used to solve for variables $C_A$, $C_B$, $C_C$, and R as function of time by the four point Adams-Bashworth-Moulton method. The program using this approach was found to converge when the time difference dt was less than 0.001 minutes. The differences in concentration for the three gases and the changing radius between 1000 time divisions and 2000 time divisions were found to be less than 0.1 ppm. The FORTRAN 77 computer program using this approach is listed in Appendix C. The flow diagram is illustrated in Figure 36. Results from this computer program were imported into QPRO software and were arranged with the corrected data, which were taken from Table 25, and are presented in Table 29 and Figure 37 and Figure 38. Results from the computer simulation for the gas concentrations vs reaction time were compared with the experimental results. Since the radius of shrinking core of the solid could not be obtained experimentally, the computer simulation was used to predict how fast the dry sorbent will be used.

From Figure 37, we can see that there is almost no difference between NO and $NO_x$ and no $NO_2$ production. After studying the effects of the three rate constants on the three gas species, which is illustrated in Table 30, it is possible to increase the concentration of $NO_2$ when the value of $k_C$ is decreased. A second set of rate constants was therefore used by changing the value of $k_C$ from 345.78 to 17. The simulated results shown in Figure 39 indicated that a large amount of $NO_2$ formed at the beginning of the reaction and finally disappeared at the end of the reaction. Obviously, this model cannot describe the kinetic phenomena very well over the entire concentration region.

The EPRI model assumes that the removal of $NO_x$ occurs as a series reaction sequence. Initially, NO reacts to form $NO_2$, which reacts with the solid to result in the removal of $NO_x$. Thus, no $NO_x$ is removed until a buildup of $NO_2$ occurs in the reaction system. This means that initially the curve of $NO_x$ concentration versus time must be

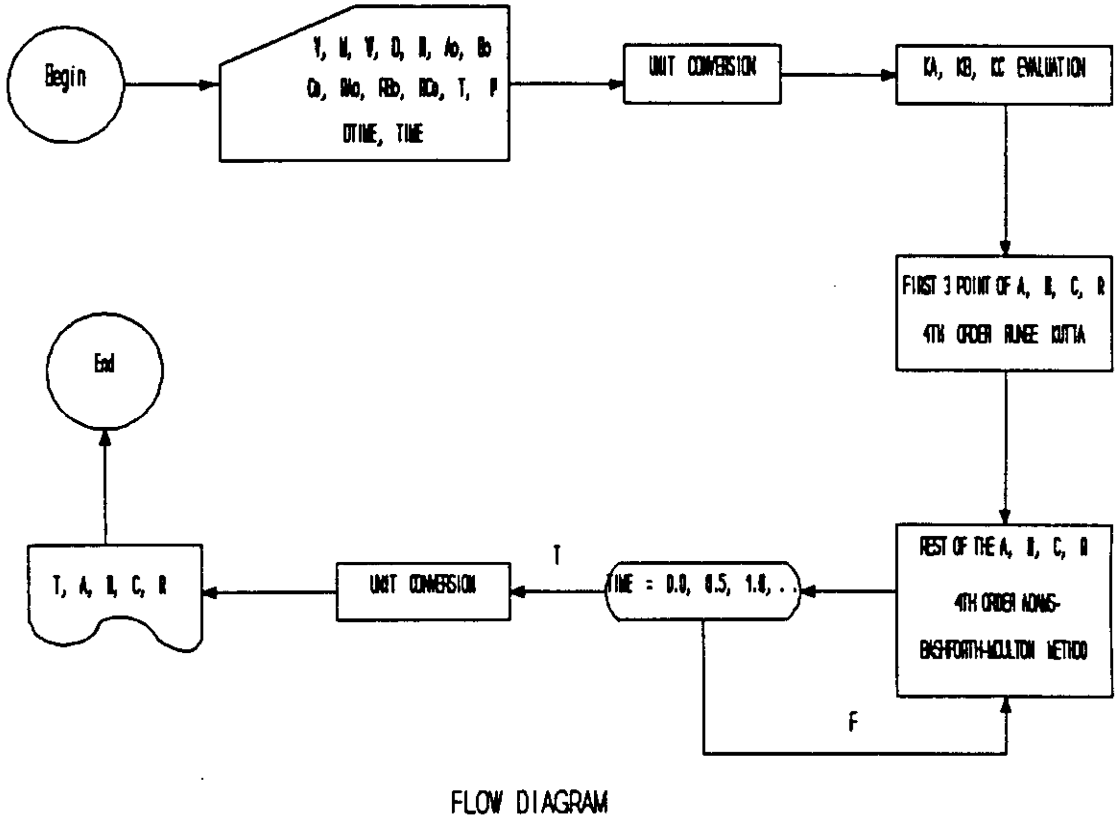


Figure 36. Flow diagram of computer programming for EPRI's model.

Table 29. Simulation Results for EPRI's reaction scheme :

|  | Corrected Data |  |  | Simulated Data |  |  |  |  |
|---|---|---|---|---|---|---|---|---|
| Time (min) | (SO2) (ppm) | (NOx) (ppm) | (NO) (ppm) | (SO2) (ppm) | (NOx) (ppm) | (NO) (ppm) | R (um) | R X 100 |
| 0 | 1745.432 | 1497.932 | 1482.139 | 1745.43 | 1482.14 | 1497.93 | 29 | 2900 |
| 0.25 | 1652.04 |  |  | 1654.55 | 1397.65 | 1413.8 | 28.9816 | 2898.16 |
| 0.5 |  | 1338.24 |  | 1568.5 | 1322.1 | 1336.58 | 28.9637 | 2896.37 |
| 1 |  |  | 1124.605 | 1409.87 | 1193.37 | 1205.11 | 28.9285 | 2892.85 |
| 1.5 |  |  |  | 1267.6 | 1088.62 | 1098.24 | 28.8949 | 2889.49 |
| 2 |  |  | 956.858 | 1139.97 | 1002.49 | 1010.45 | 28.863 | 2886.3 |
| 2.5 |  | 933.5955 |  | 1025.42 | 931.01 | 937.65 | 28.8333 | 2883.33 |
| 2.75 | 1065.018 |  |  | 972.61 | 899.8 | 905.88 | 28.8192 | 2881.92 |
| 3 |  |  |  | 922.57 | 871.19 | 876.77 | 28.8056 | 2880.56 |
| 3.5 |  | 884.3528 |  | 830.2 | 820.74 | 825.47 | 28.7801 | 2878.01 |
| 4 |  |  | 805.3983 | 747.22 | 777.91 | 781.95 | 28.7567 | 2875.67 |
| 4.5 |  | 853.1195 |  | 672.63 | 741.34 | 744.8 | 28.7352 | 2873.52 |
| 5 |  |  | 764.1749 | 605.59 | 709.92 | 712.91 | 28.7155 | 2871.55 |
| 5.25 | 578.8172 |  |  | 574.65 | 695.88 | 698.65 | 28.7064 | 2870.64 |
| 5.5 |  |  |  | 545.3 | 682.82 | 685.4 | 28.6976 | 2869.76 |
| 6 |  |  | 705.6983 | 491.08 | 659.32 | 661.57 | 28.6813 | 2868.13 |
| 6.5 |  | 826.6717 |  | 442.29 | 638.88 | 640.83 | 28.6665 | 2866.65 |
| 7 |  |  | 681.7283 | 398.4 | 621.02 | 622.73 | 28.6531 | 2865.31 |
| 7.5 |  | 789.4352 |  | 358.89 | 605.38 | 606.88 | 28.6409 | 2864.09 |
| 7.75 | 250.0586 |  |  | 340.64 | 598.29 | 599.7 | 28.6352 | 2863.52 |
| 8 |  |  | 652.0072 | 323.33 | 591.63 | 592.96 | 28.6298 | 2862.98 |
| 8.5 |  | 764.205 |  | 291.32 | 579.53 | 580.7 | 28.6198 | 2861.98 |
| 9 |  |  |  | 262.49 | 568.84 | 569.87 | 28.6107 | 2861.07 |
| 9.5 |  |  |  | 236.53 | 559.38 | 560.3 | 28.6025 | 2860.25 |
| 10 |  |  |  | 213.15 | 551 | 551.82 | 28.5951 | 2859.51 |
| 10.25 | 83.29007 |  |  | 202.35 | 547.17 | 547.94 | 28.5916 | 2859.16 |
| 10.5 |  |  |  | 192.09 | 543.56 | 544.28 | 28.5884 | 2858.84 |
| 11 |  |  |  | 173.12 | 536.94 | 537.59 | 28.5823 | 2858.23 |
| 12 |  |  |  | 140.63 | 525.8 | 526.31 | 28.5719 | 2857.19 |
| 12.75 | 6.109091 |  |  | 120.34 | 518.95 | 519.38 | 28.5653 | 2856.53 |
| 13 |  |  |  | 114.26 | 516.92 | 517.32 | 28.5634 | 2856.34 |

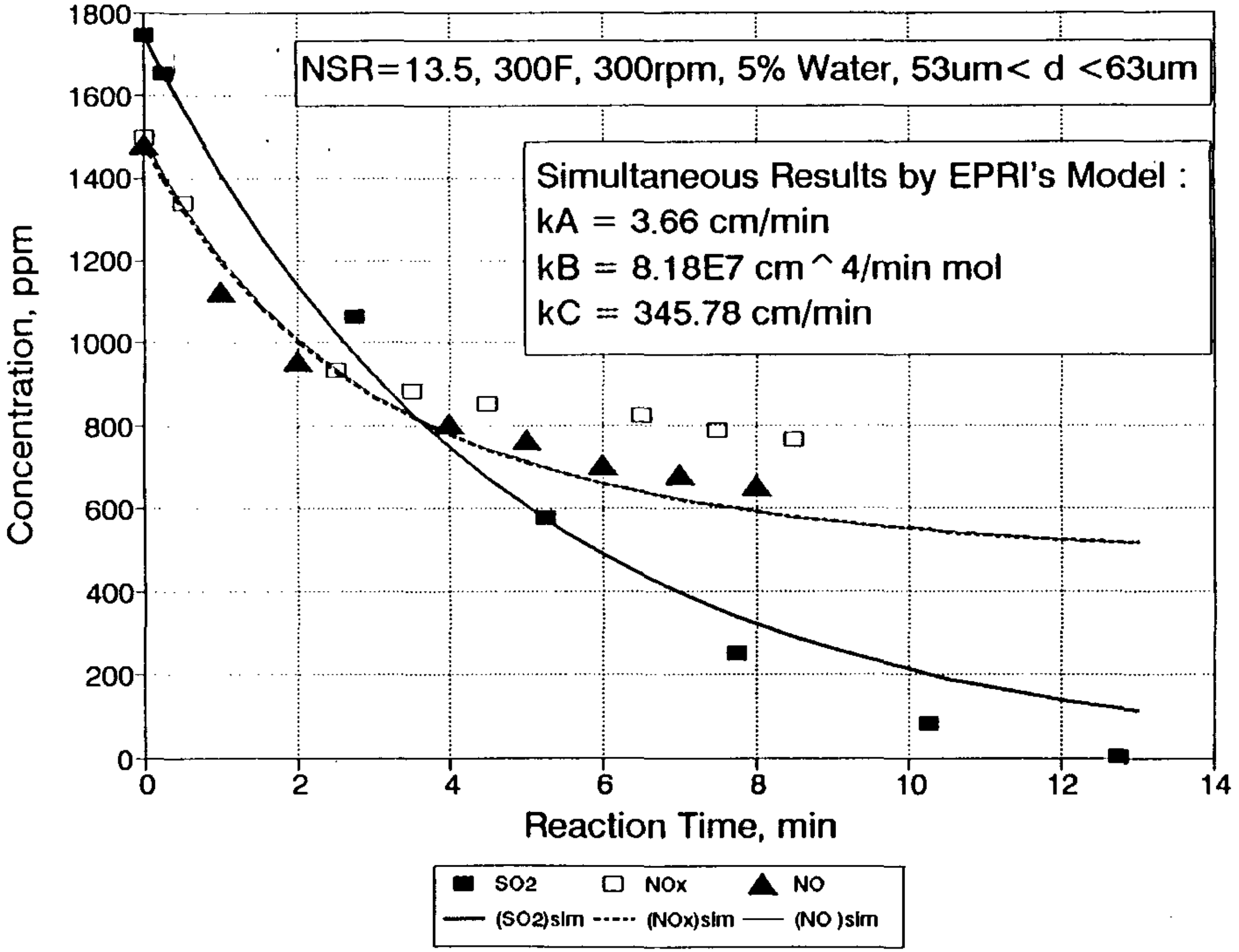


Figure 37. SO2 and NOx Simultaneous Reaction by Sodium Bicarbonate

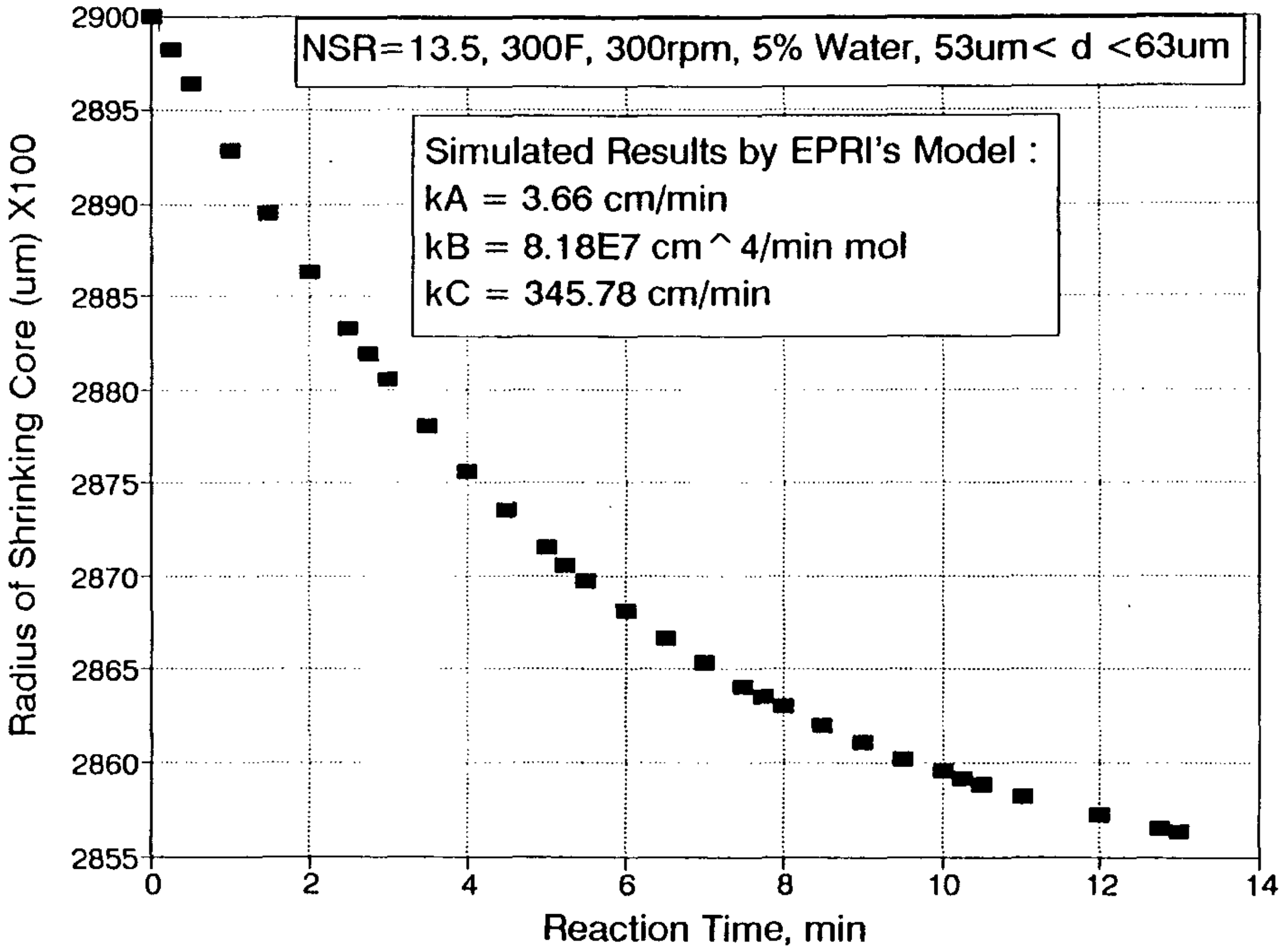


Figure 38. Prediction for the Shrinking Radius of Sodium Bicarbonate Particle

Table 30. Rate constant effect on the concentrations of three gases

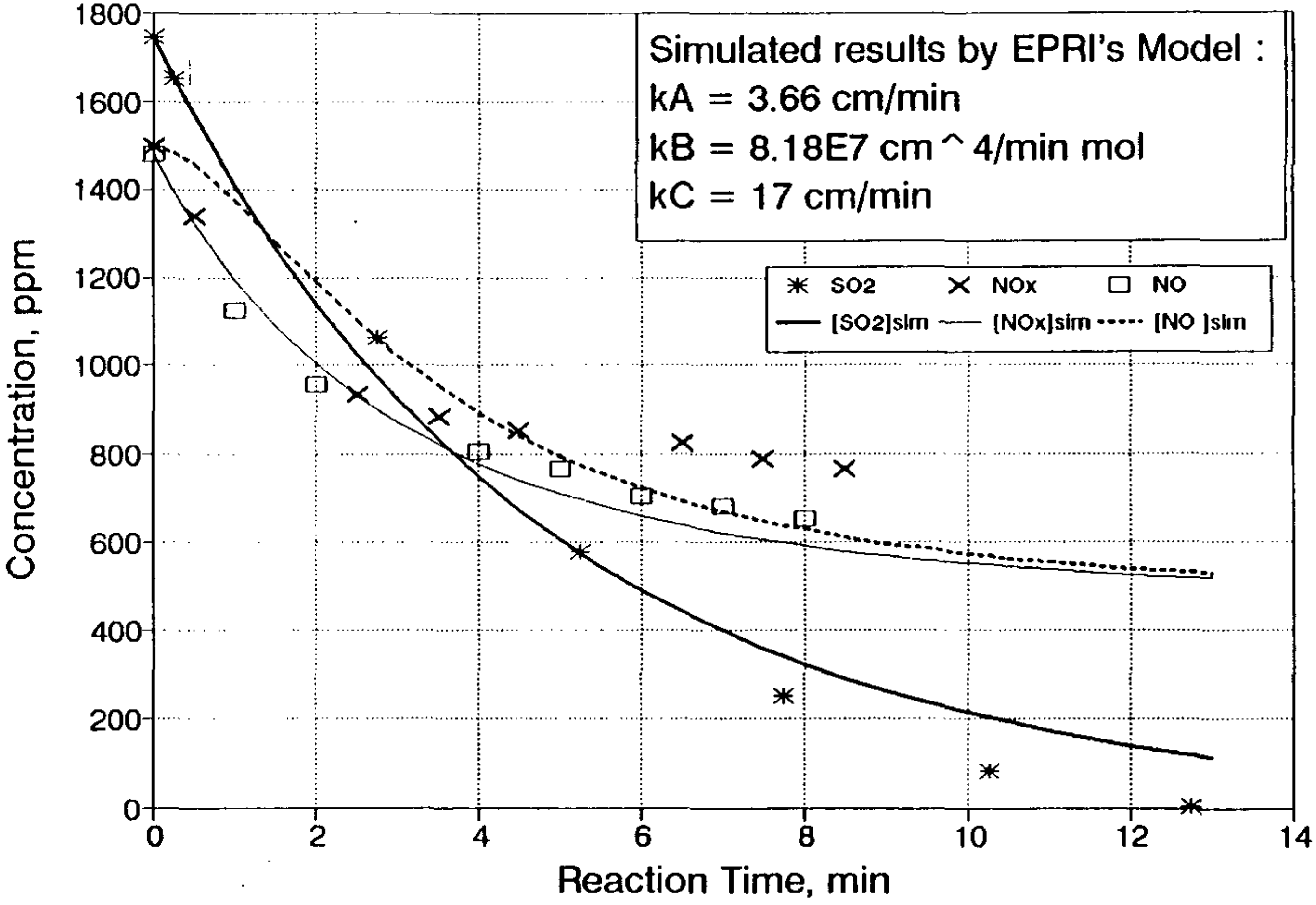
| $k_A$ | $k_B$ | $k_C$ | A | B | C |
|---|---|---|---|---|---|
| IN | -- | -- | DE | IN | IN |
| -- | IN | -- | -- | DE | DE |
| -- | -- | IN | -- | -- | DE |

* $k_A$, $k_B$, and $k_C$ : rate constants in EPRI's mechanism

* A : $SO_2$, B : NO, C : NOx

* IN : increase, DE : decrease

* -- : remain constant



NSR=13.5, 300F, 300rpm, 5% Water, 53um< d <63um

Figure 39. SO2 and NOx Simultaneous Reaction by Sodium Bicarbonate

horizontal. However, by observing any of our experimental results, it is quite clear that the concentration of $NO_x$ immediately begins to decrease. This can occur only if the NO which is initially present actually reacts with the solid. For this reason we believe that the Solvay model is more realistic.

### 5.3 Experimental curve fitting for Solvay's model

Solvay's mechanism was used to simulate the experimental data, which eventually was shown to be capable of describing the simultaneous removal of $SO_2$ and $NO_x$ using the two dry sorbents. Six experimental results with sodium sesquicarbonate, four experiments with NSR=3.38 and two experiments with NSR=0.8, were used to demonstrate the validity of this model. These results are presented in Figures 27 through 32. Using the same procedure, rate constants, k's, and the selectivity constant x for the six experiments were obtained.

### 5.3.1 Simplified rate expressions for Solvay's model in the $SO_2$-$NO_x$-[$NaHCO_3$-$Na_2CO_3$-$2H_2O$] reaction system

As in Section 5.2.1 the total surface area per volume of $Na_2CO_3$ could be expressed as a function of core radius. For the cases of NSR=3.38, when 0.36 g sodium sesquicarbonate was injected, the initial density is 2.112 g/cm$^3$ and the initial molecular weight is 226.04 g/mol; so, the value of 1.5 M/D in Equation (3-25) is 160.54. The number of particles per volume N estimated by Equation (3-5) is 1.67E6 ea/cm$^3$ and the constant group 4 Pi N/V in Equation (3-4) is 1631.44. With the same treatment as that in Chapter 5.2.1 Equation (3-3), Equation (3-8) Equation (3-21) and Equation (3-25) can be rewritten as:

Removal rate of $SO_2$

$$R_A = dC_A/dt = R_A(C_A, R) = -1631.44\ k_A\ C_A\ R^2 \qquad (5\text{-}5)$$

Removal rate of NO

$$R_B = dC_B/dt = R_B(C_A, C_B, R) = -1631.44\ k_B\ C_A\ C_B\ R^2 \qquad (5\text{-}6)$$

Formation rate of $NO_2$

$$R_C = dC_C/dt = R_C(C_A, C_B, R) = -x/2\ dC_B/dt = 815.72 x k_B C_A C_B R^2 \qquad (5\text{-}7)$$

Shrinking rate of radius R

$$R_R = dR/dt = R_R(C_A, C_B) = -160.54\ [k_A\ C_A + (1-x/2)/2\ k_B\ C_A\ C_B] \qquad (5\text{-}8)$$

With the above equations, simulation of the $SO_2$ and $NO_x$ simultaneous removal by sodium sesquicarbonate with NSR equal to 3.38 could be programmed.

### 5.3.2 Evaluations of kinetics parameters $k_A$, $k_B$, and x for the gas-sodium sesquicarbonate reaction system

Evaluation of rate constants $k_A$ and $k_B$ and the selectivity constant x for the $SO_2$-

$NO_x$-[$NaHCO_3$-$Na_2CO_3$-$2H_2O$] reaction system is similar to the procedure described in Chapter 5.3.2. The resultant data taken from Figure 27 through Figure 32 were also corrected by the system bleeding rate and were used to obtain the rate constants and the selectivity constant and then compared with the simulated results. Information required to determine the rate constants using the initial rate approach are initial concentrations of $SO_2$, NO, and $NO_2$; the initial radius of [NaHCO3-$Na_2CO_3$-$2H_2O$]; and the initial rates of $SO_2$, NO, and $NO_2$. The initial radius of [$NaHCO_3$-$Na_2CO_3$-$2H_2O$] R is identical to that used in $NaHCO_3$ and is equal to 0.0028 cm. The selectivity constant x can be evaluated from equation (5-8) from the initial formation rate of $NO_2$, which is the initial rate difference between $NO_x$ and NO, and the initial values of $SO_2$, NO and radius R. The best curve fitting was accomplished as described above. Experimental results taken from Figure 28, or Table 22, is used to demonstrate the procedure for obtaining rate constants. Correction of the system bleeding for this experiment has been shown in Table 28 and Figure 35; and the demonstration of the kinetics parameter evaluation is shown in Figure 40. This same procedure was used for the parameters obtained for runs taken from Figure 27 and Figure 29 through Figure 32. The bleeding rate corrections are shown in Appendix B. The kinetic parameters obtained for all runs are shown in Table 31. It should be noted that the range of values for the parameters obtained is quite satisfactory. Average values for the parameters at NSR of 3.38 are as follows:

$k_A$ = 8.77 cm/min

Figure 40. Evaluation of kinetics parameters :

Step 1. Initial rate study.

INITIAL CONCENTRATION (mol/cc)

| SO2 | NOx | NO | NO2 |
|---|---|---|---|
| 2.48E-08 | 3.44E-08 | 3.26E-08 | 1.73E-09 |

INITIAL RATE (mol/cc min)

| SO2 | NOx | NO | NO2 |
|---|---|---|---|
| -2.9E-09 | -9.6E-10 | -1.4E-09 | 3.87E-10 |

Step 2. Constant evaluation :

N= W/(4/3 Pi Ro^3 Den)= 1668501

4 Pi N/V=1629.896

-dCA/dt = K1 CA 4 Pi R^2 N/1629.896 K1 CA R^2

-dCB/dt = 4 K2 CA CB Pi R^2 N / V

= 16K2 CA CB R^2

dCC/dt = -X/2 * dCB/-814.948 K2 CA CB X R^2

M'/D' = 107.0265

dR/dt = -M'/D' * [K1 CA + (1-X/2)/2 * K2 CA CB]

-107.027 * [K1 CA + (1-X/2)/2 * K2 CA CB]

Ro = 0.0029 cm

(1) -dCAo/dt=1629.896 K1 CAo Ro^2

K1 = 8.546949

(2) -dCBo/dt=1629.896 K2 CAo CBo Ro^2

K2 = 1.22E+08

(3) dCCc/dt = -X/2 * dCBo/dt = 3.87E-10

X = 0.572526

Table 31. $k_A$, $k_B$, and x obtained from initial rate approach :

| Source | Sorbent | NSR | $k_A$ (cm/min) | $k_B$ ($cm^4$/cm mol) | x |
|---|---|---|---|---|---|
| Figure 27 | Sesq- | 0.85 | 7.42 | 1.24E8 | 0.61 |
| Figure 32 | Sesq- | 0.85 | 9.59 | 1.47E8 | 0.54 |
| Figure 28 | Sesq- | 3.38 | 8.55 | 1.22E8 | 0.57 |
| Figure 29 | Sesq- | 3.38 | 9.37 | 1.17E8 | 0.54 |
| Figure 30 | Sesq- | 3.38 | 7.94 | 1.21E8 | 0.54 |
| Figure 31 | Sesq- | 3.38 | 9.20 | 1.34E8 | 0.55 |

* Sesq- : Sodium Sesquicarbonate

$k_B$ = 1.24E8 $cm^4$/min mol

x = 0.55

These average values are the values used in the computer simulation.

### 5.3.3 Computer simulation using Solvay's model in the $SO_2$-$NO_x$-[$NaHCO_3$-$Na_2CO_3$-$2H_2O$] reaction system

Once the rate constants $k_A$ and $k_B$, and the stoichiometric constant x were obtained, the Adams-Bashforth-Moulton, as discussed above, was employed. The results using the average parameters are shown in Appendix B and were plotted on Figures 41 through Figure 52. The model does a reasonably good job in fitting the data at NSR = 3.38. However, for NSR = 0.85, the curves deviate from the data at longer times. We believe that this is due to a portion of the solid not entering the reaction system at the start of the run. This would result in a flattening out of the concentrations at higher values than expected. This is what is observed in the experimental results.

### 5.3.4 Computer simulation for the $SO_2$-$NO_x$-$NaHCO_3$ reaction system

Equations used for the $SO_2$-$NO_x$-$NaHCO_3$ reaction system are the Equation (3-3),Equation (3-8), Equation (3-21) and Equation (3-24). The simplified equations are shown below:

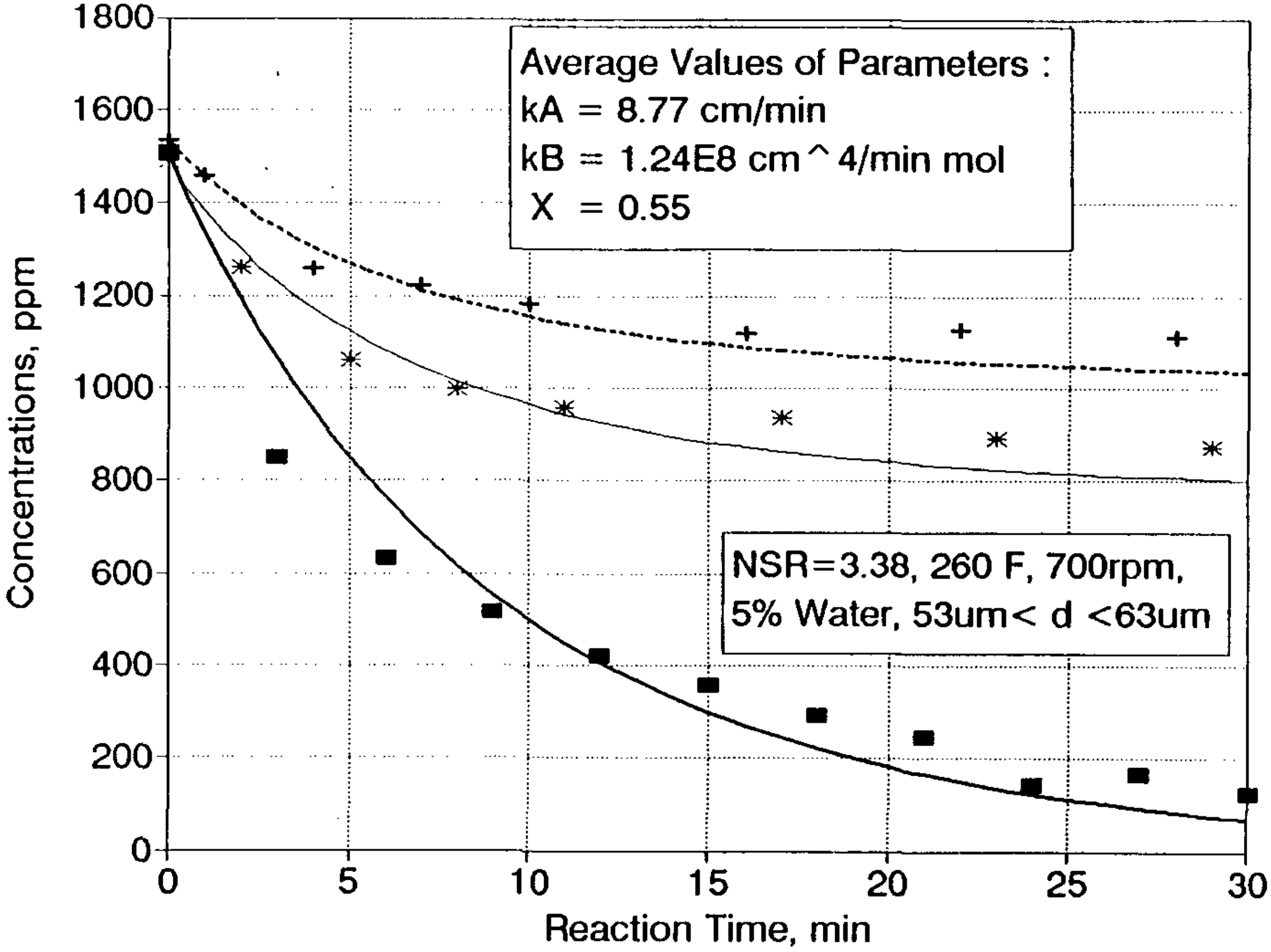


Figure 41. SO2 and NOx Removal by Sodium Sesquicarbonate

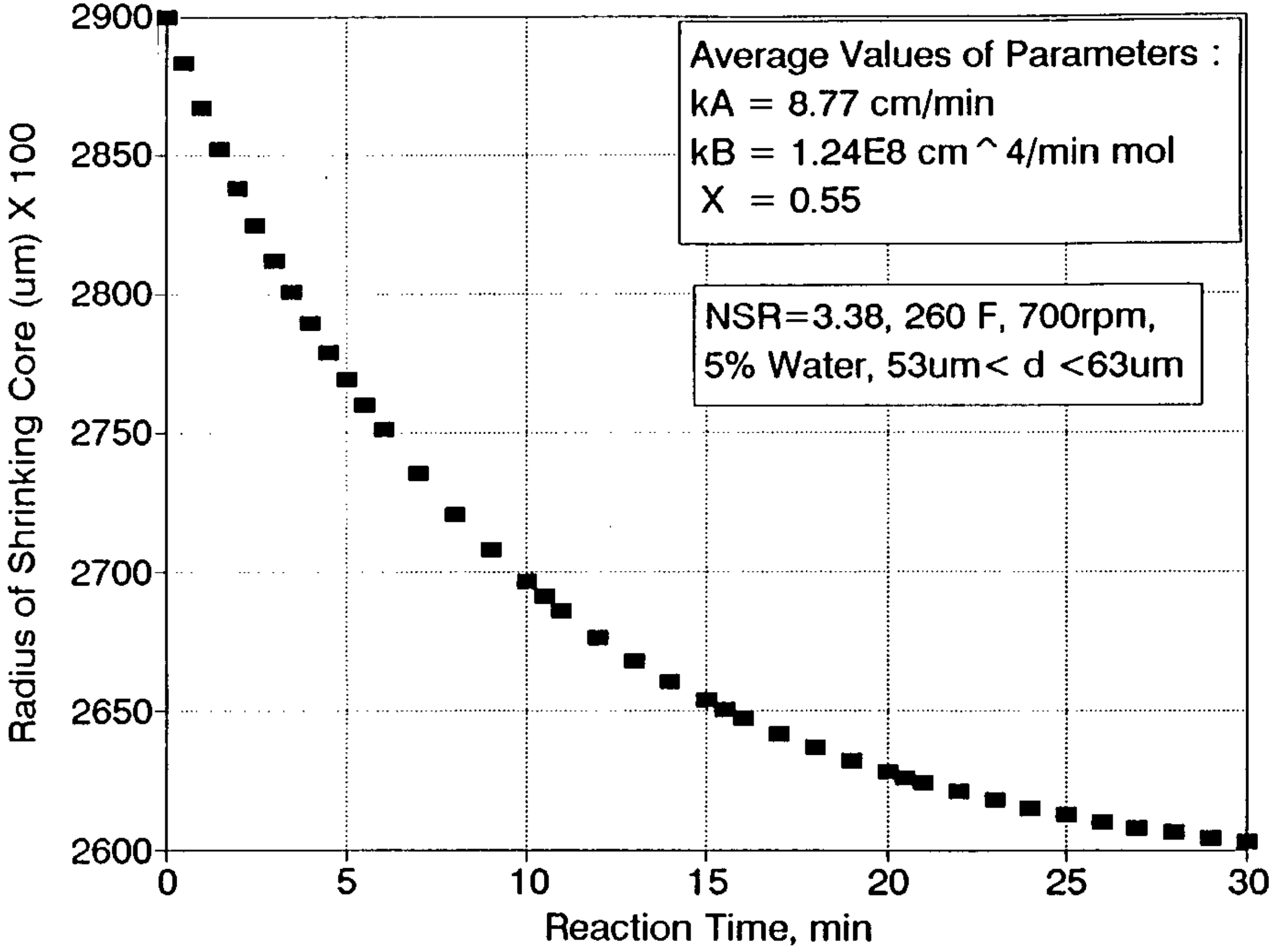


Figure 42. SO2 and NOx Removal by Sodium Sesquicarbonate

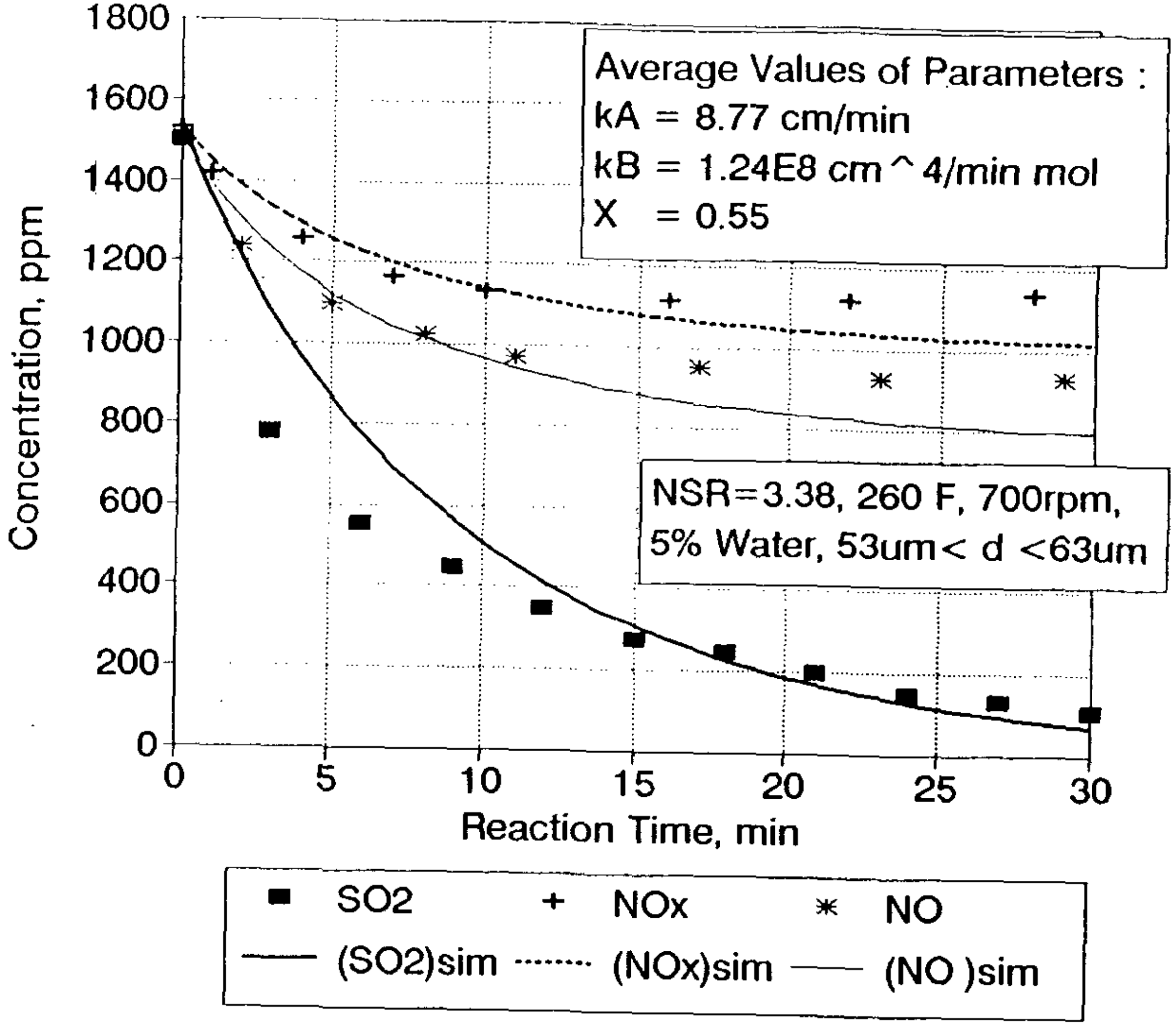


Figure 43.. SO2 and NOx Removal by Sodium Sesquicarbonate

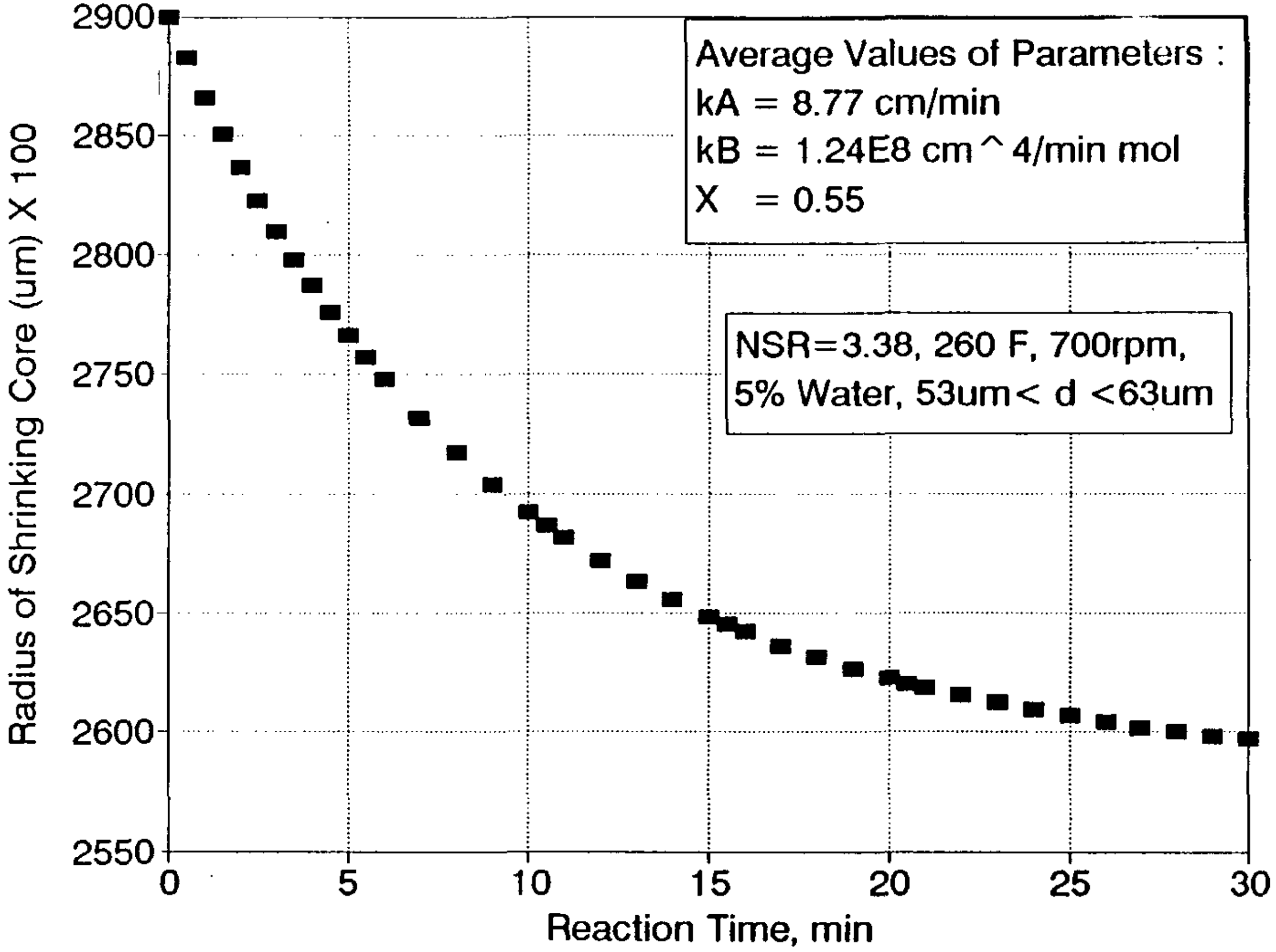


Figure 44. SO2 and NOx Removal by Sodium Sesquicarbonate

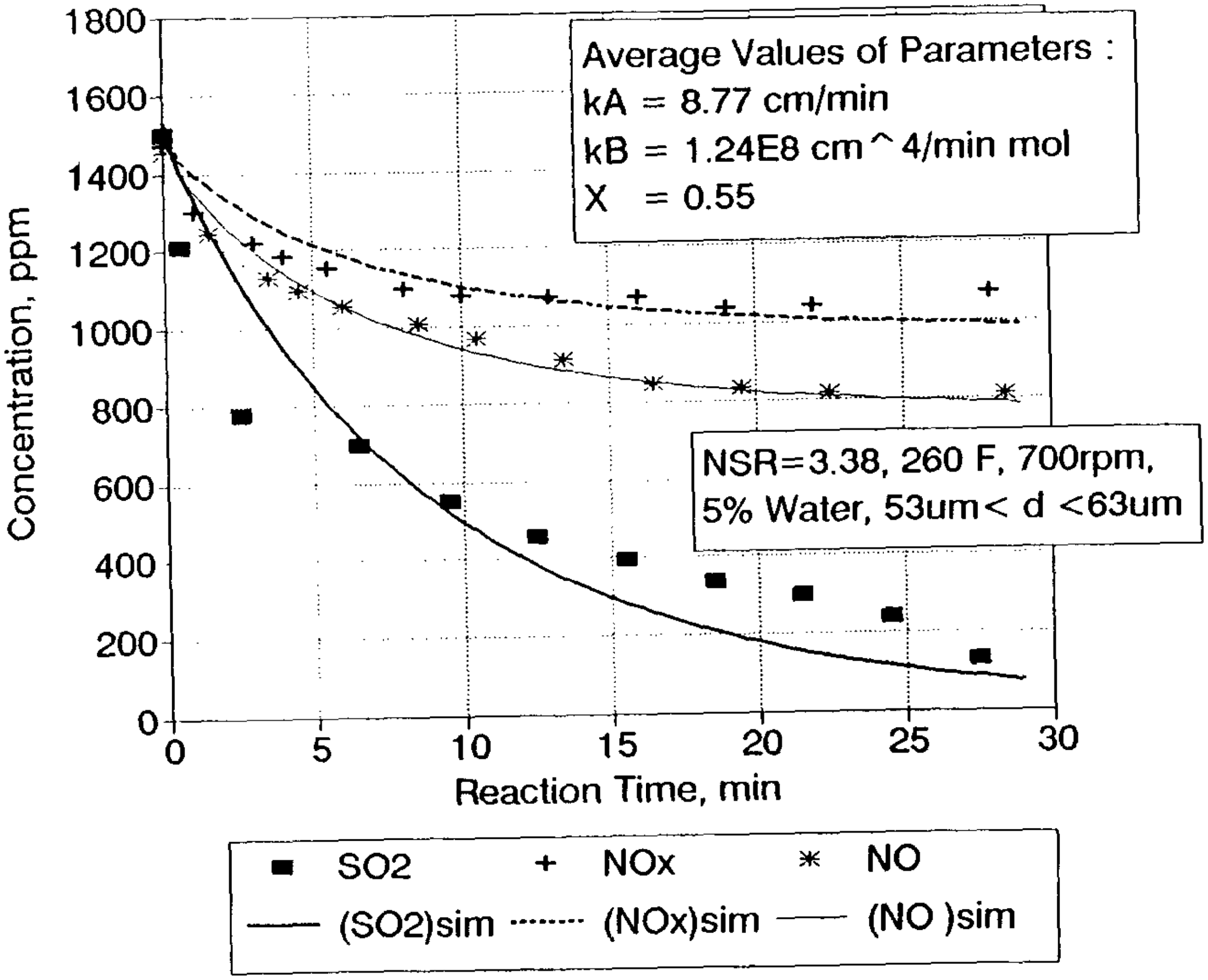


Figure 45. SO2 and NOx Removal by Sodium Sesquicarbonate

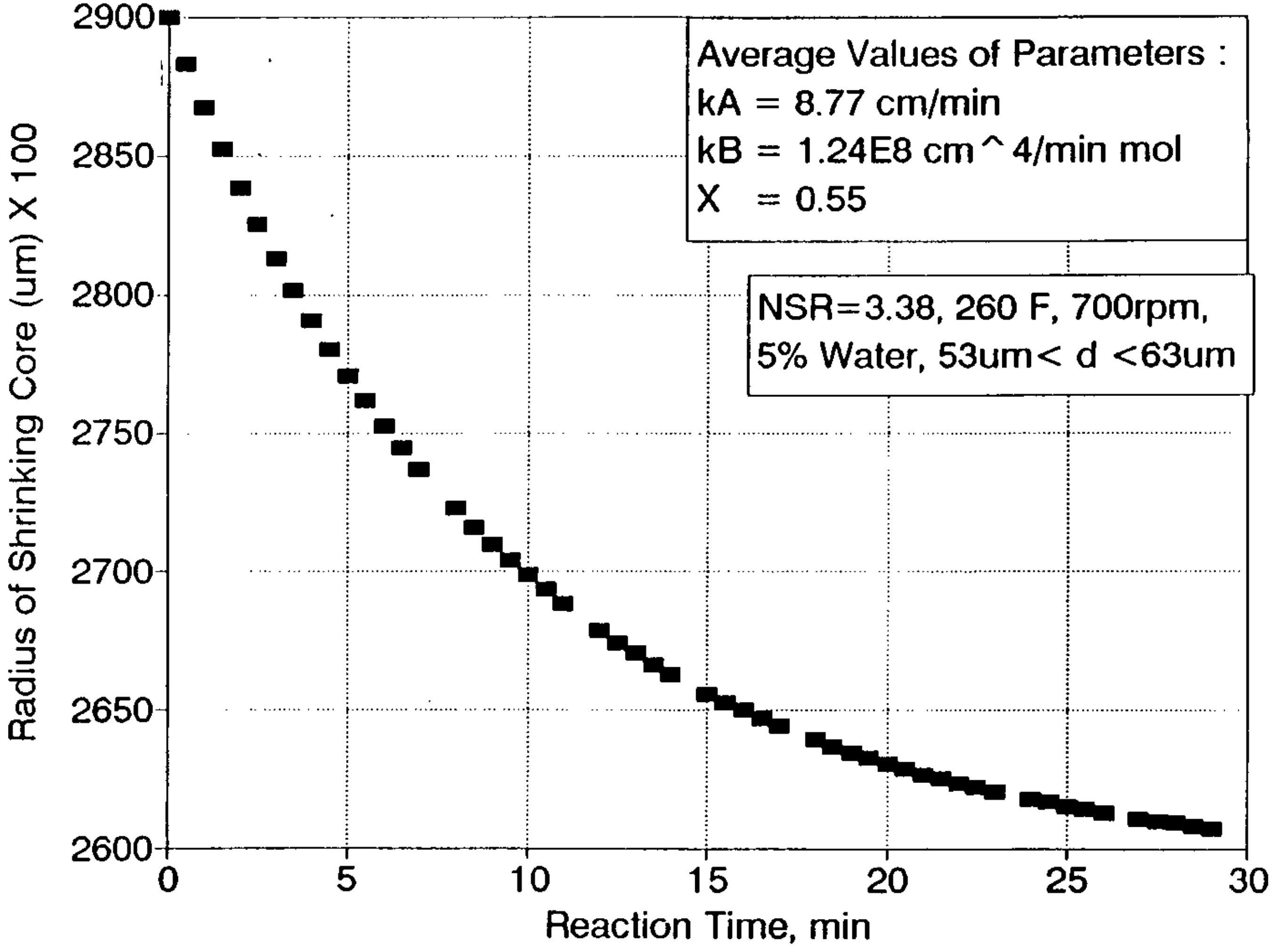


Figure 46. SO2 and NOx Removal by Sodium Sesquicarbonate

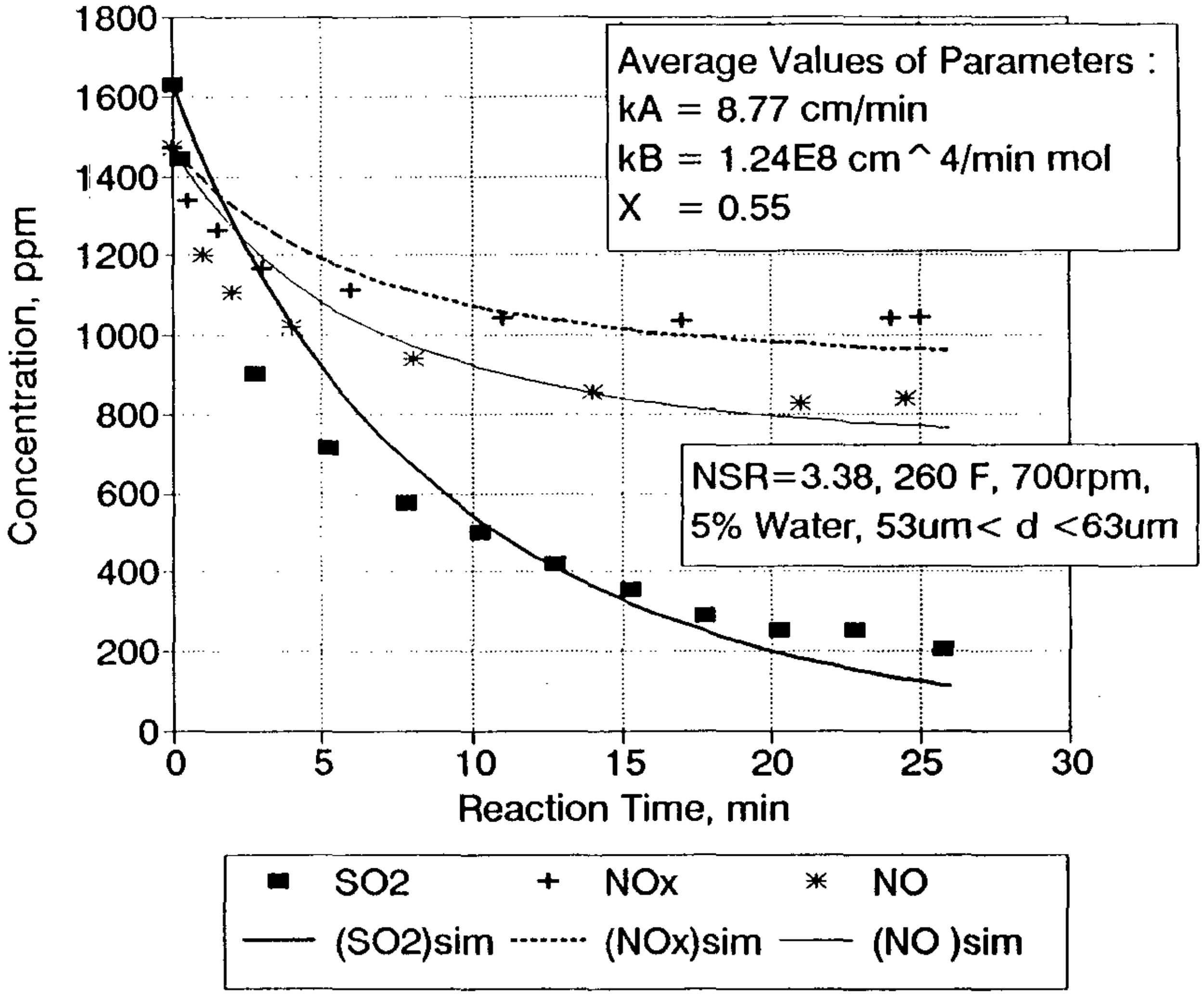


Figure 47. SO2 and NOx Removal by Sodium Sesquicarbonate

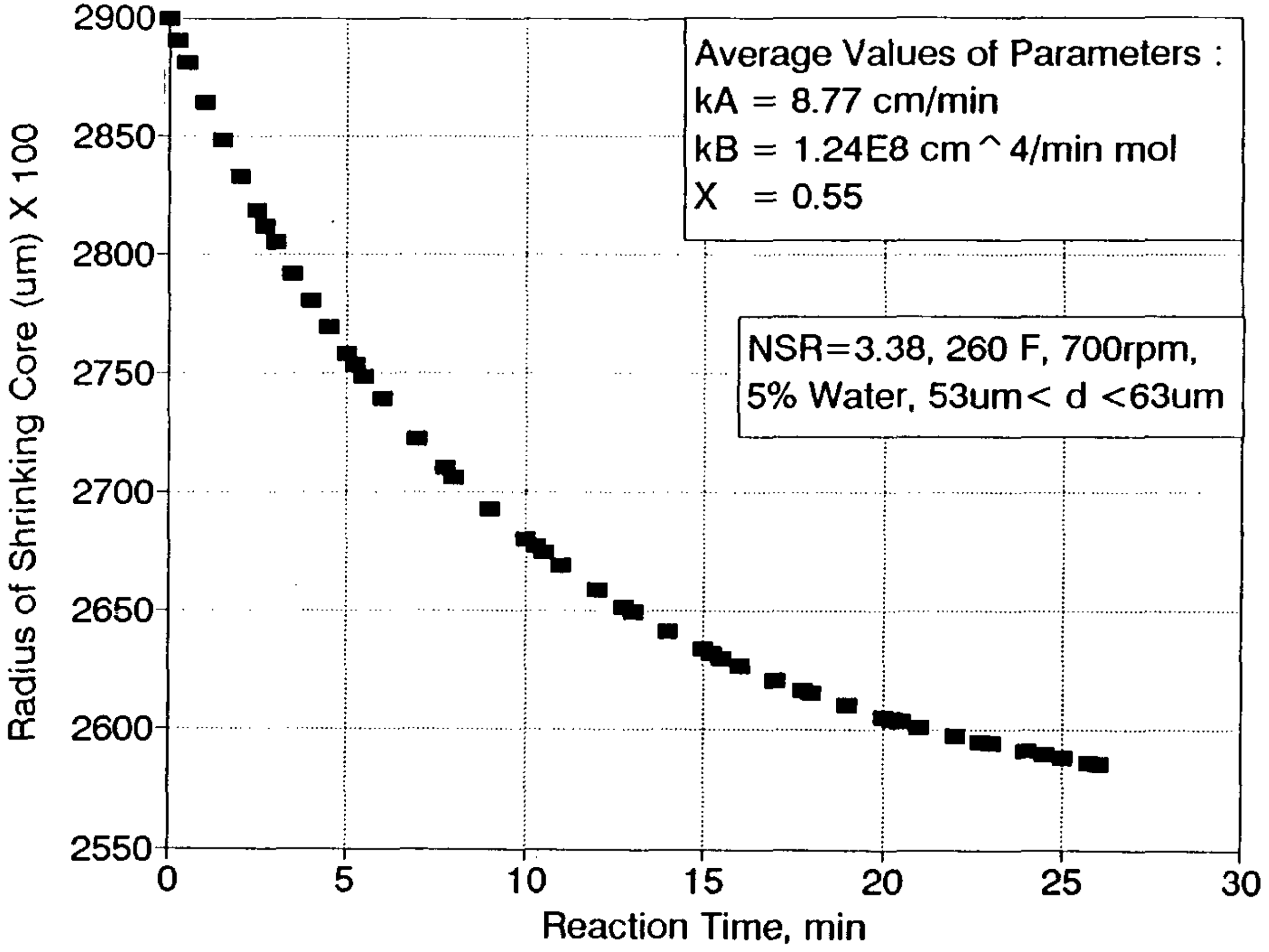


Figure 48. SO2 and NOx Removal by Sodium Sesquicarbonate

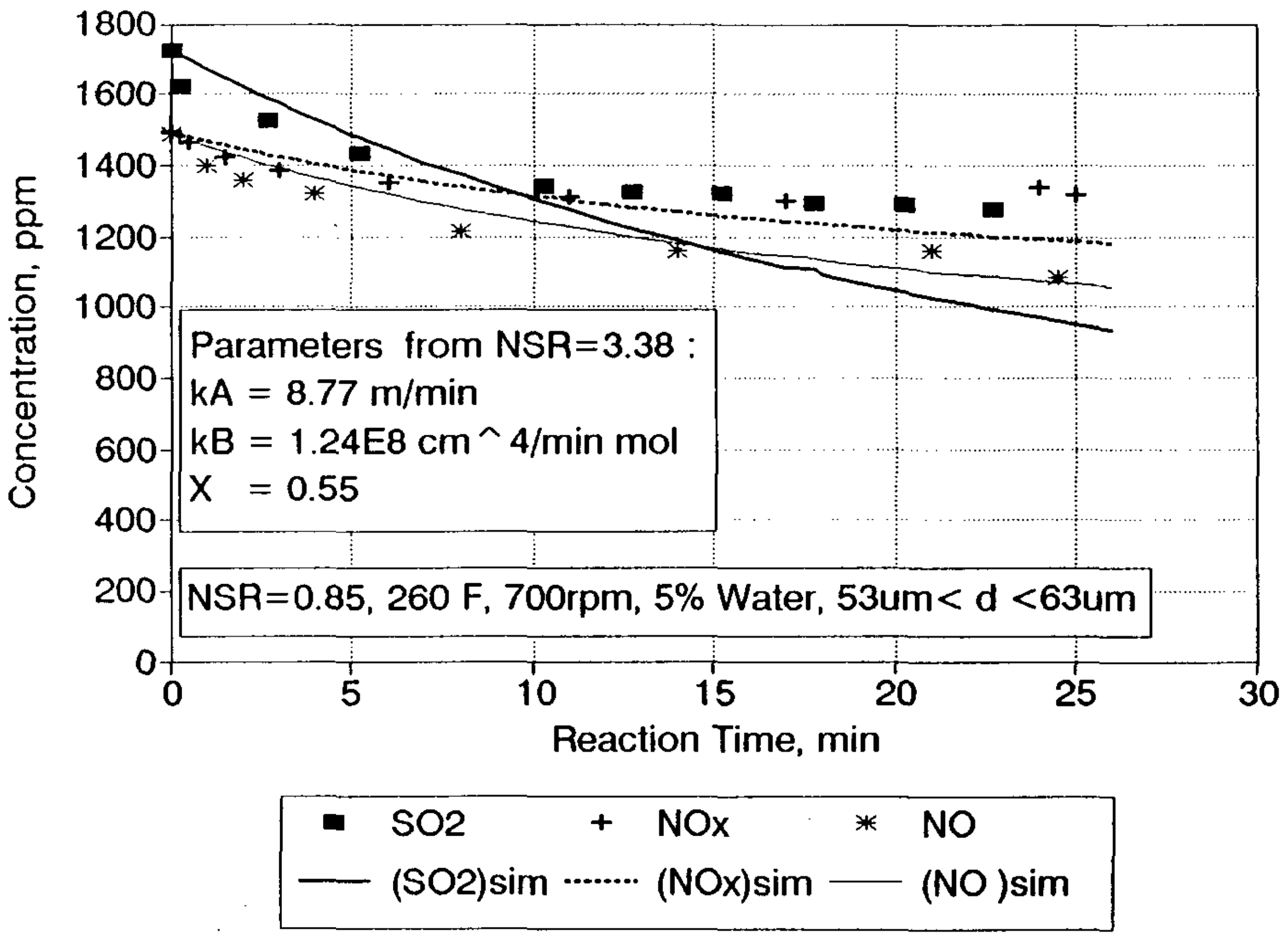


Figure 49. SO2 and NOx Removal by Sodium Sesquicarbonate

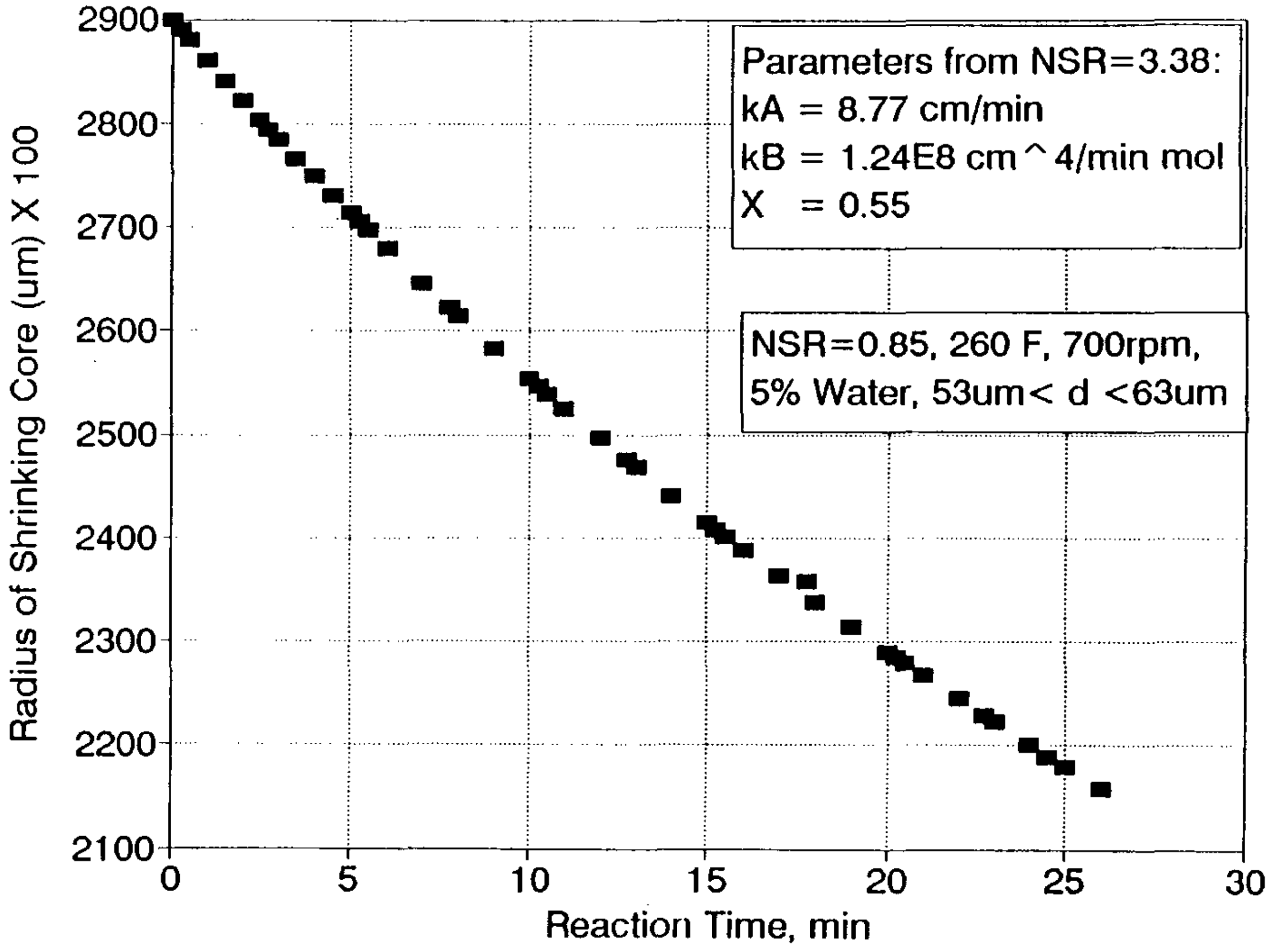


Figure 50. SO2 and NOx Removal by Sodium Sesquicarbonate

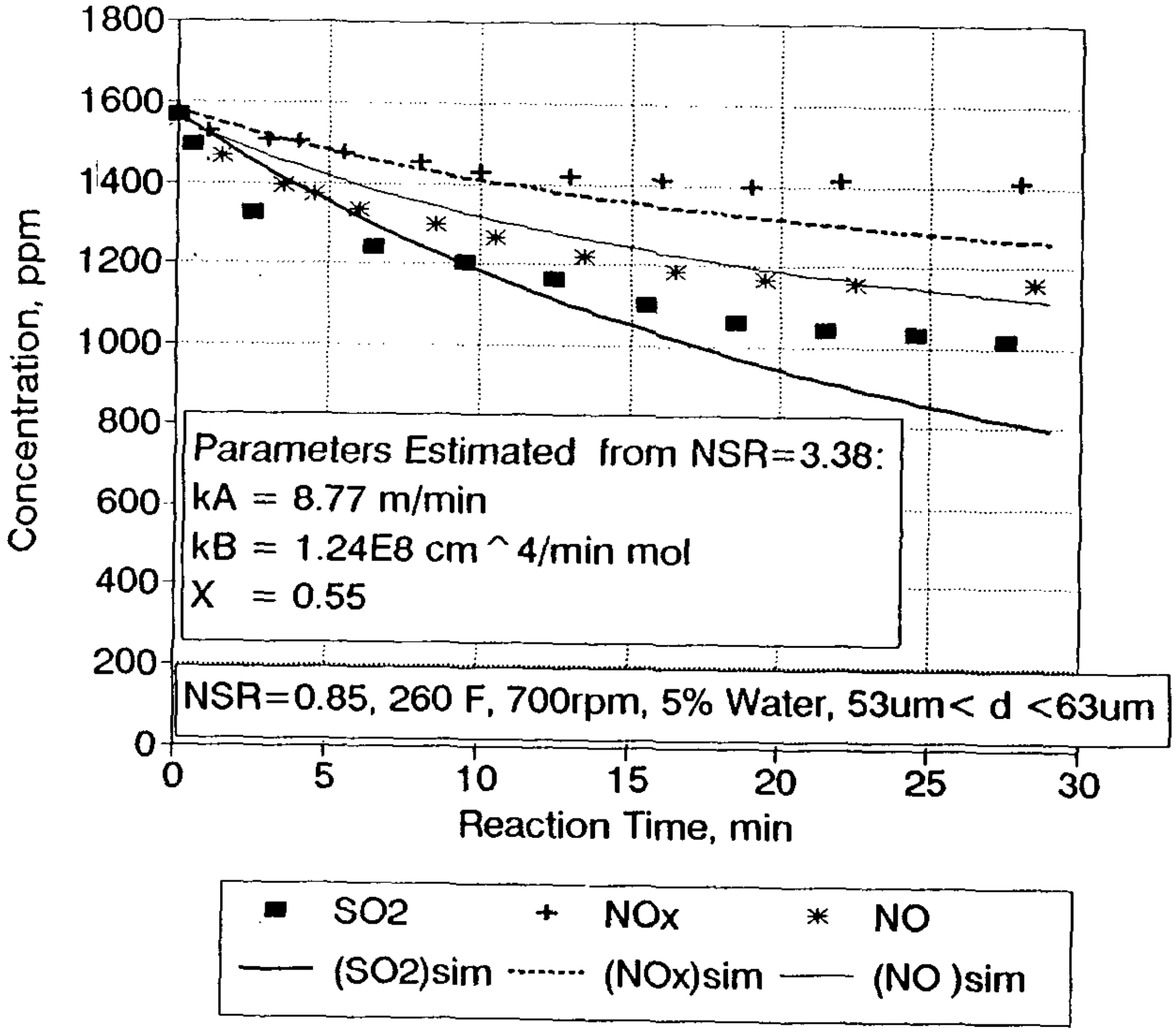


Figure 51. SO2 and NOx Removal by Sodium Sesquicarbonate

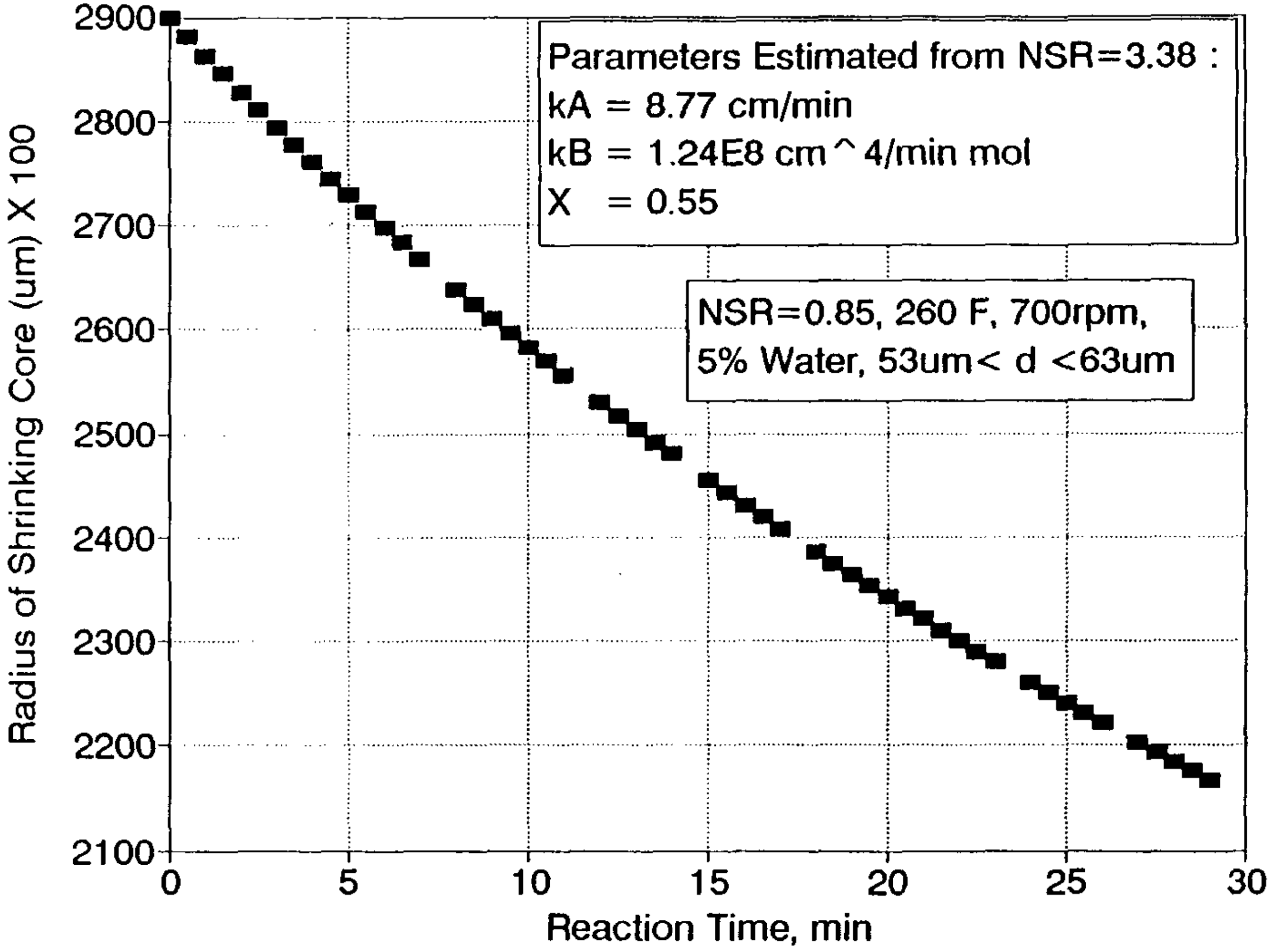


Figure 52. SO2 and NOx Removal by Sodium Sesquicarbonate

Removal rate of $SO_2$

$$R_A = dC_A/dt = -6954.22\ k_A\ C_A\ R^2 \tag{5-9}$$

Removal rate of NO

$$R_B = dC_B/dt = -6954.22\ k_B\ C_A\ C_B\ R^2 \tag{5-10}$$

Formation rate of $NO_2$

$$R_C = dC_C/dt = 3477.11\ x\ k_B\ C_A\ C_B\ R^2 \tag{5-11}$$

Shrinking rate of radius R

$$R_R = dR/dt = -20.92\ [k_A\ C_A + (1-x/2)/2\ k_B\ C_A\ C_B] \tag{5-12}$$

As in the previous section, average kinetics parameter are obtained from the case of NSR=3.37 first, with these values of $k_A$, $k_B$, and x, then used to predict results for the case of NSR=13 and the case of NSR=0.8. Kinetics parameters of these runs are shown in Table 32. Except for the case of the large NSR = 13.49. The average values for $k_A$, $k_B$ and x for the case of NSR=3.37 are as follow :

$k_A$ = 7.65 cm/min

$k_B$ = 1.06E7 $cm^4$/min mol

x = 0.7

Table 32. $k_A$, $k_B$, and x Obtained from Initial Rate Approach :

| Source | Sorbent | NSR | $k_A$ (cm/min) | $k_B$ (cm$^4$/cm mol) | x |
|---|---|---|---|---|---|
| Figure 23 | Bic- | 0.85 | 6.56 | 1.47E8 | 0.97 |
| Figure 24 | Bic- | 3.37 | 7.42 | 1.07E8 | 0.70 |
| Figure 25 | Bic- | 3.37 | 7.88 | 1.04E8 | 0.70 |
| Figure 26 | Bic- | 13.5 | 4.16 | 8.27E7 | 0.26 |

* Bic- : Sodium bicarbonate

With these values, simulation have been done and are plotted on Figures 53 through 60. The results are similar to those for sodium sesquicarbonate. Again it appears that some solid is remaining in the injection system resulting in less removal of gases at low NSR. For the high NSR run is appears that the actual reaction rate for the removal of $SO_2$ is somewhat less than that predicted by the model. The average kinetic parameters for the two solids are listed in table 33. From Table 33, it appears that sodium sesquicarbonate has the higher reaction rate constant for removing both $SO_2$ and NO and lower potential in forming $NO_2$ which is characterized by the parameter x.

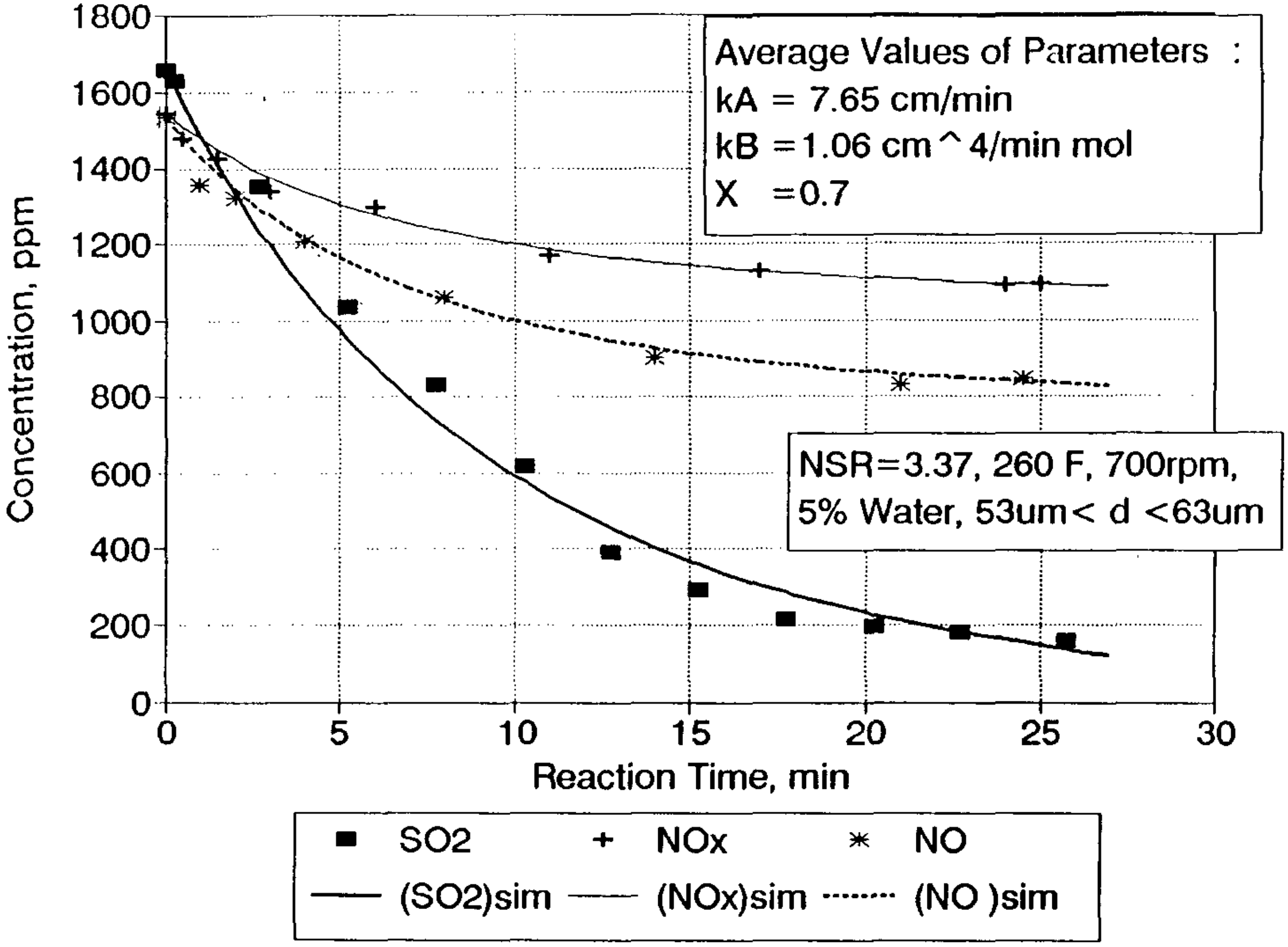


Figure 53. SO2 and NOx Removal by Sodium Bicarbonate

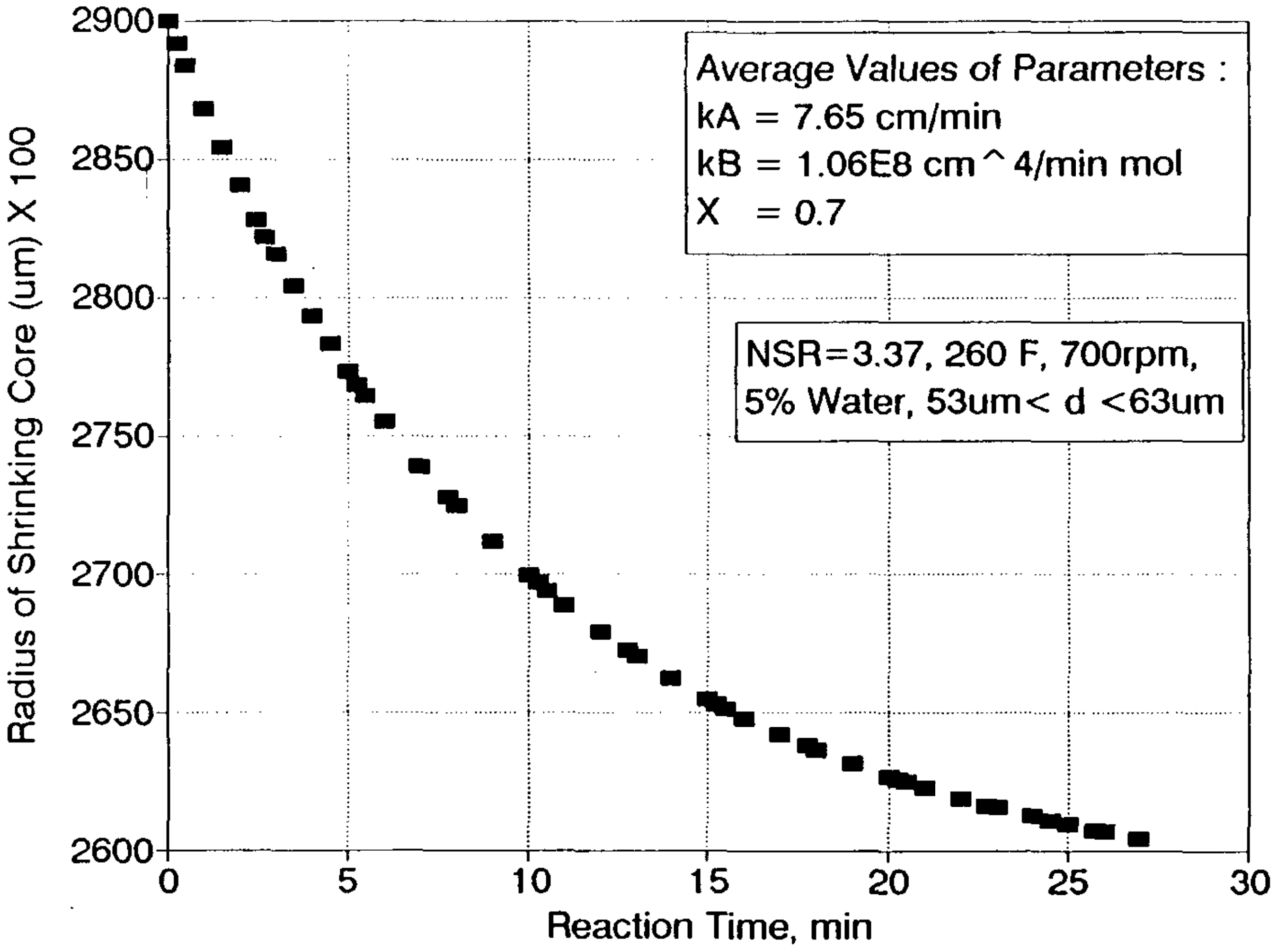


Figure 54. SO2 and NOx Removal by Sodium Bicarbonate

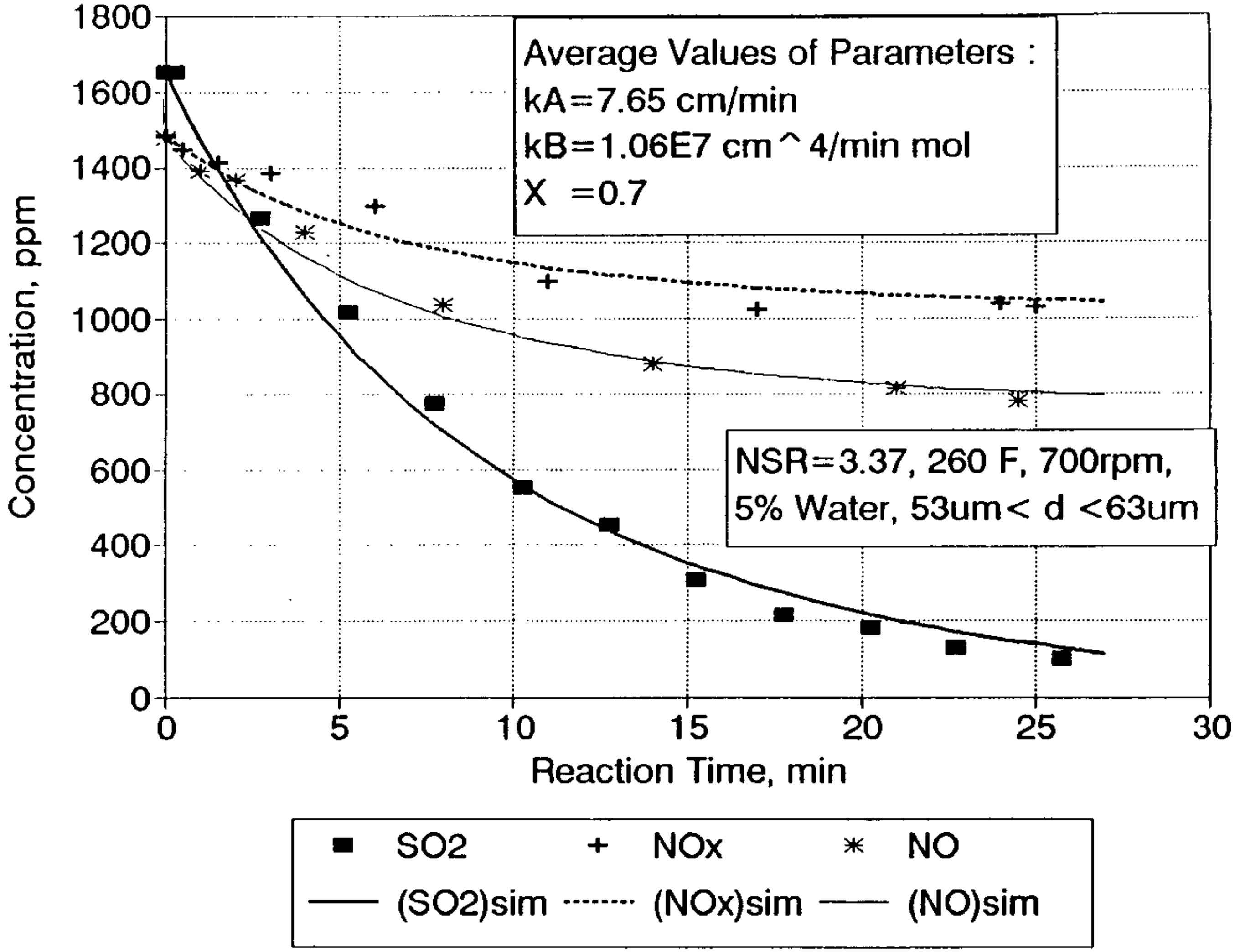


Figure 55. SO2 and NOx Removal by Sodium Bicarbonate

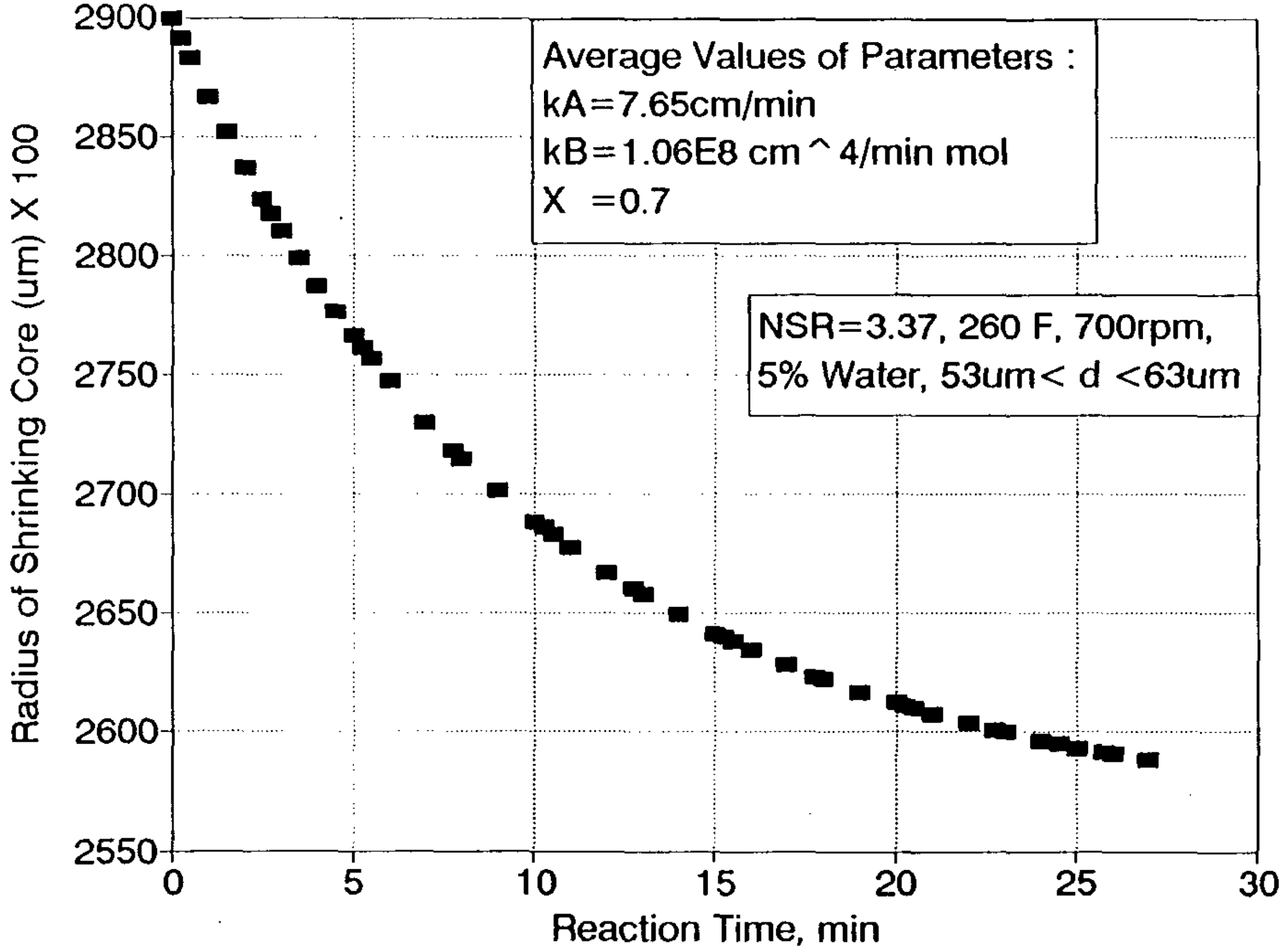


Figure 56. SO2 and NOx Removal by Sodium Bicarbonate

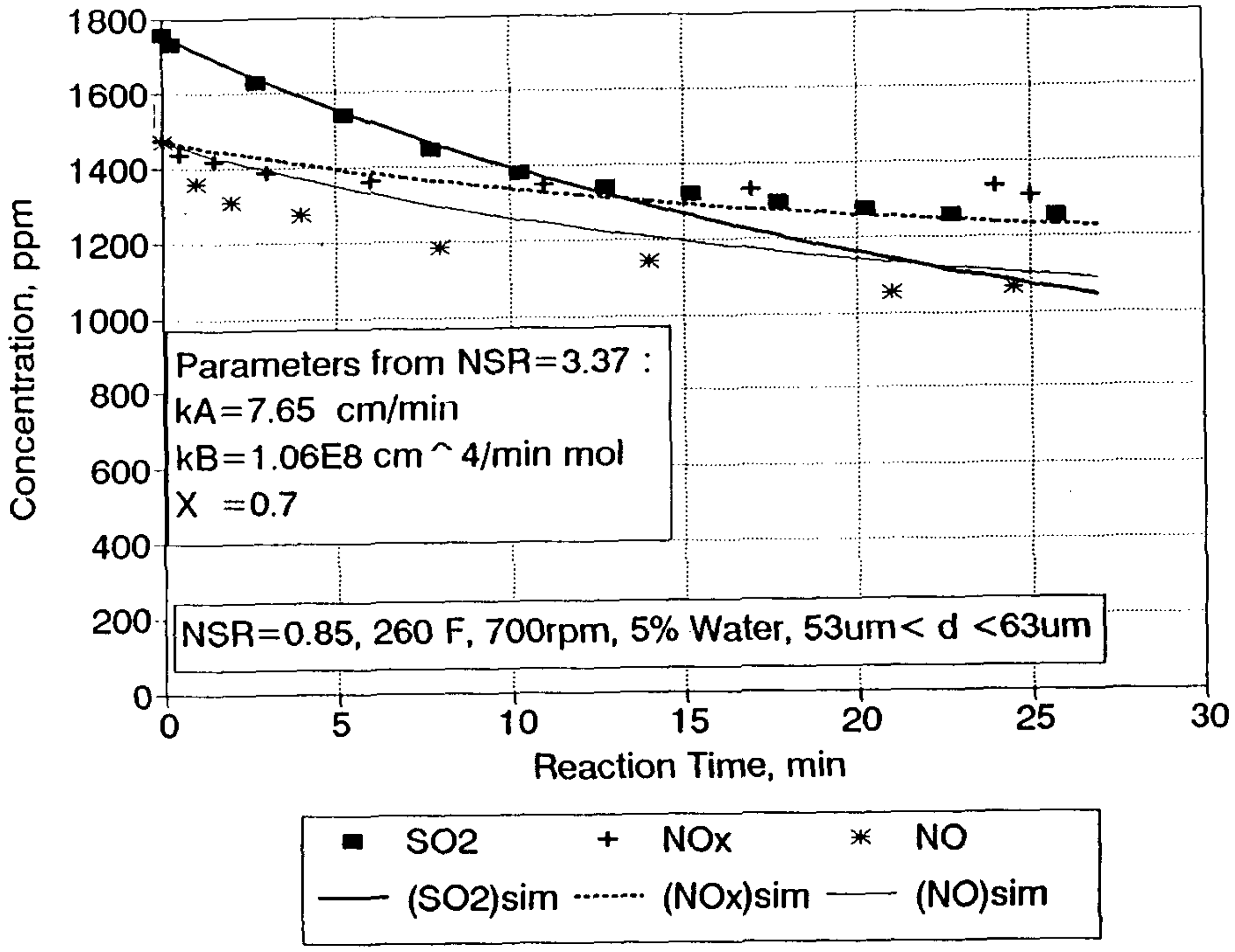


Figure 57. SO2 and NOx Removal by Sodium Bicarbonate

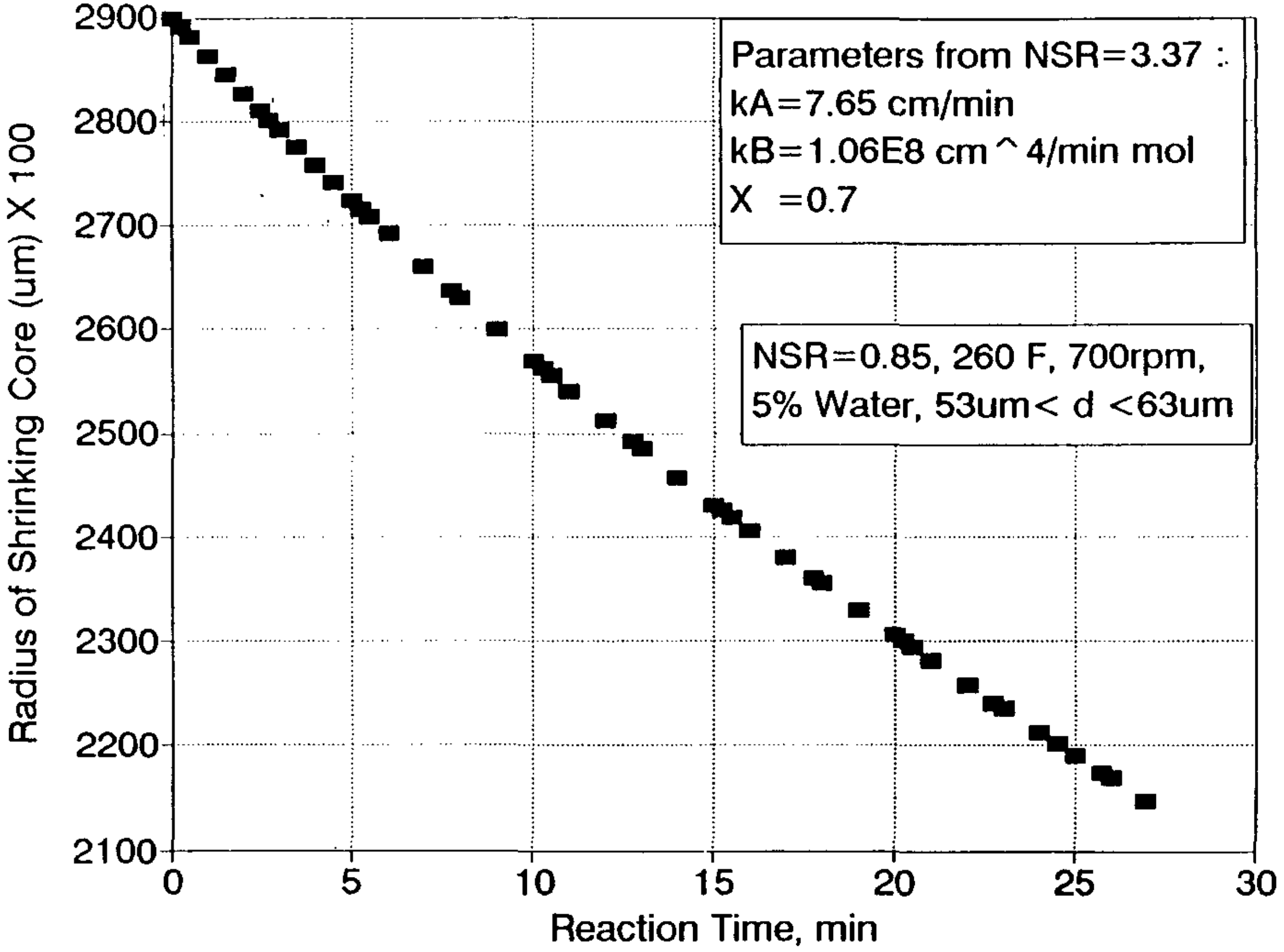


Figure 58. SO2 and NOx Removal by Sodium Bicarbonate

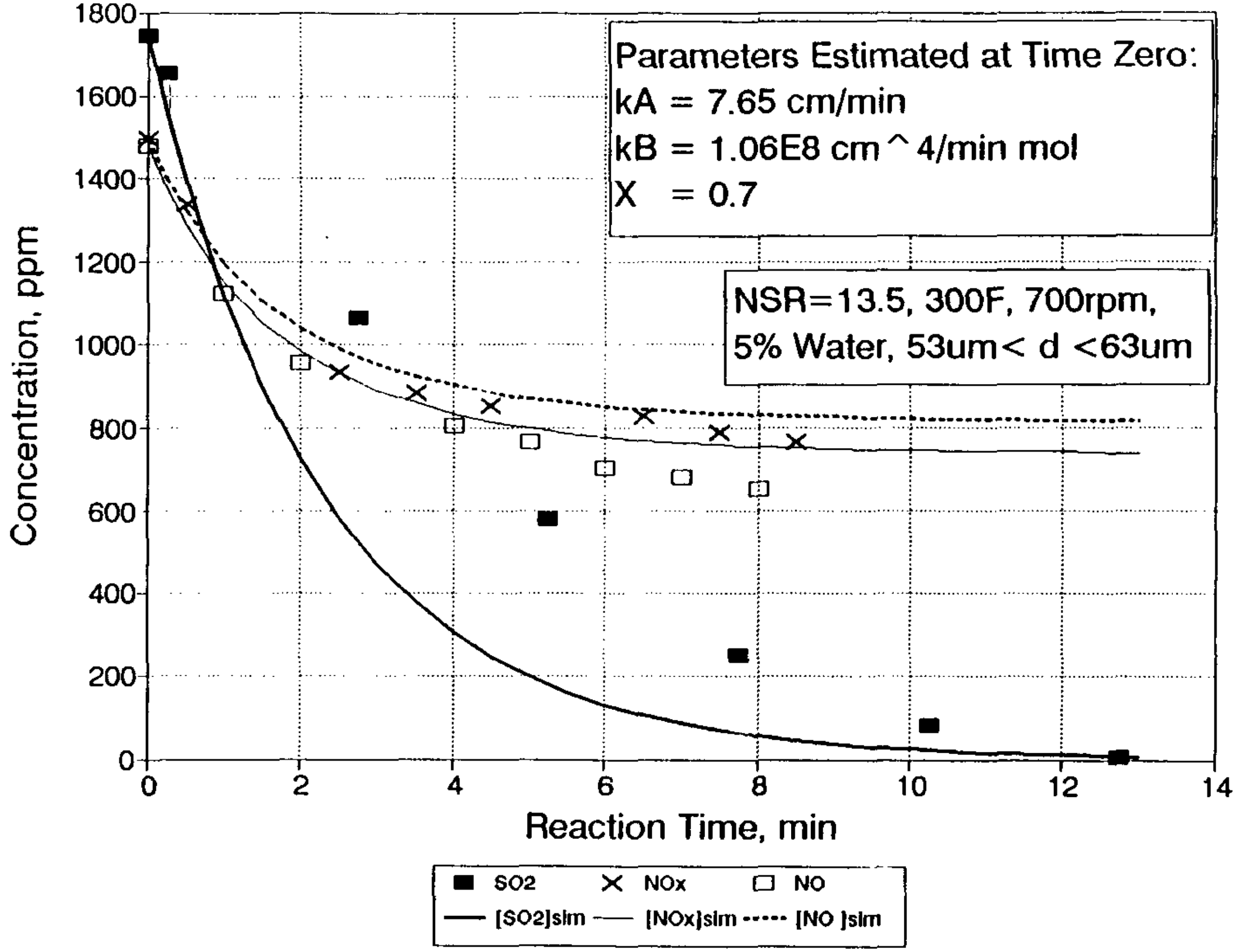


Figure 59. SO2 and NOx Simultaneous Reaction by Sodium Bicarbonate

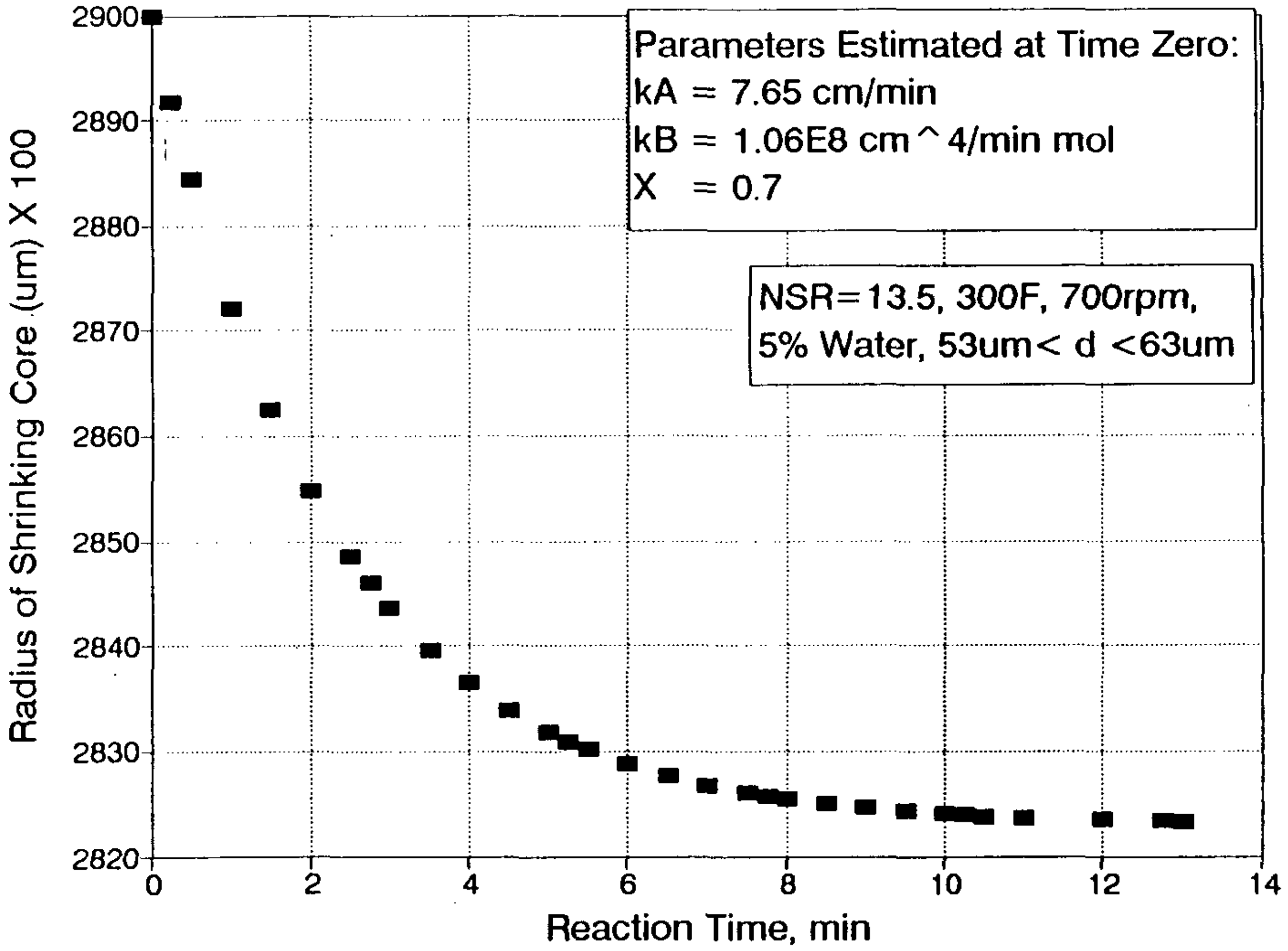


Figure 60. SO2 and NOx Simultaneous Reaction by Sodium Bicarbonate

Table 33. $k_A$, $k_B$, and x Obtained from Initial Rate Approach :

| Sorbent | $k_A$ (cm/min) | $k_B$ ($cm^4$/cm mol) | x |
|---|---|---|---|
| Sesquiicarbonate | 8.77 | 1.24E8 | 0.55 |
| Bicarbonate | 7.65 | 1.06E8 | 0.70 |

# CHAPTER VI

# CONCLUSION AND RECOMMENDATION

The following conclusions and recommendations may be drawn from the above results:

1. Sodium sesquicarbonate shows higher promise over sodium bicarbonate due to higher $NO_x$ removal rate and lower $NO_2$ formation rate.
2. The preferred reaction sequence for the removal of $NO_x$ and the formation of $NO_2$ appears to be that proposed by the Solvay group. NO reacts directly with the solid in the presence of intermediate sulfur compounds to form sodium nitrite and sodium nitrate. $NO_2$ appears to be formed by decomposition of sodium nitrite.
3. Sodium pyrosulfite appears to be an intermediate in the reaction of sodium based solids with NO.
4. Sodium sesquicarbonate with a high percent of water at low temperature resulted in the lowest $NO_2$ formation.
5. Higher NSR values resulted in higher $NO_x$ removal rate for both sodium bicarbonate and sodium sesquicarbonate and resulted in higher $NO_2$ formation rate.
6. The particle size effect study for sodium sesquicarbonate showed higher $NO_x$ removal rate and lower $NO_2$ formation rate with smaller particles.
7. Increasing reaction temperature for sodium bicarbonate or sodium sesquicarbonate and the flue gas system will increase $NO_x$ removal rate but will result in higher $NO_2$

formation.

8. Lower stirrer speed seemed to have little effect.
9. The previously used $SO_2$ analytical procedure resulted in erroneous $SO_2$ concentrations.
10. From Solvay's model, sodium sesquicarbonate was found to have a higher rate constant for removing both $SO_2$ and NO and lower potential in forming $NO_2$ while compared with the simulation results from sodium bicarbonate.

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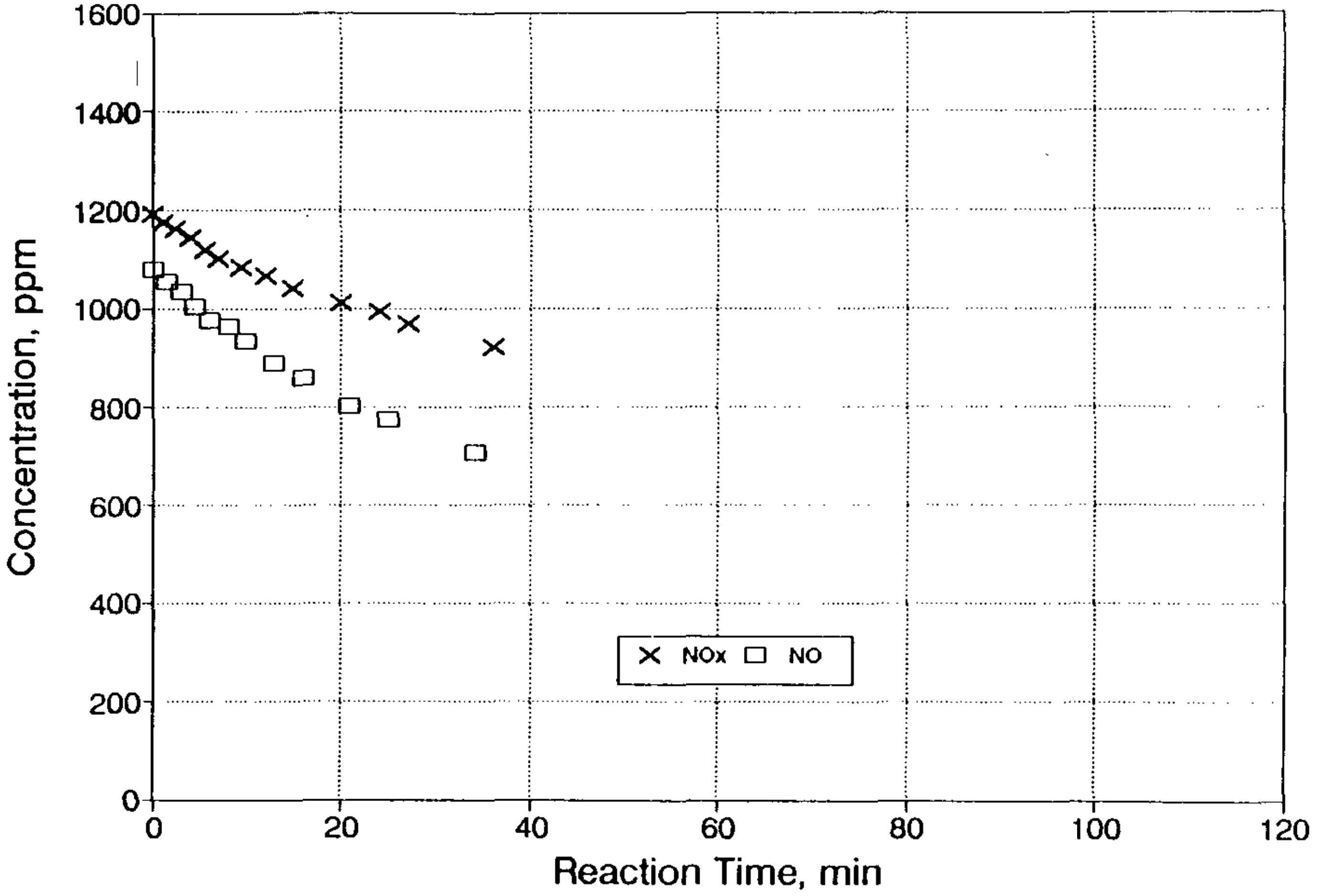
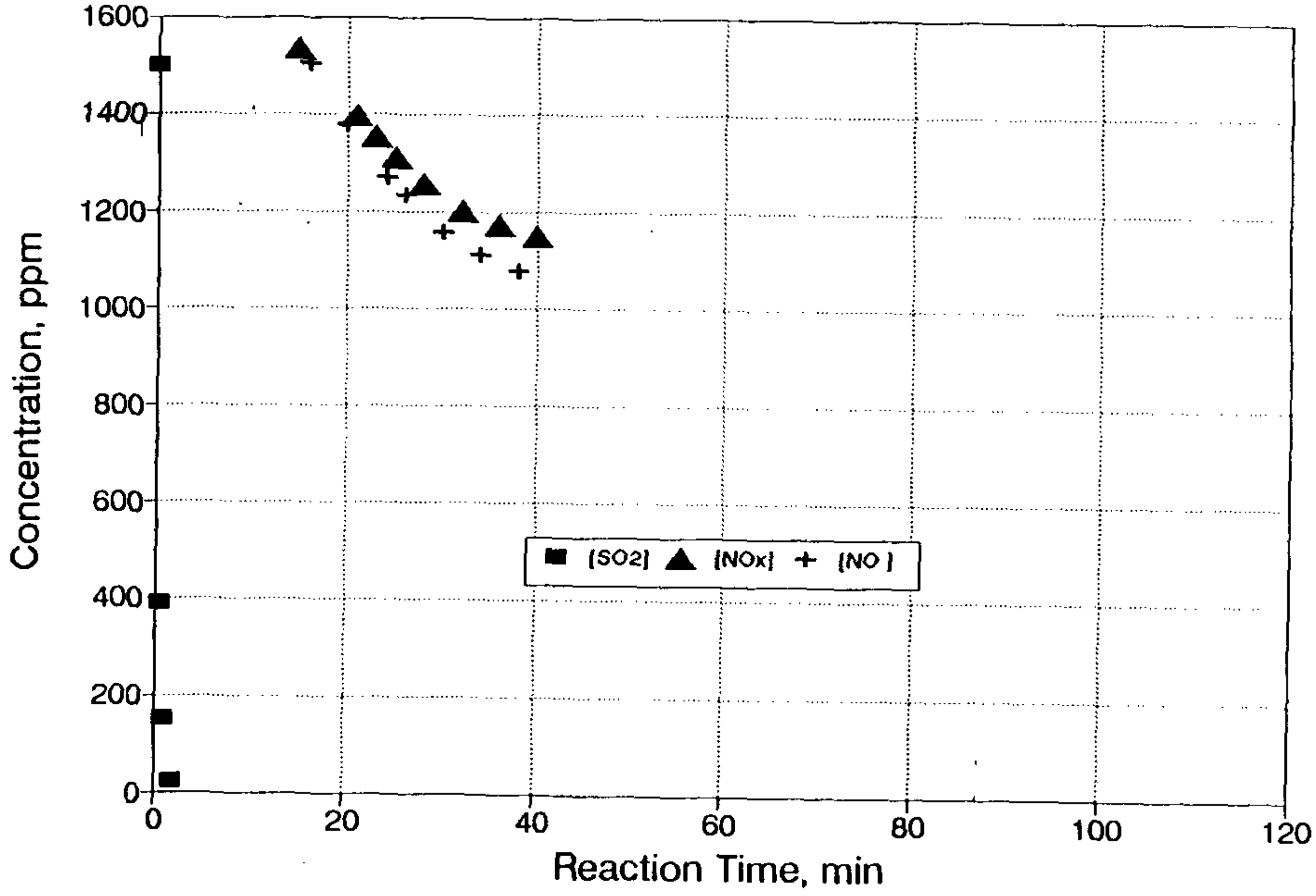
# APPENDIX A



NSR=13.5, Water=3%, 300F, 300 rpm, 53um< d < 63um

Figure A1. 02-26-93 : NOx Removal by Sodium Bicarbonate



NSR=13.5, Water=3%, 300 F, 300 rpm, 53um< d <63um

Figure A2. 03-13-93 : SO2 and NOx Removal by Sodium Bicarbonate

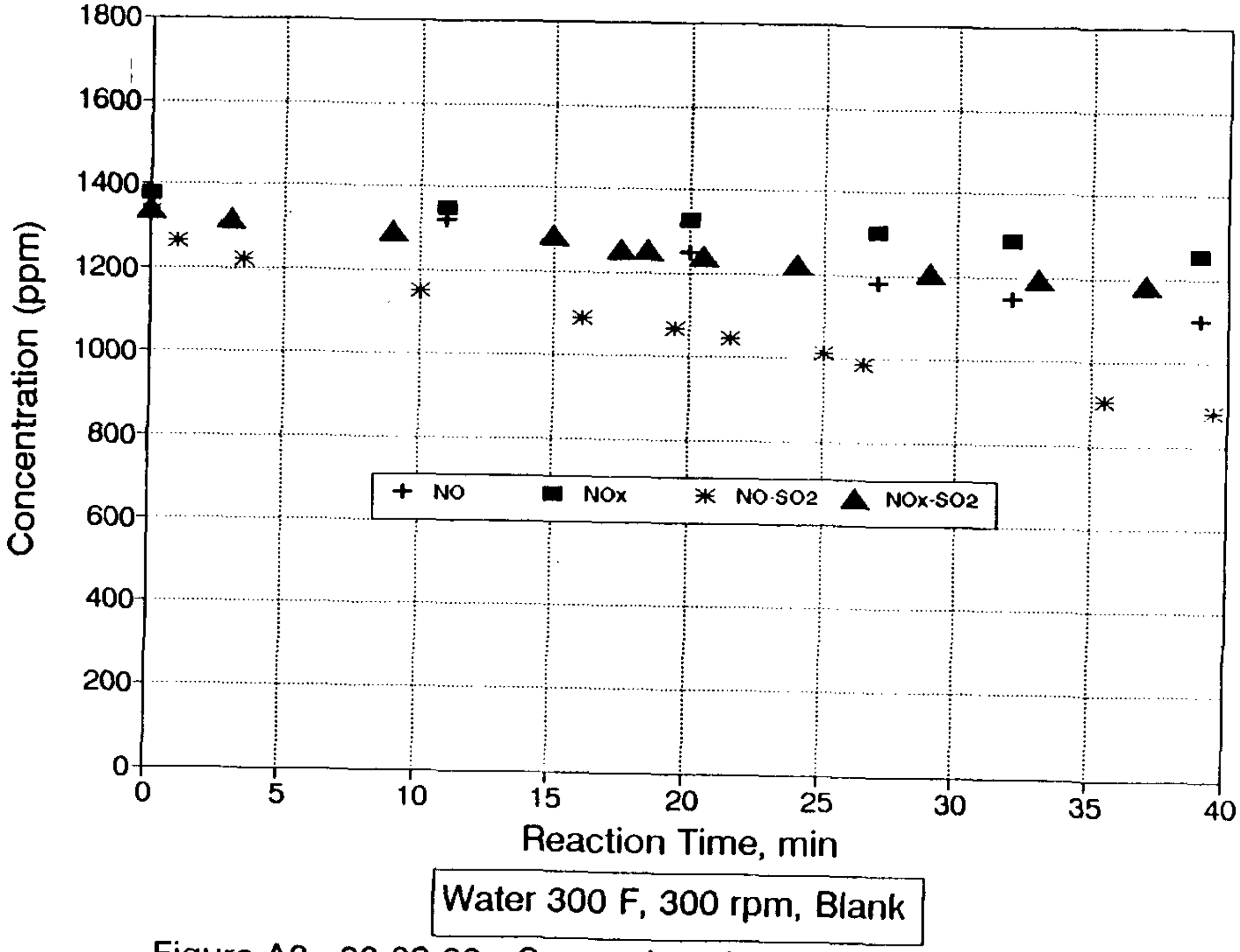
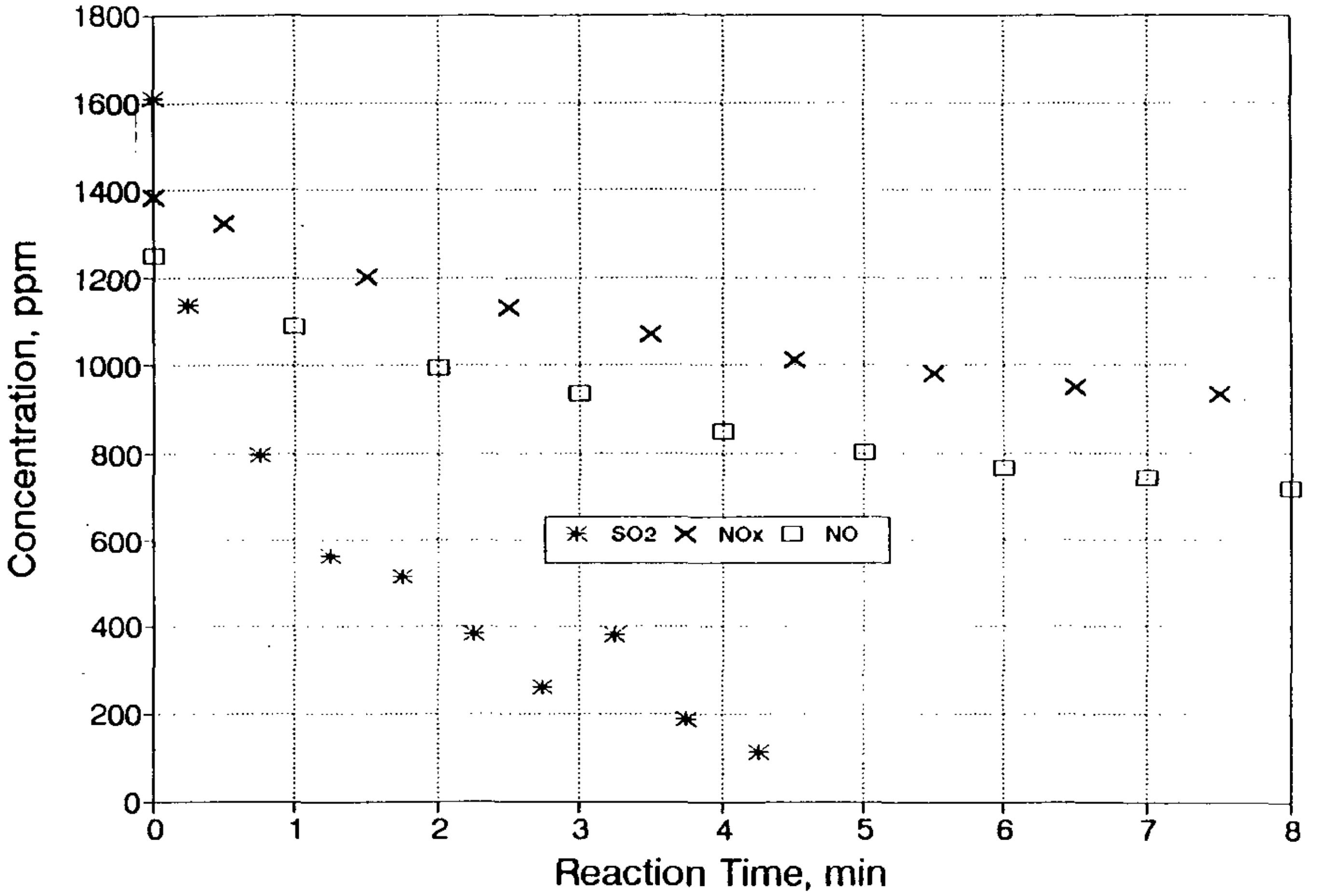
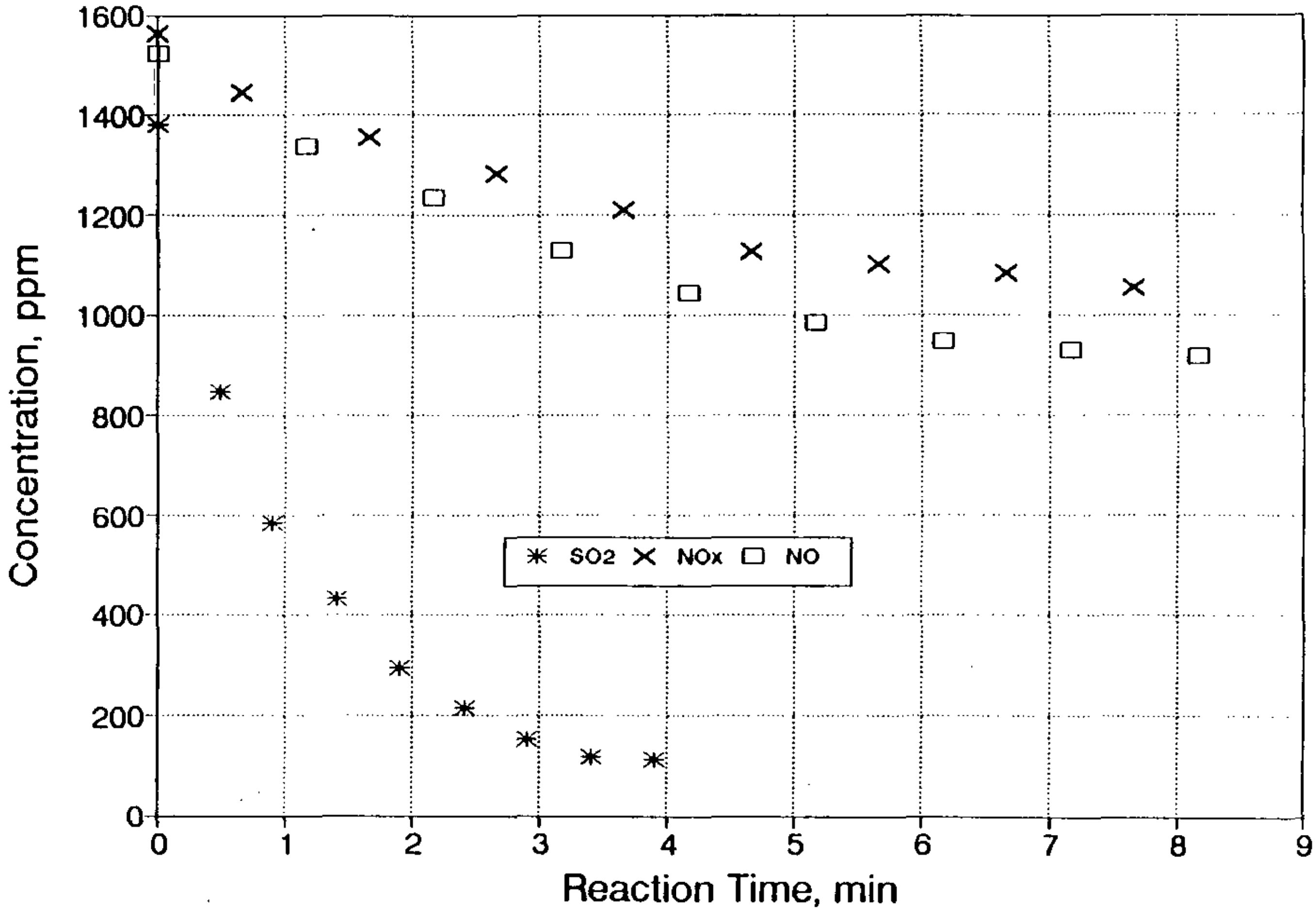


Figure A3. 03-02-93 : Comparison between the NOx System with SO2 and the NOx System without SO2



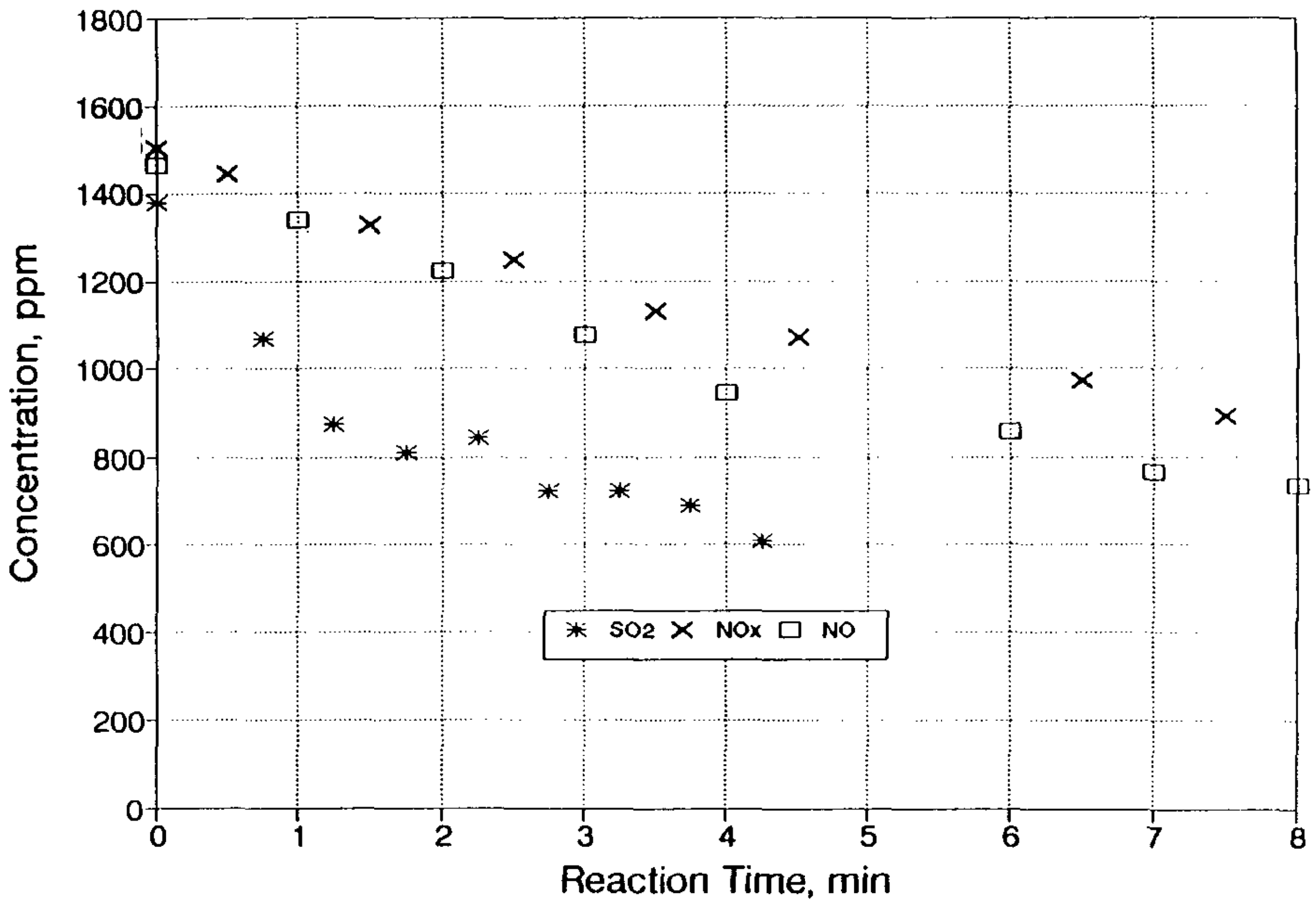
NSR=13.5, Water=3.5%, 300F, 300 rpm, 53um< d < 63um

Figure A4. 04-16-93 : SO2 and NOx Removal by Sodium Bicarbonate



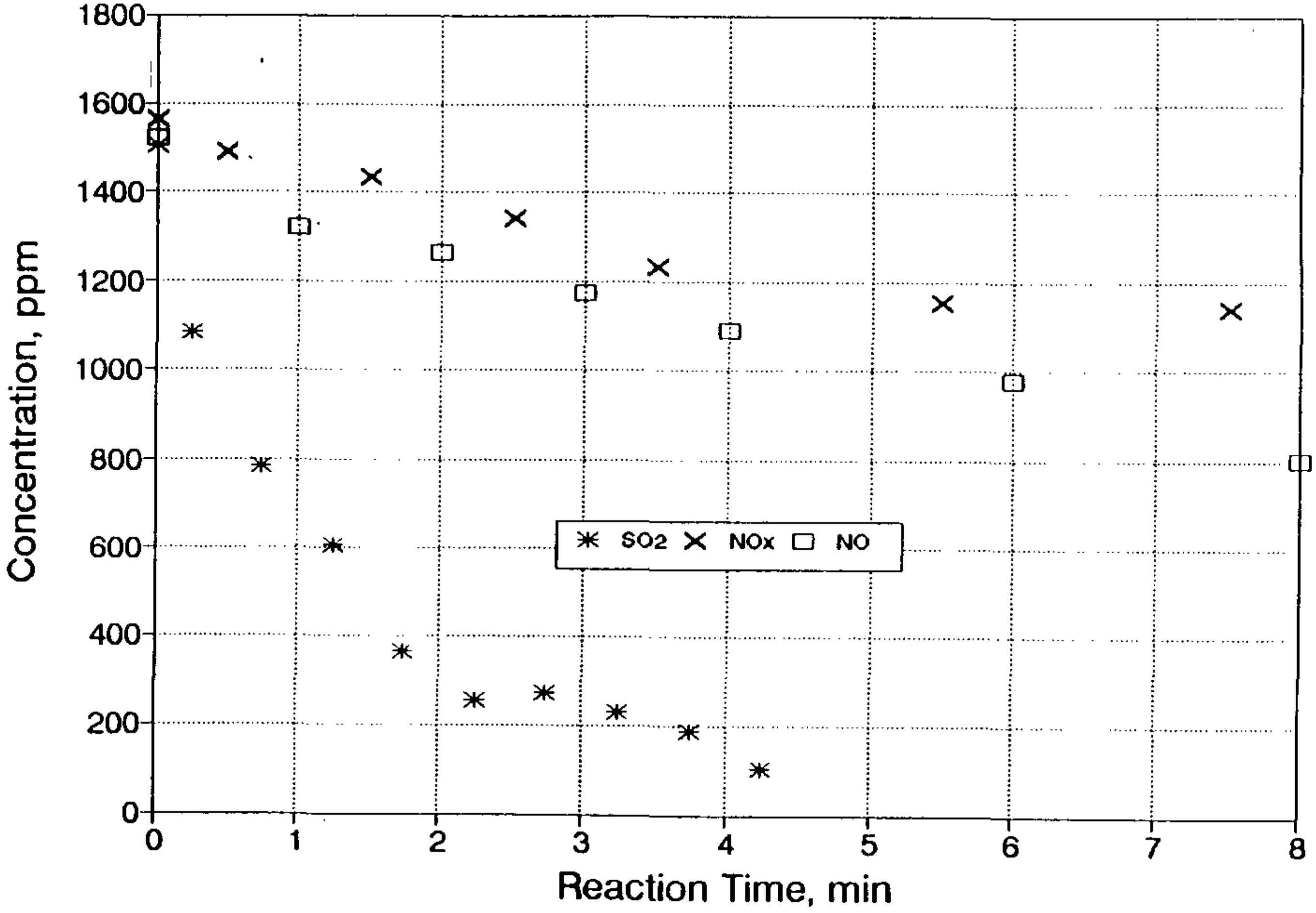
NSR=13.5, Water=7%, 300F, 300 rpm, 53um< d < 63um

Figre A5. 04-20-93 : SO2 and NOx removal by Sodium Biarbonate



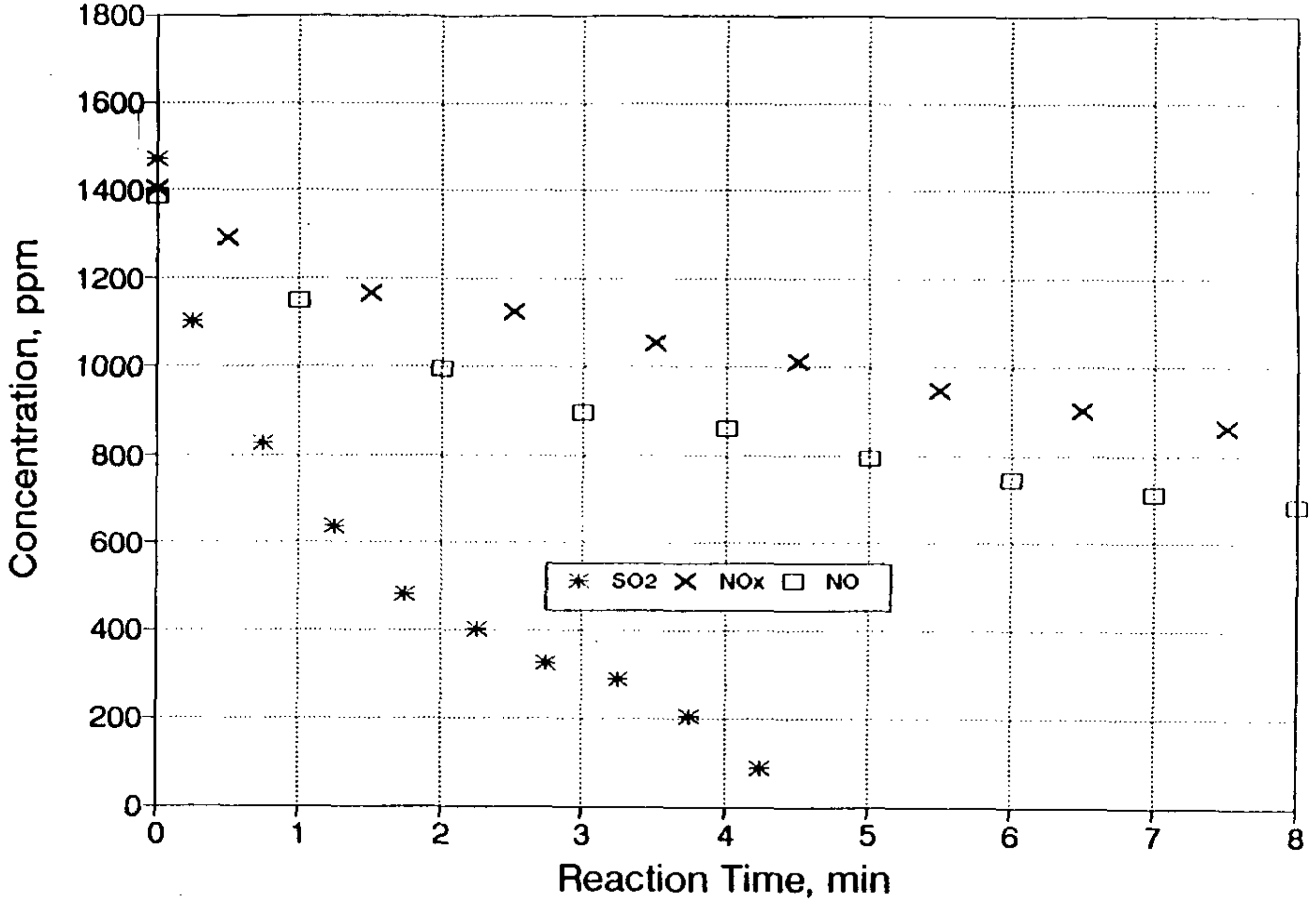
NSR=13.5, Water=0%, 300F, 300rpm, 53um< d < 65um

Figure A6. 04-21-93 : SO2 and NOx Removal by Sodium Bicarbonate



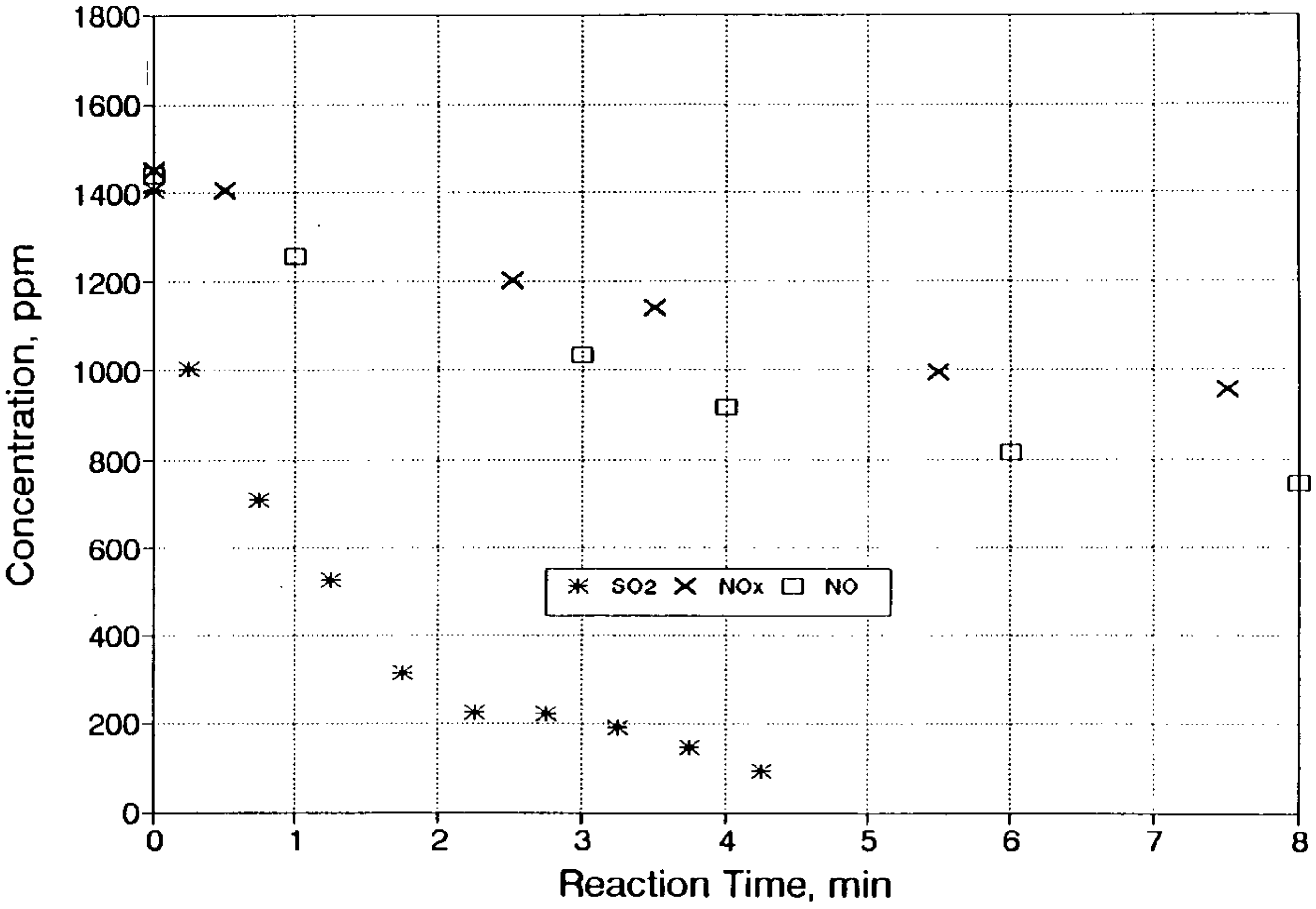
NSR=13.5, Water=7%, 300F, 300 rpm, 53um< d <63um

Figure A7. 04-23-93 : SO2 and NOx Removal by Sodium Bicarbonate



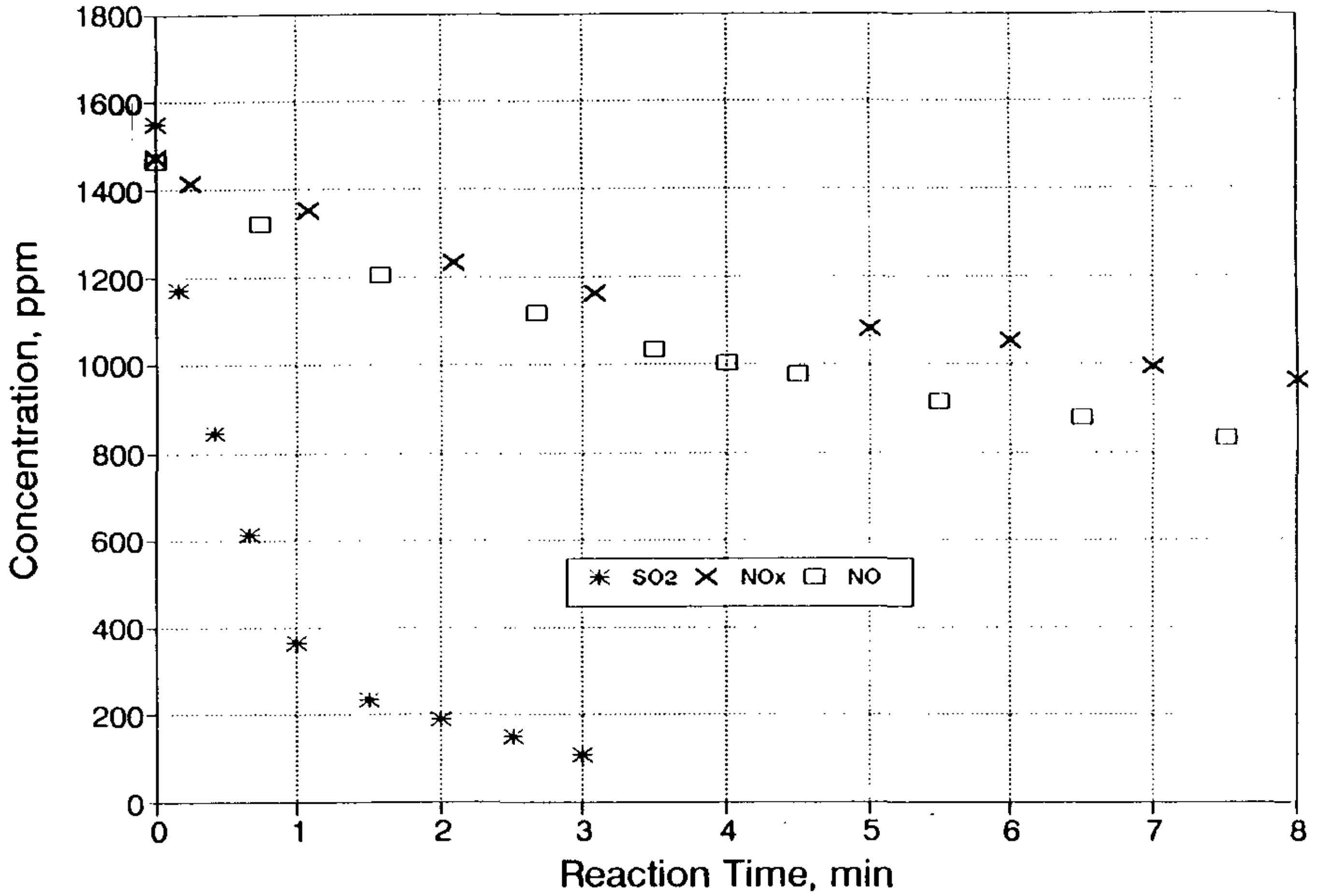
NSR=13.5, Water=2.9, 300F, 300 rpm, 53um< d <63um

Figure A8. 04-27-93 : SO2 and NOx Removal by Sodium Bicarbonate



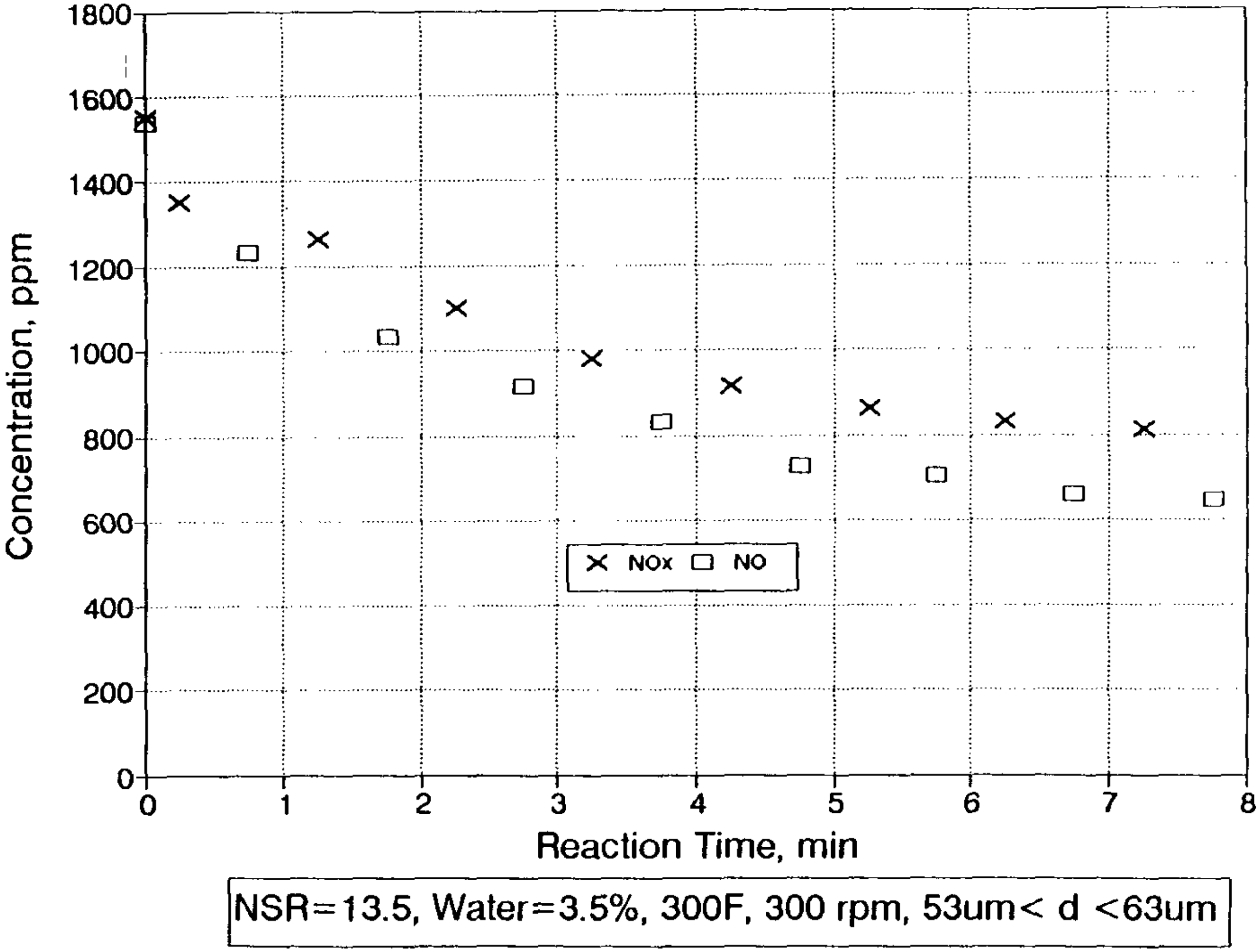
NSR=13.5, Water=3.5%, 300F, 300 rpm, 53um< d <63um

Figure A9. 04-27-93 : SO2 and NOx Removal by Sodium Bicarbonate



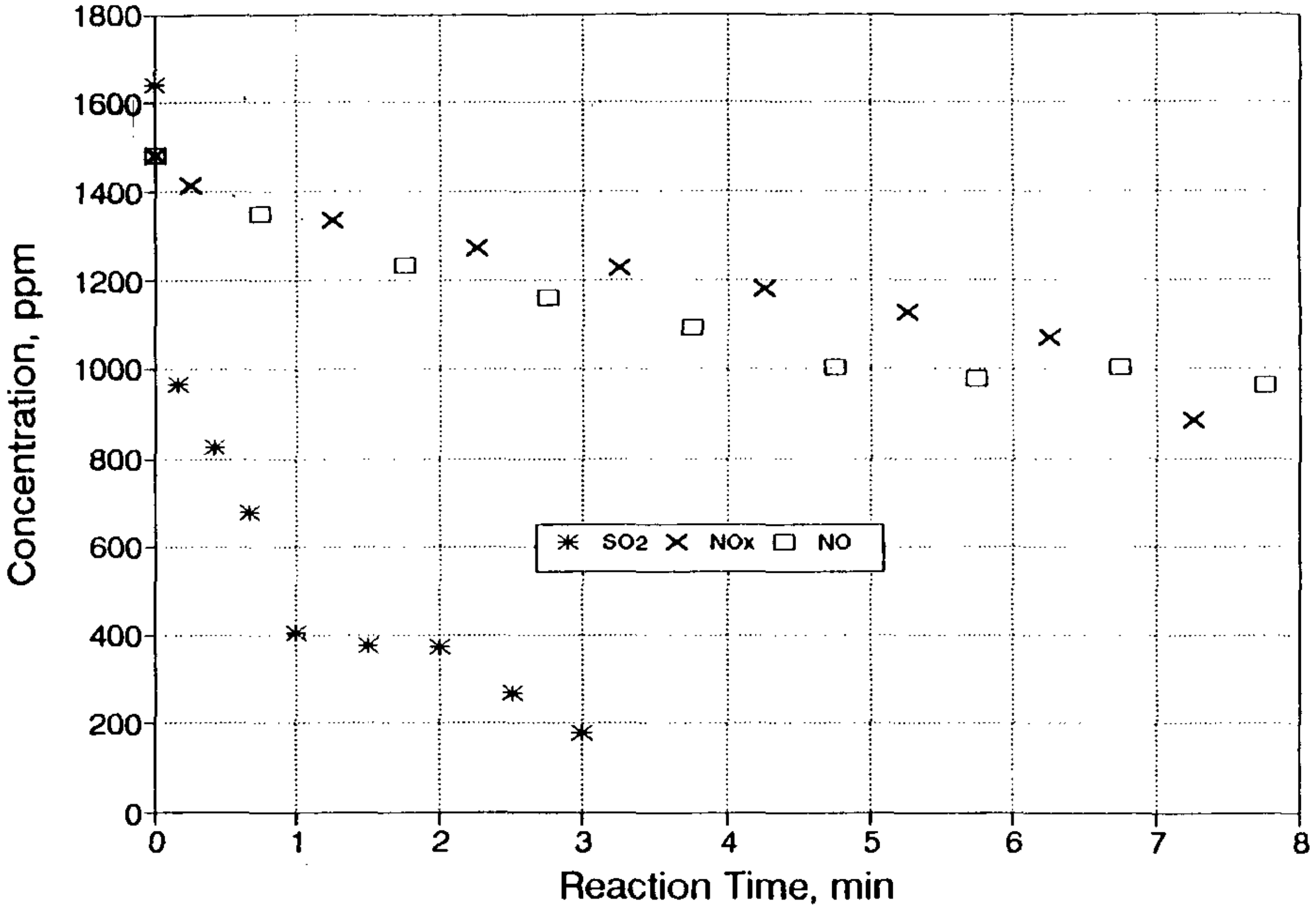
NSR=13.5, Water=10%, 300F, 300 rpm, 53um< d <63um

Figure A10. 04-30-93 : SO2 and NOx Removal by Sodium Bicarbonate



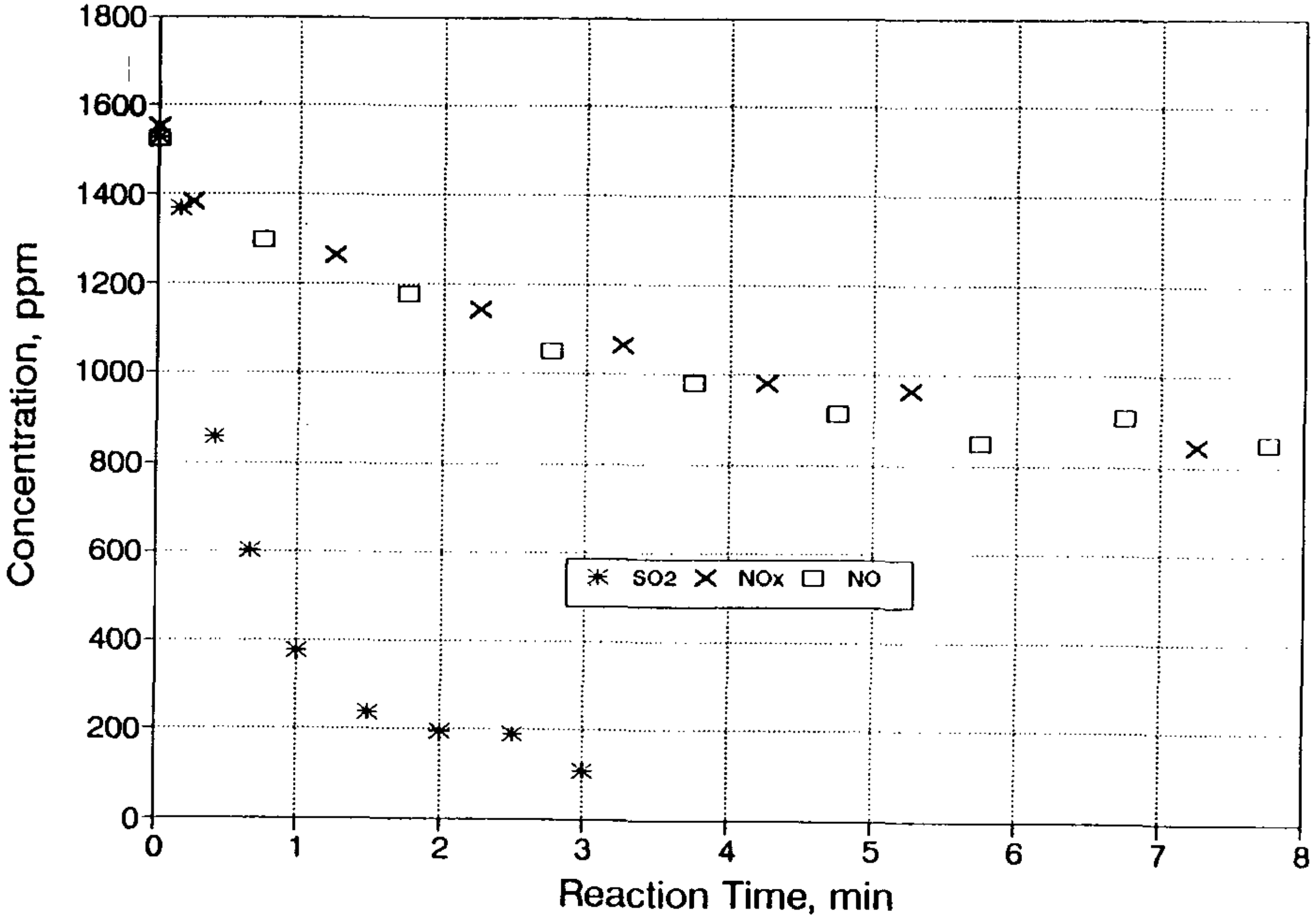
NSR=13.5, Water=3.5%, 300F, 300 rpm, 53um< d <63um

Figure A11. 05-03-93 : SO2 and NOx Removal by Sodium Sesquicarbonate



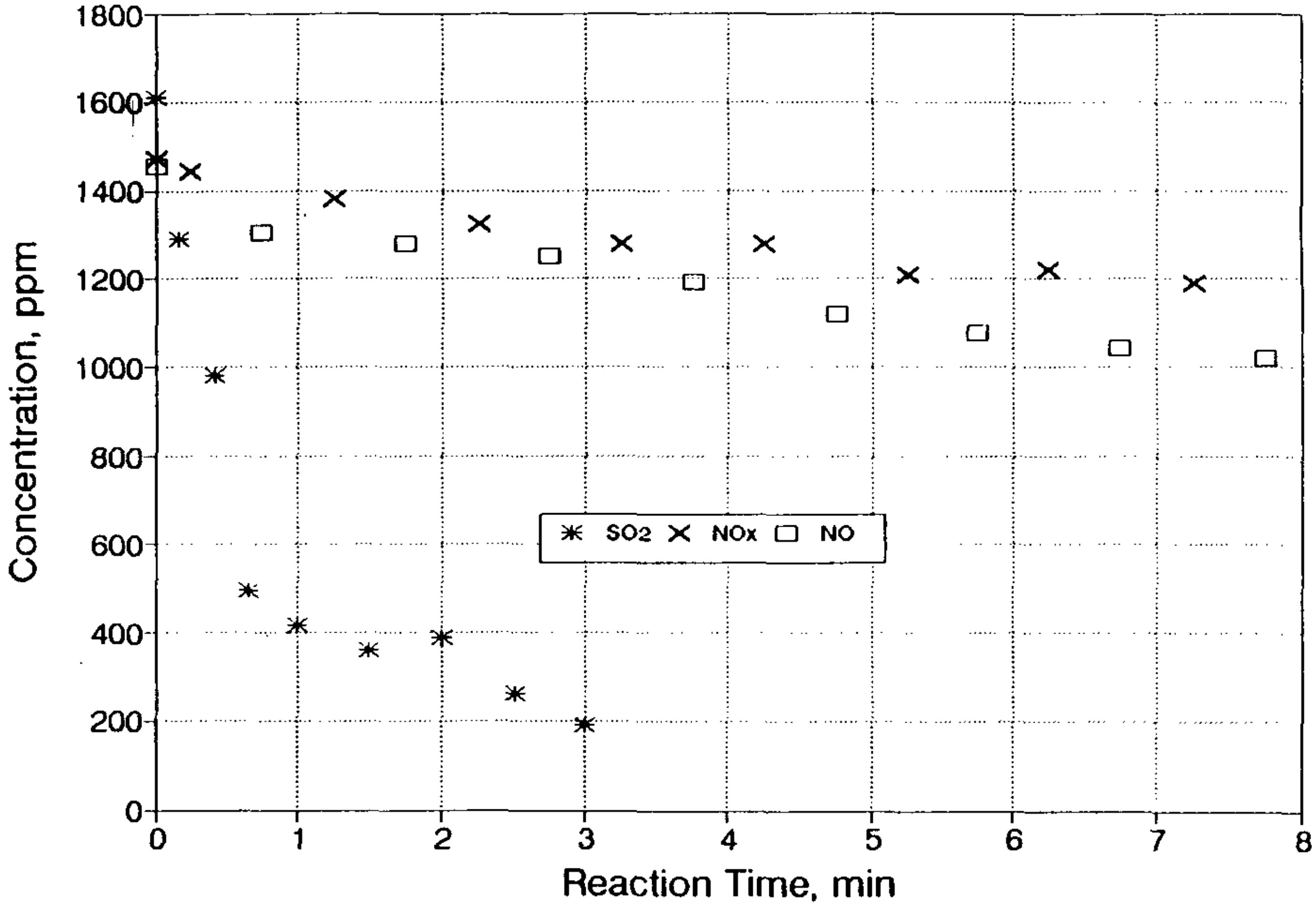
NSR=13.5, Water=6.7%, 240F, 300 rpm, 53um< d <63um

Figure A12. 05-07-93 : SO2 and NOx Removal by Sodium Bicarbonate



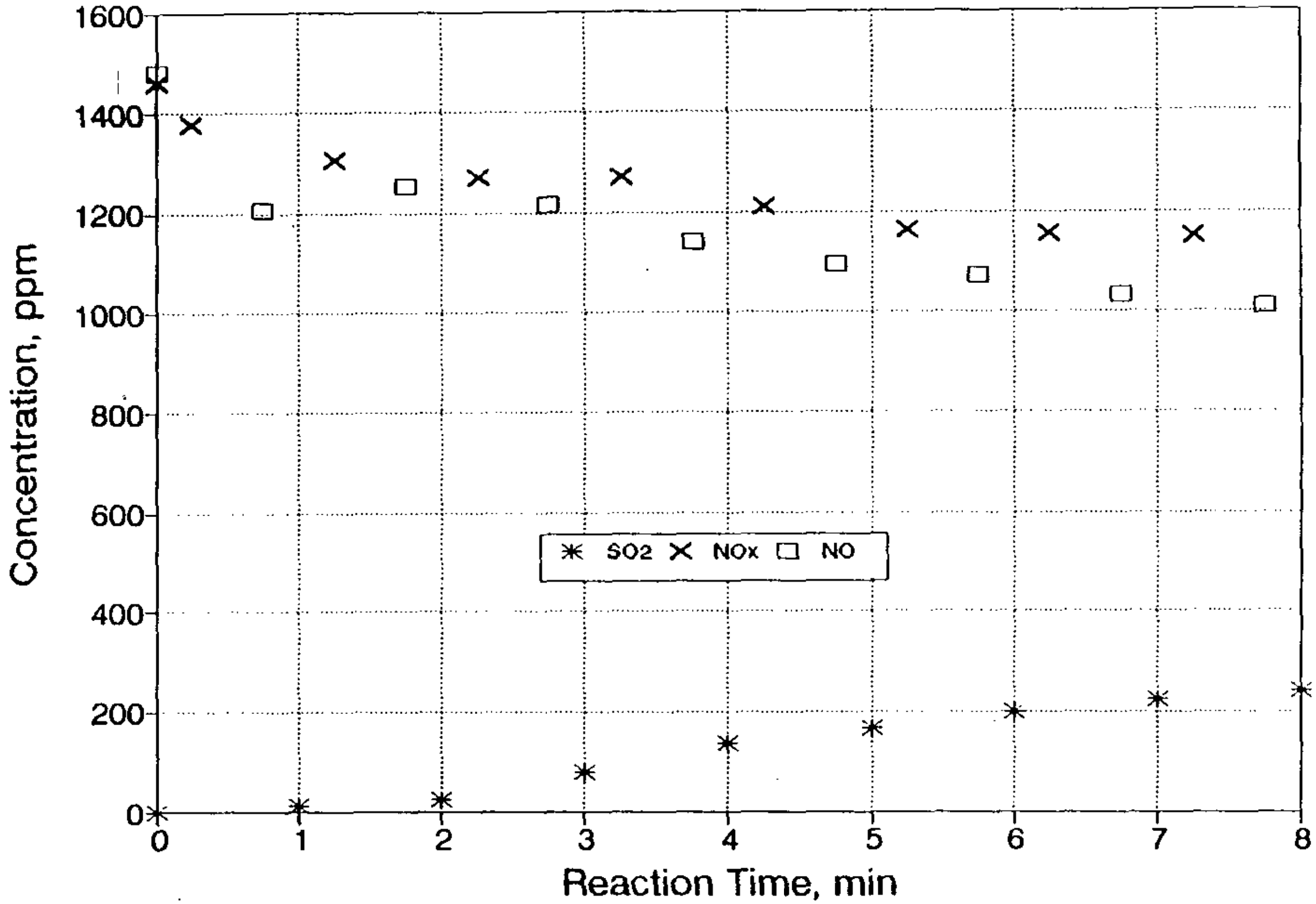
NSR=13.5, Water=6.7%, 240F, 300rpm, 53um< d <63um

Figure A13. 05-10-93 : SO2 and NOx Removal by Sodium Sesquicarbonate



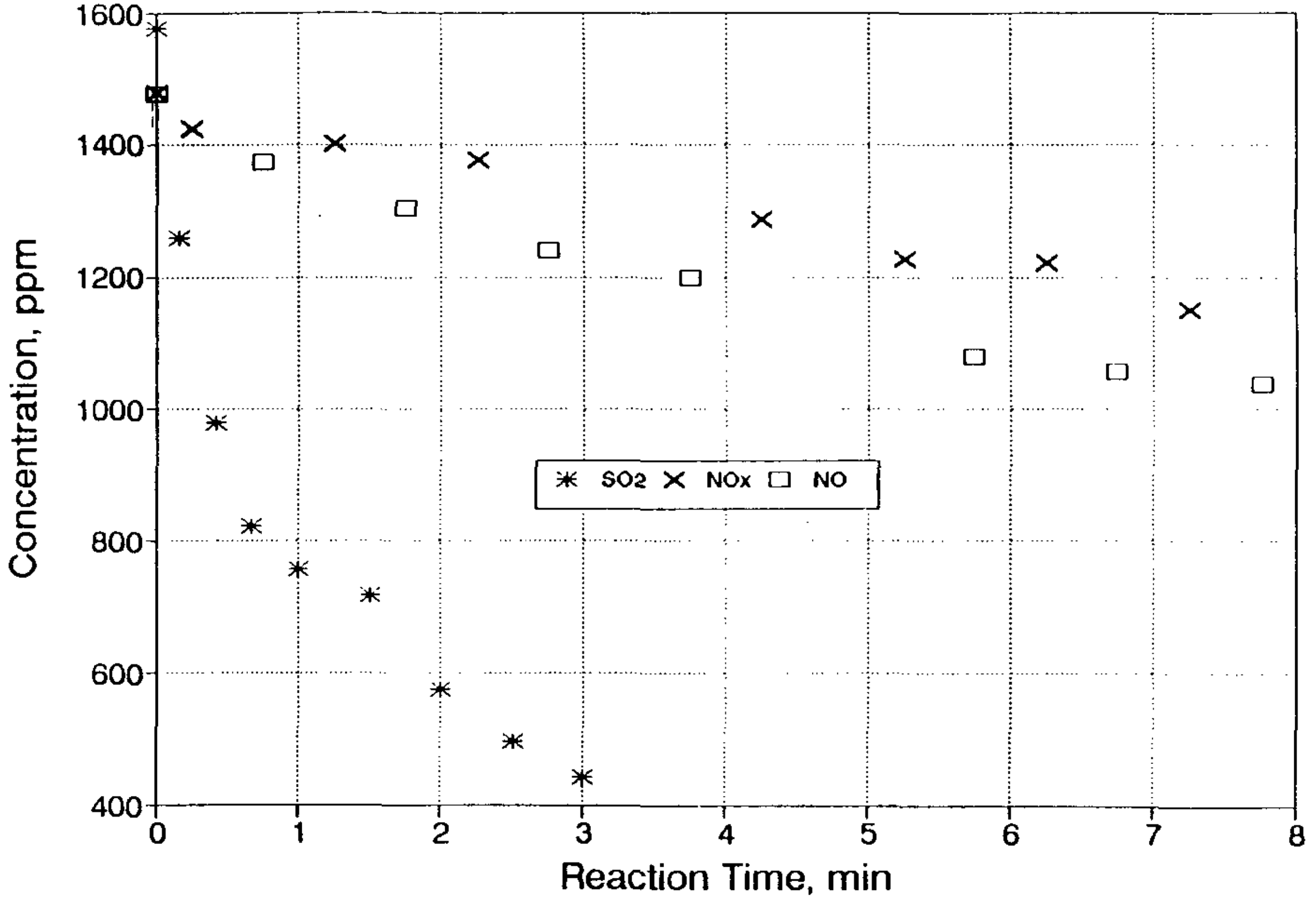
NSR=3.4, Water=5%, 260F, 300 rpm, 53um< d <63um

Figure A14. 05-20-93 : SO2 and NOx Removal by Sodium Bicarbonte



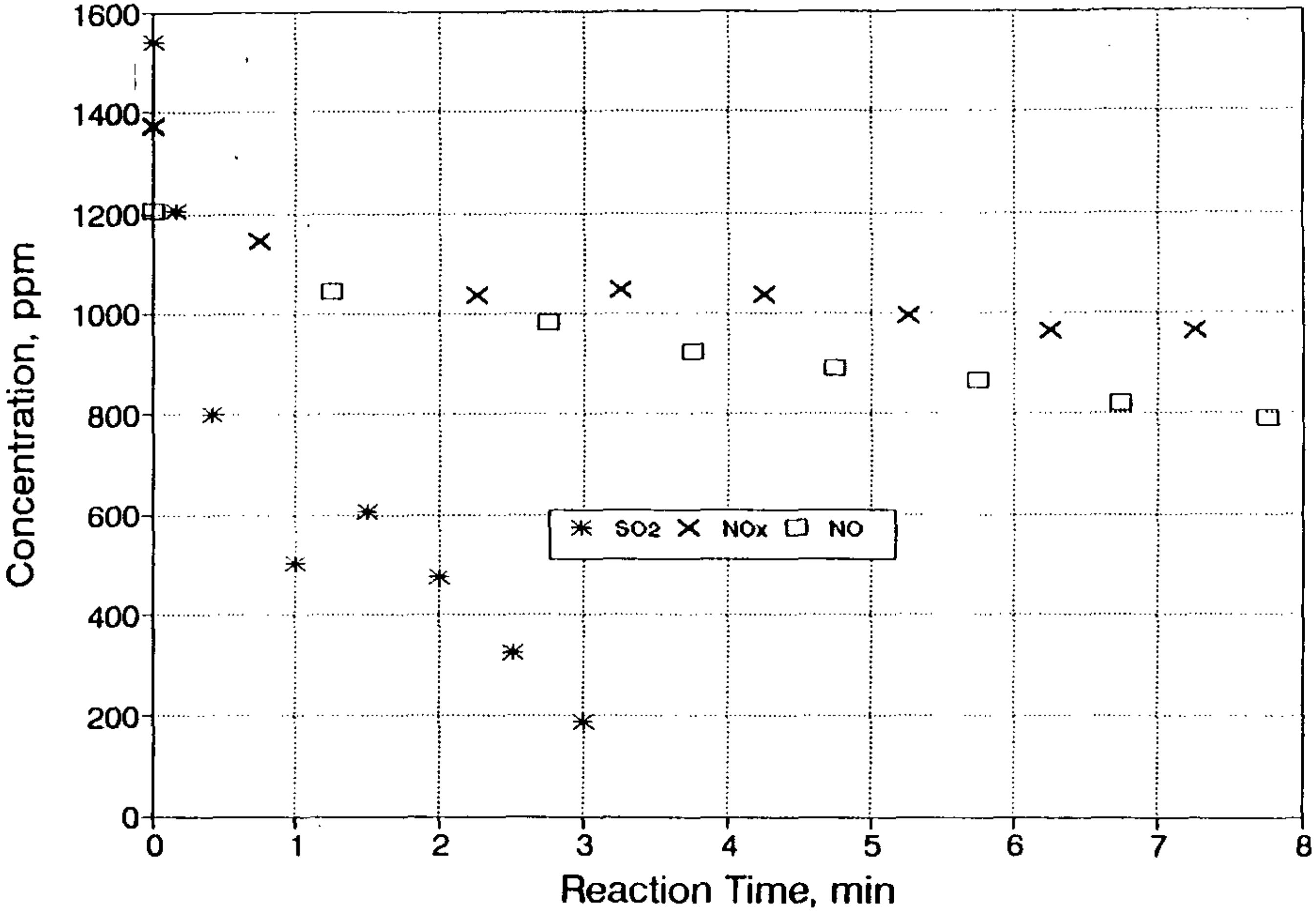
NSR=13.5, Water=5%, 260F, 300 rpm, 53um< d <63um

Figure A15. 05-24-93 : SO2 and NOx Removal by Sodium Pyrosulfite



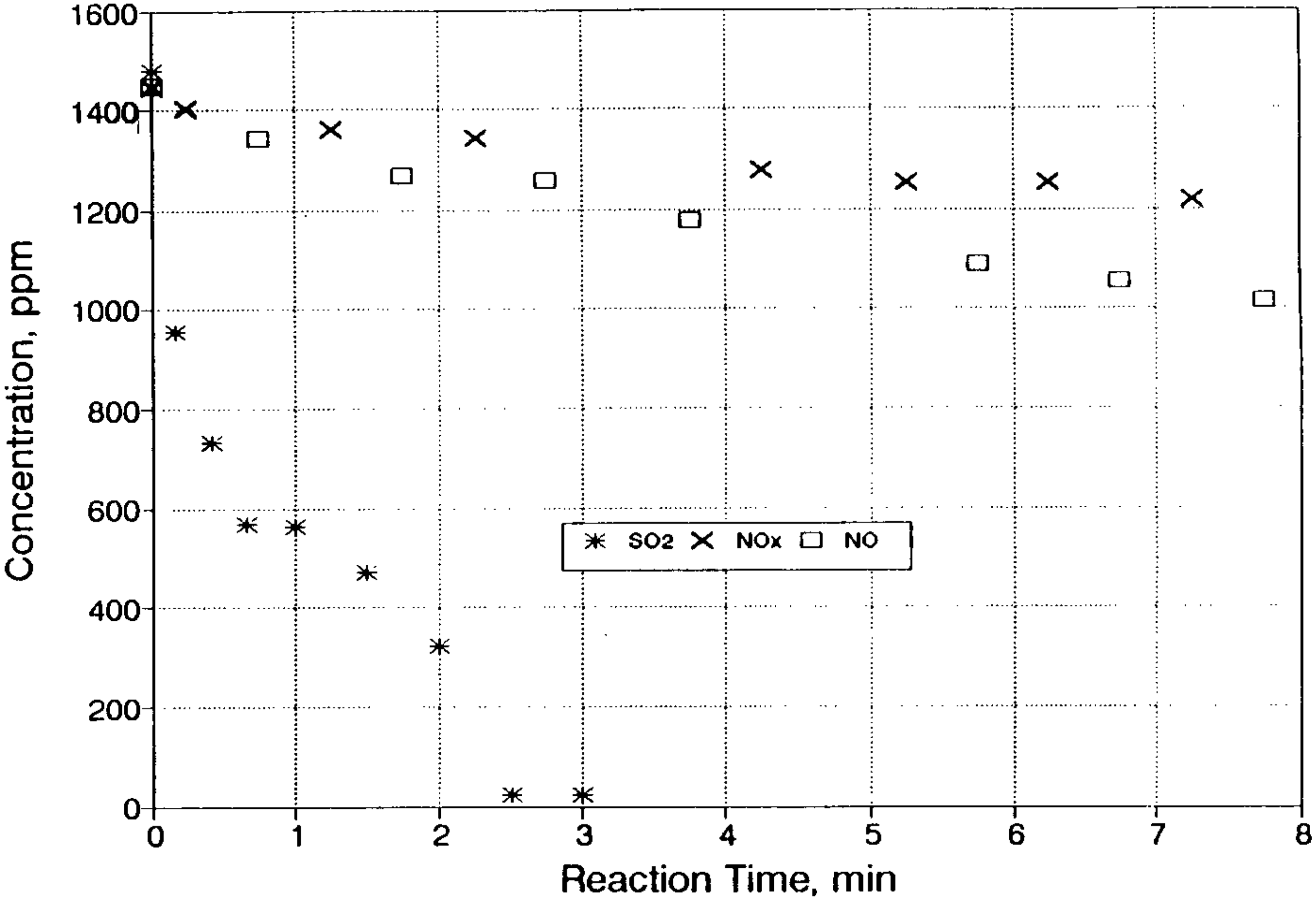
NSR=3.4, Water=5%, 260F, 700 rpm, 53um< d <63um

Figure A16. 05-25-93 : SO2 and NOx Removal by Sodium Bicarbonate



NSR=3.4, Water=5%, 260F, 700 rpm, 53um< d <63um

Figure A17. 05-27-93 : SO2 and NOx Removal by Sodium Sesquicarbonate



NSR=3.4, Water=5%, 260F, 700 rpm, 53um< d <63um

Figure A18. 05-31-93 : SO2 and NOx Removal by Sodium Bicarbonate

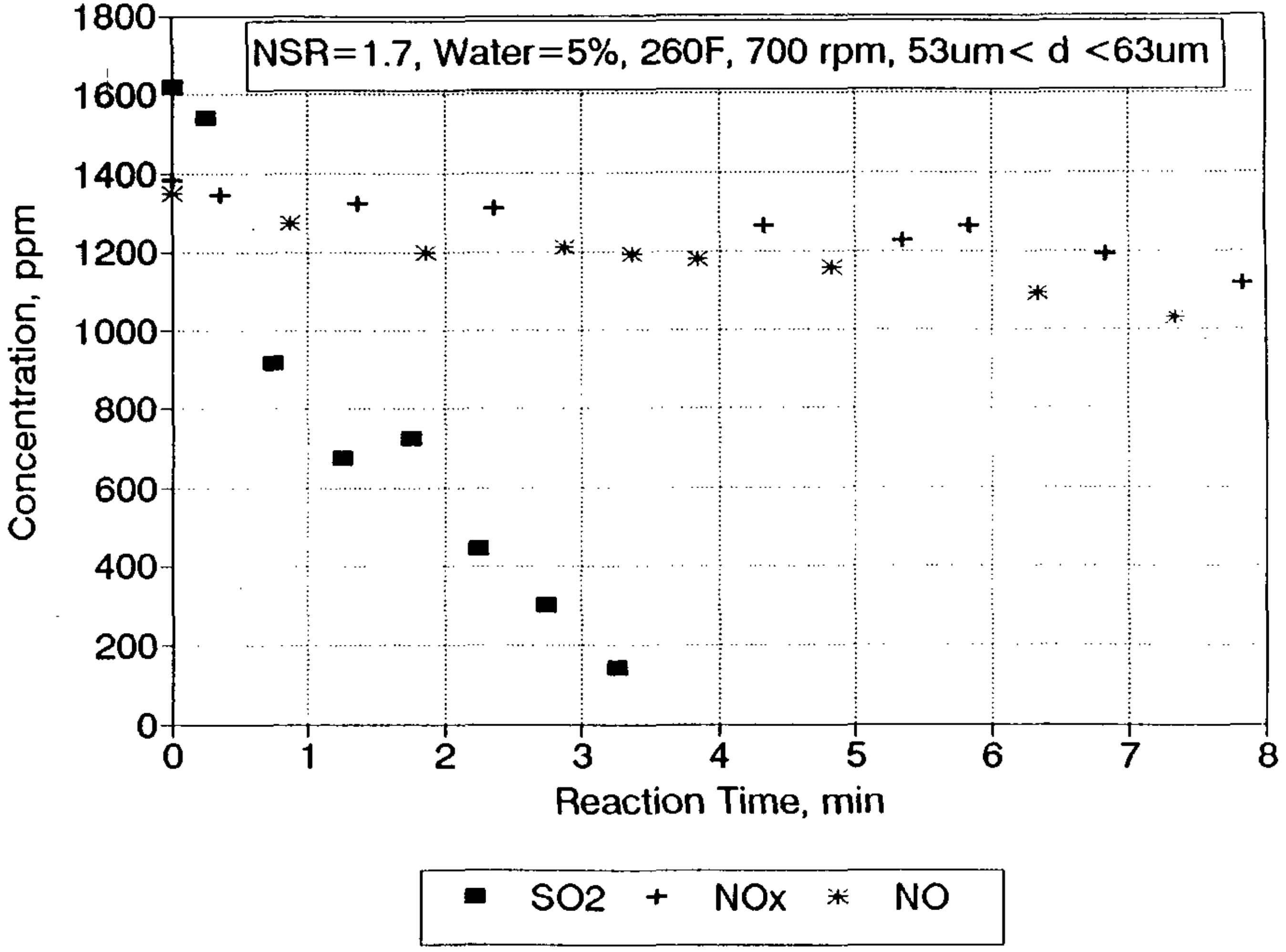


Figure A19. 06-17-93 : SO2 and NOx Removal by Sodium Sesquicarbonate

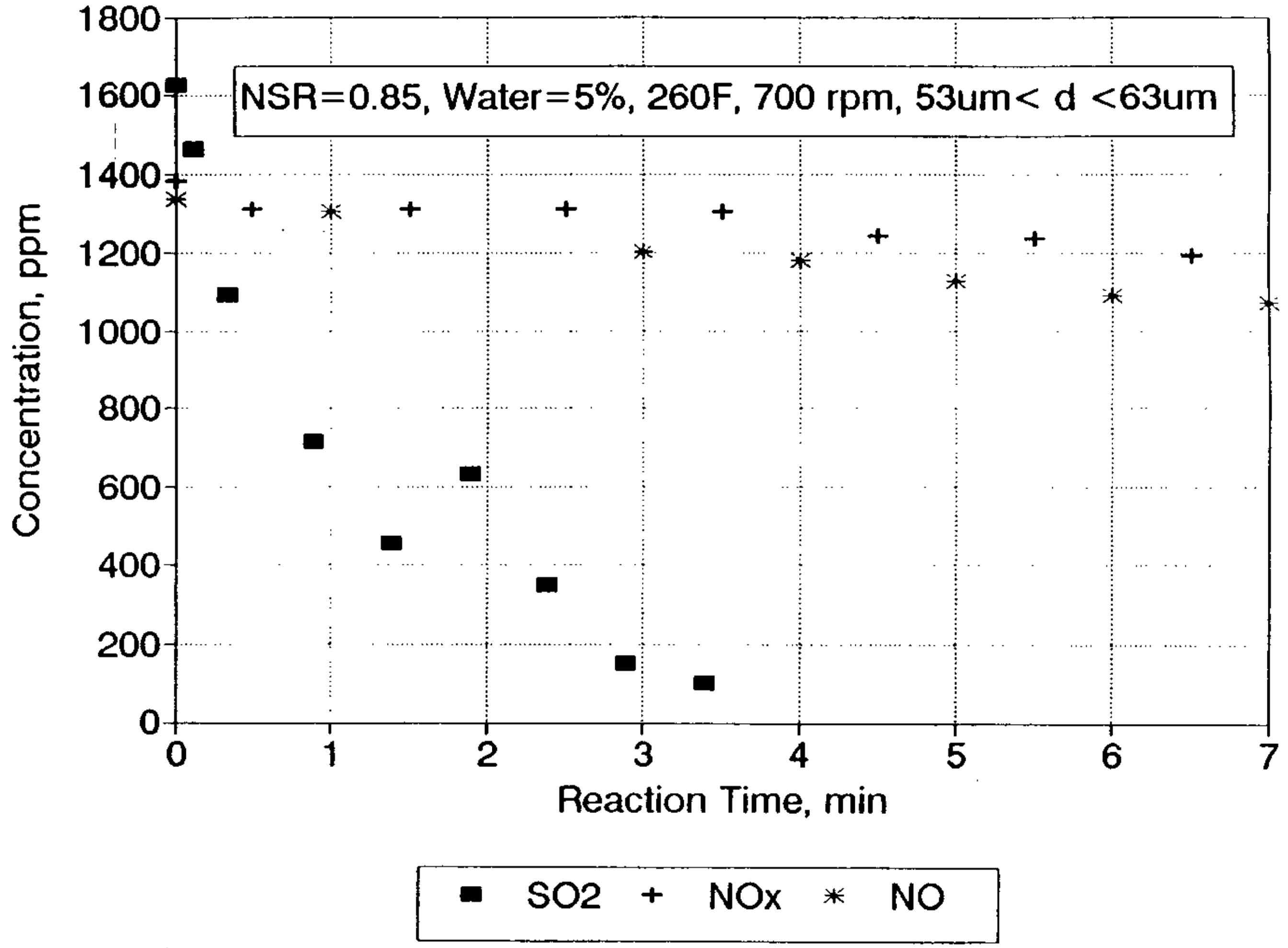


Figure A20. 06-18-93 : SO2 and NOx Removal by Sodium Sesquicarbonate

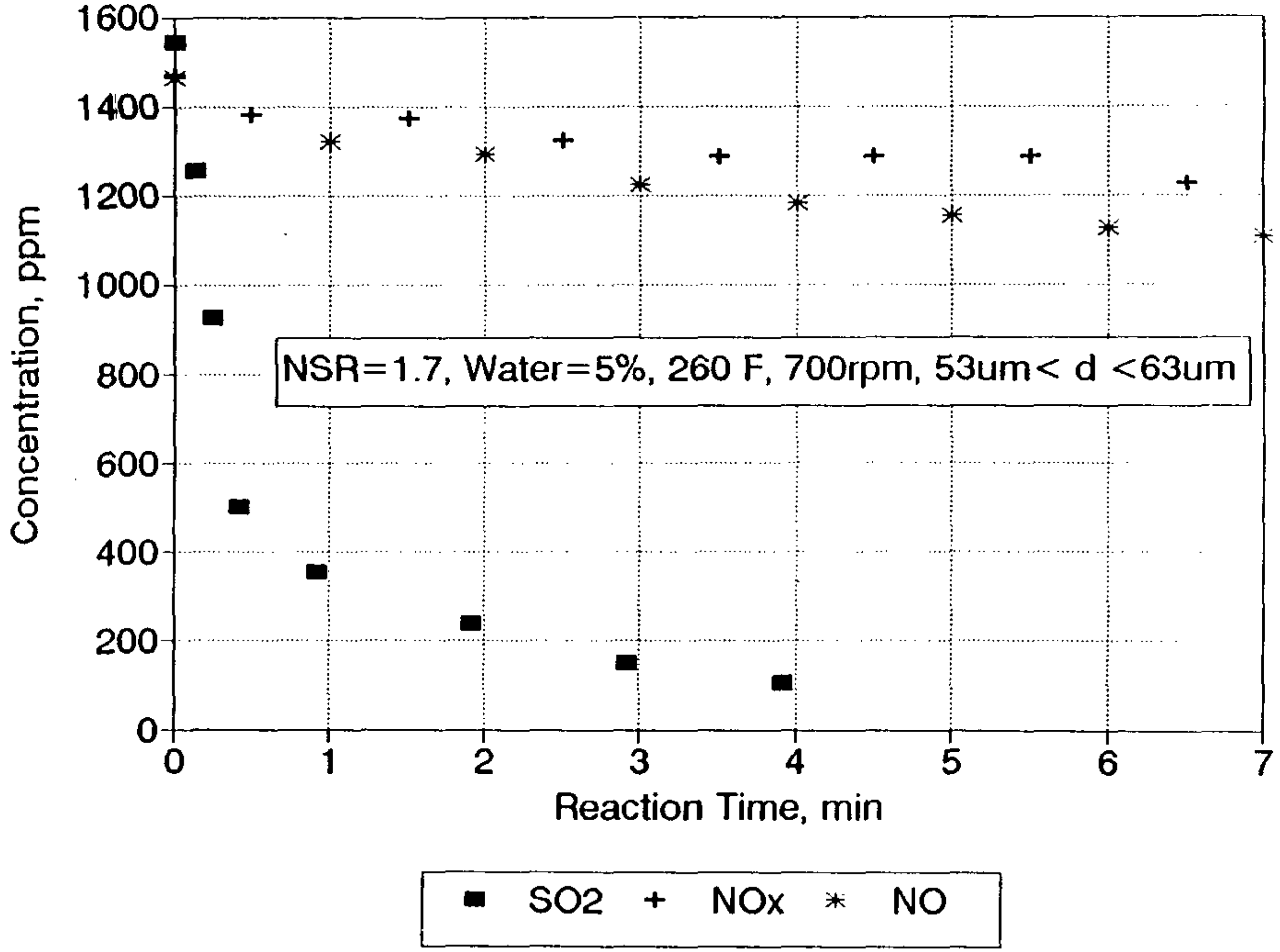


Figure A21. 06-21-93 : SO2 and NOx Removal by Sodium Sesquicarbonate

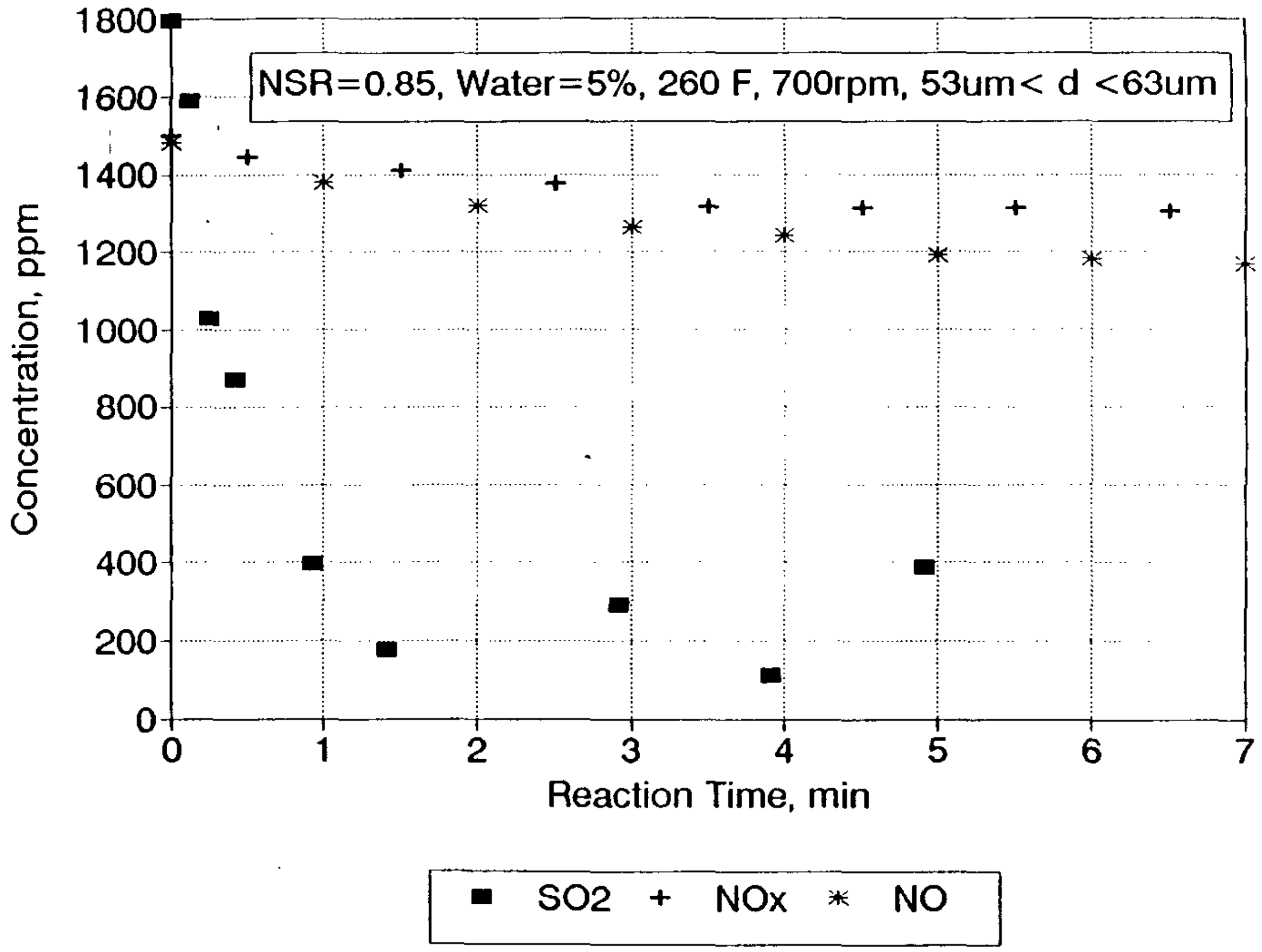


Figure A22. 06-22-93 : SO2 and NOx Removal by Sodium Sesquicarbonate

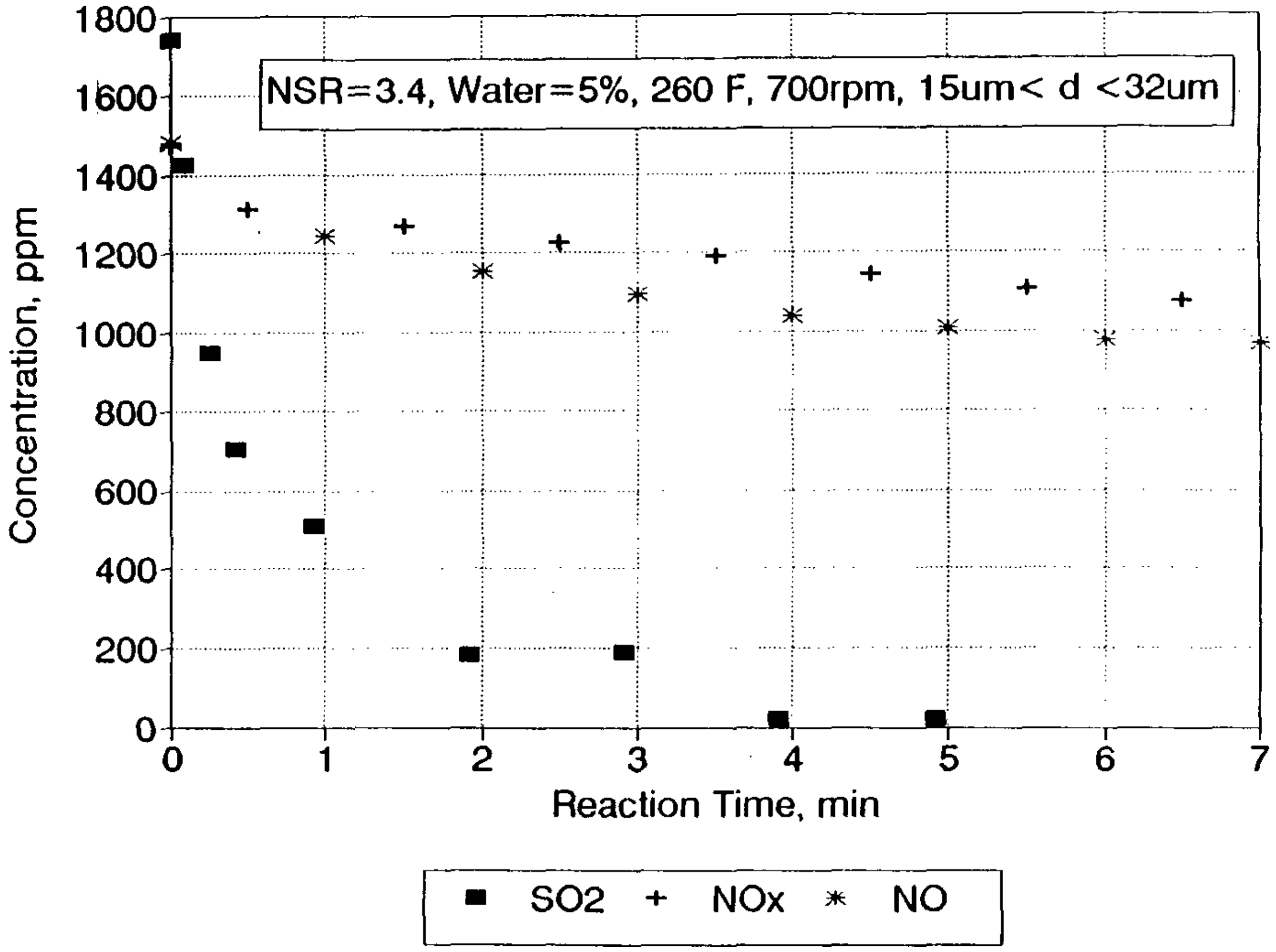


Figure A23. 06-23-93 : SO2 and NOx Removal by Sodium Sesquicarbonate

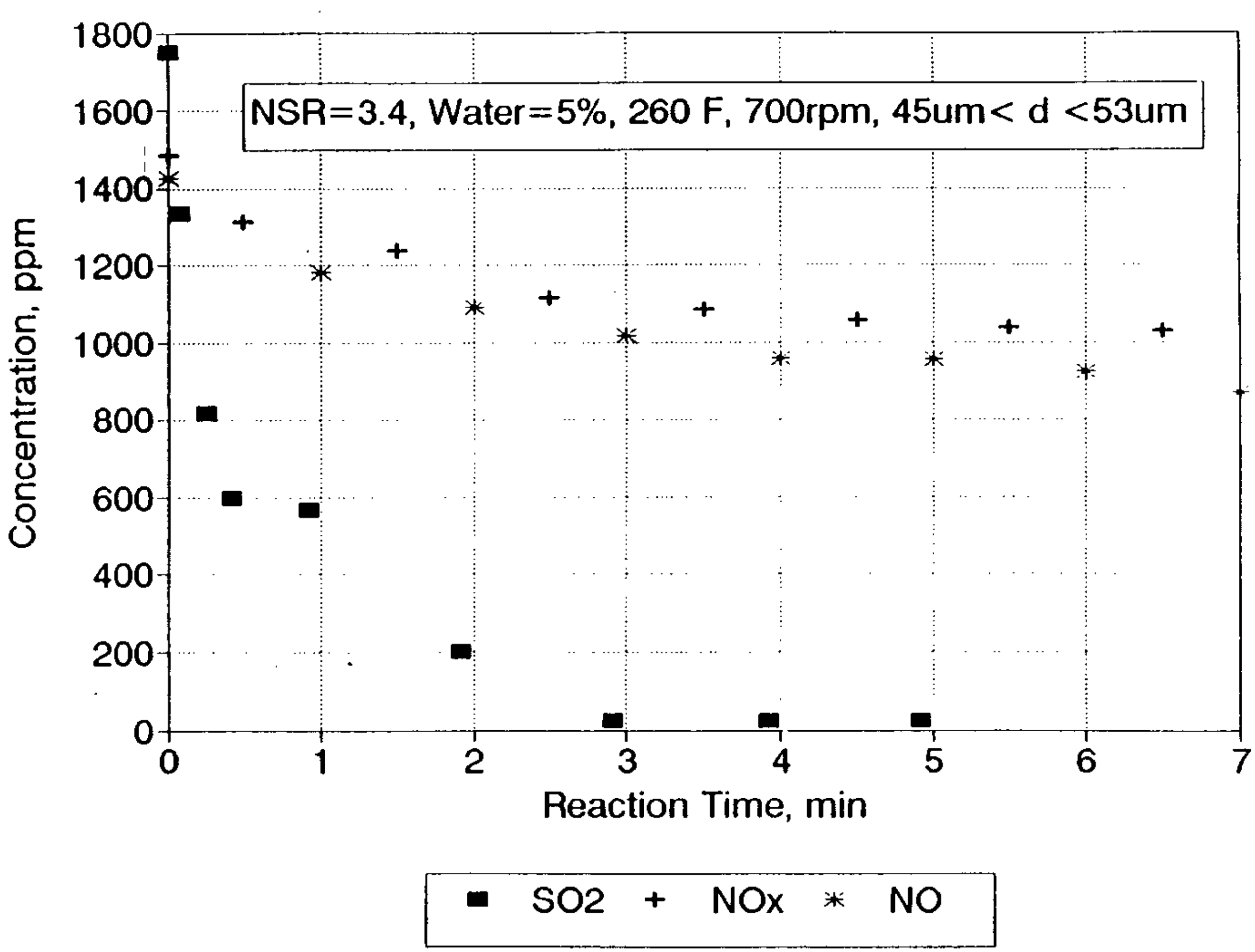
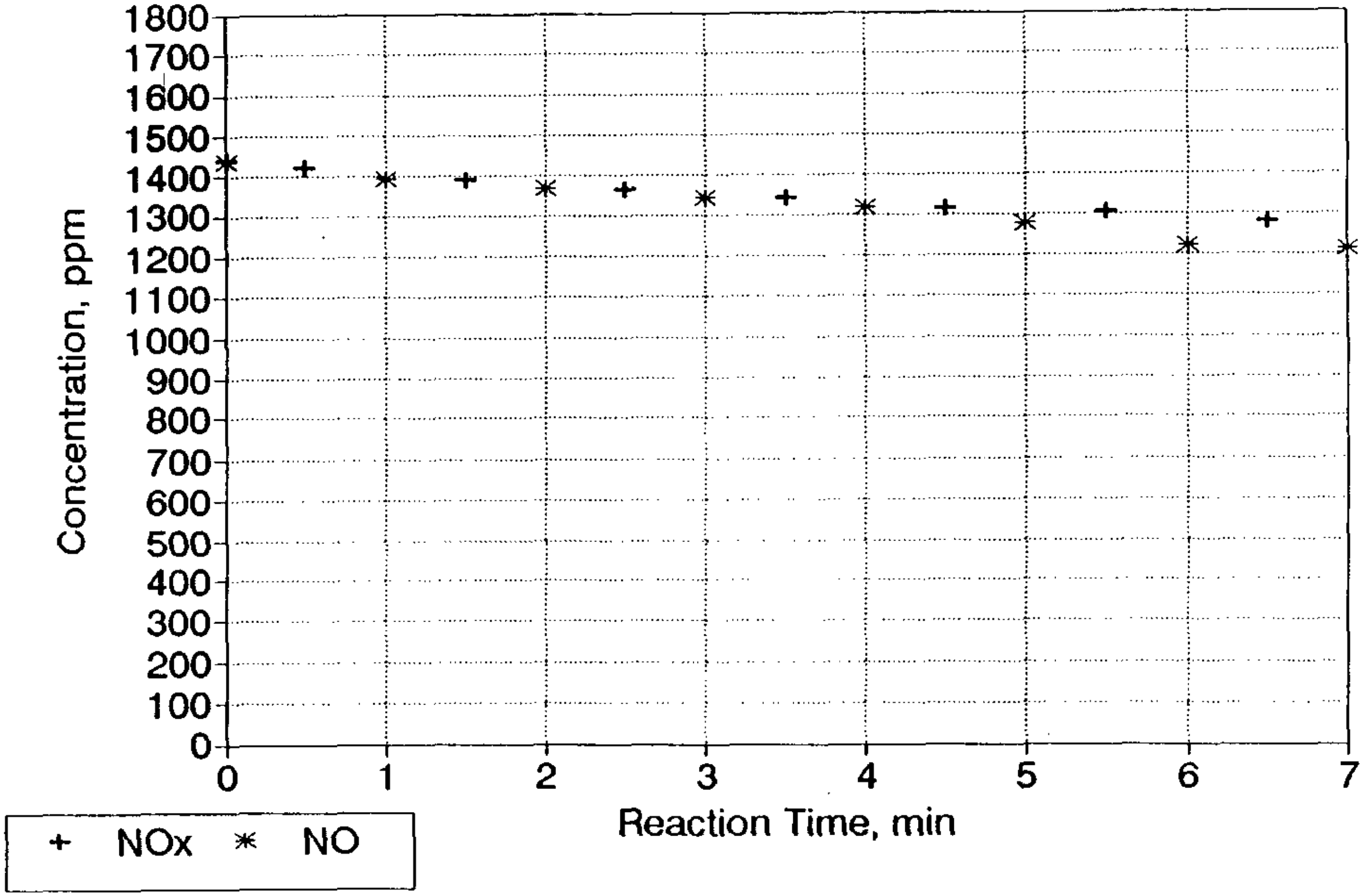


Figure A24. 06-23-93 : SO2 and NOx Removal by Sodium Sesquicarbonate



NSR=2, Water=5%, 260 F, 700rpm, 53um< d <63um

Figure A25. 06-25-93 : NO and NOx Removed by Sodium Sulfite

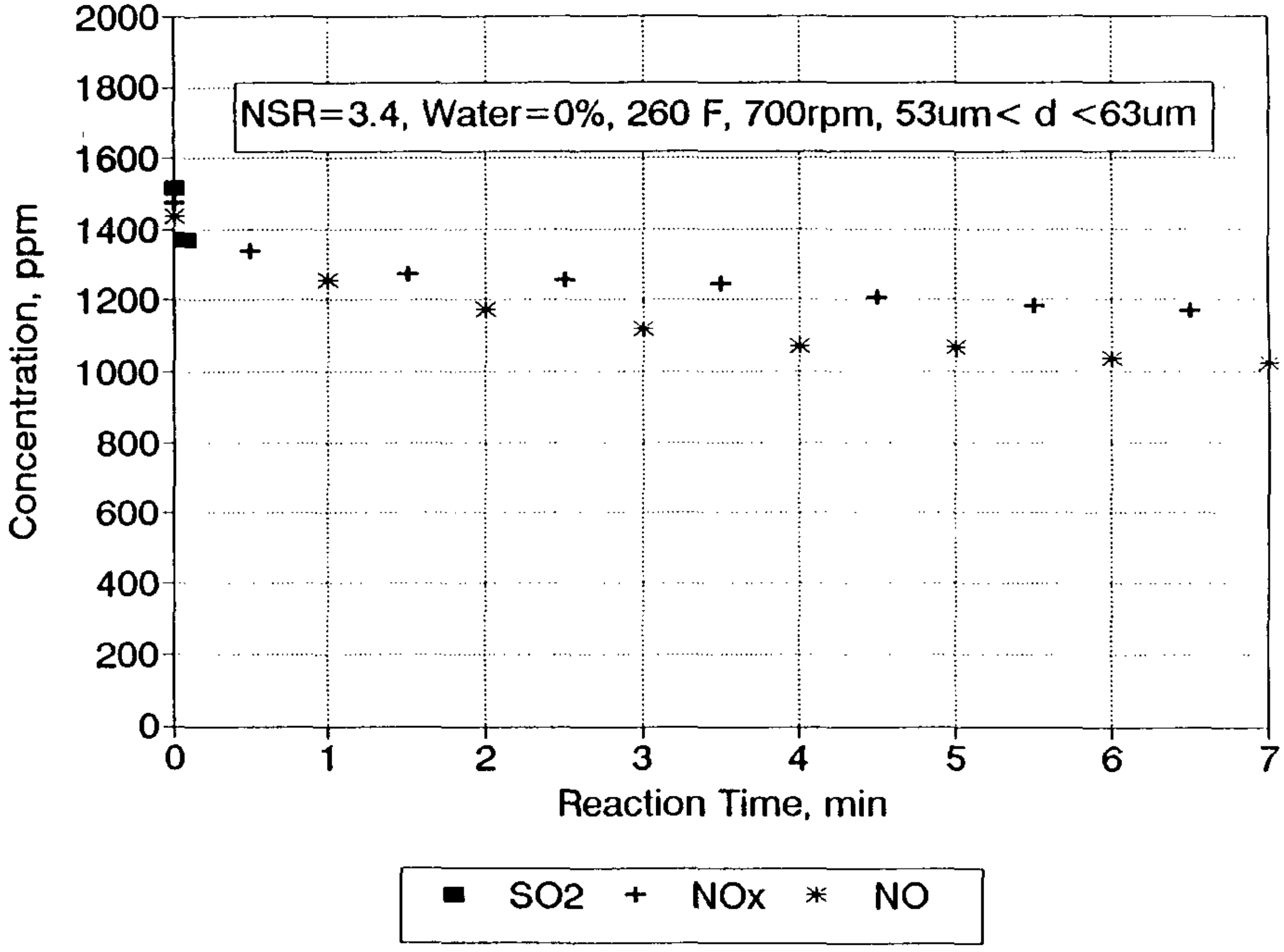


Figure A26. 07-22-93 : SO2 and NOx Removal by Sodium Sesquicarbonate

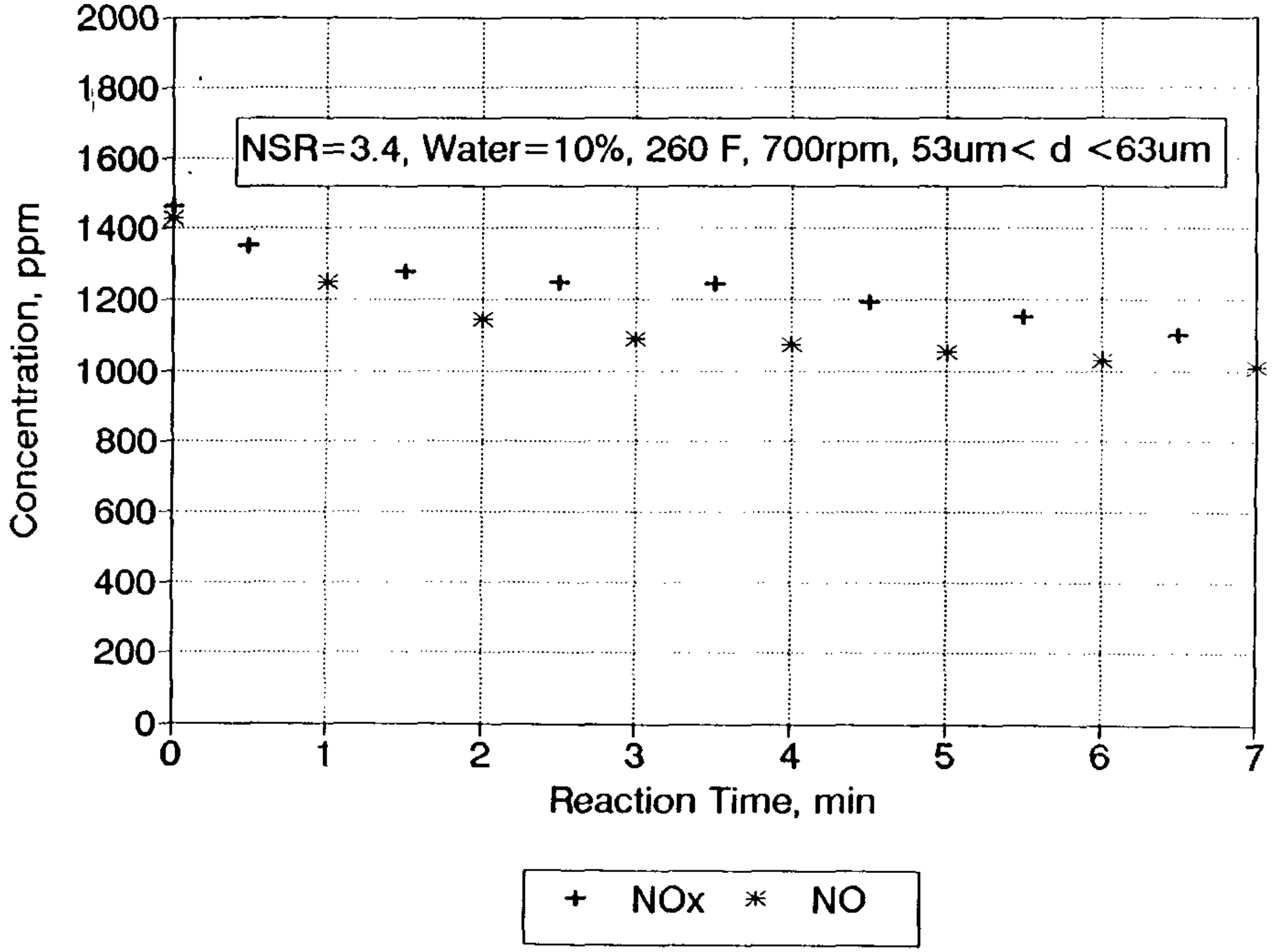


Figure A27. 07-22-93 : SO2 and NOx Removal by Sodium Sesquicarbonate

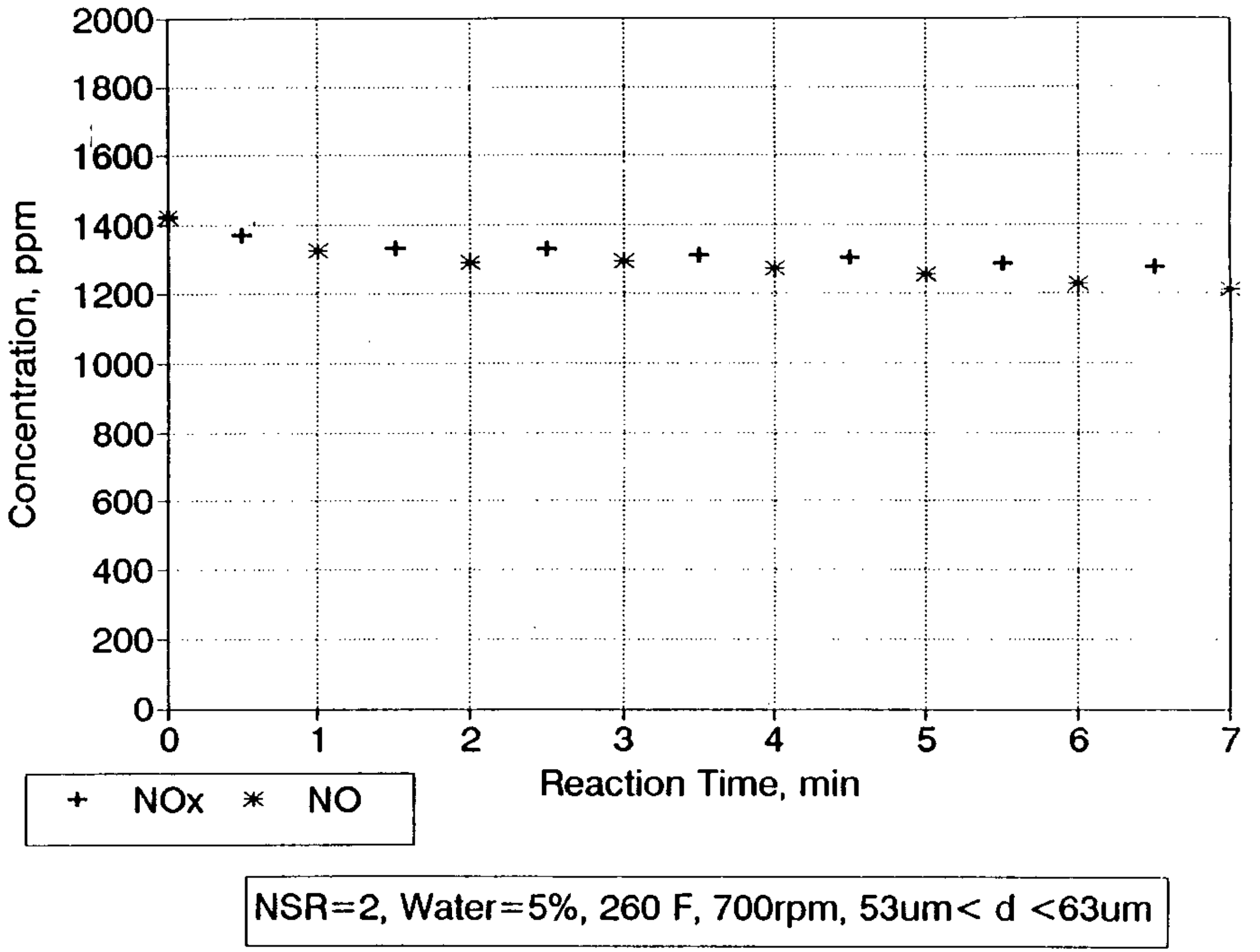


Figure A28. 07-24-93 : NO and NOx Removed by Sodium Sulfite

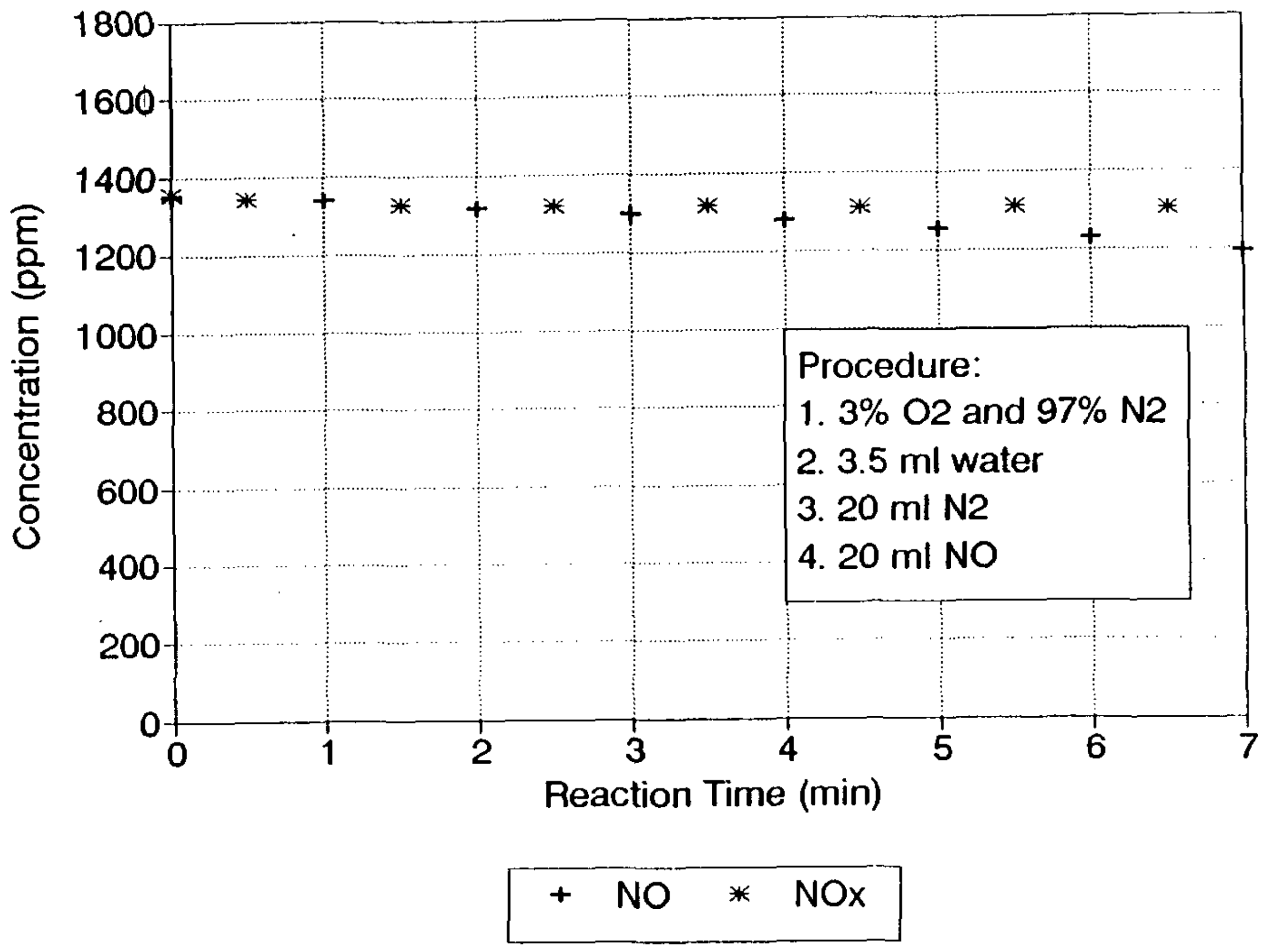


Figure A29. 08-01-93 : Blank test without SO2

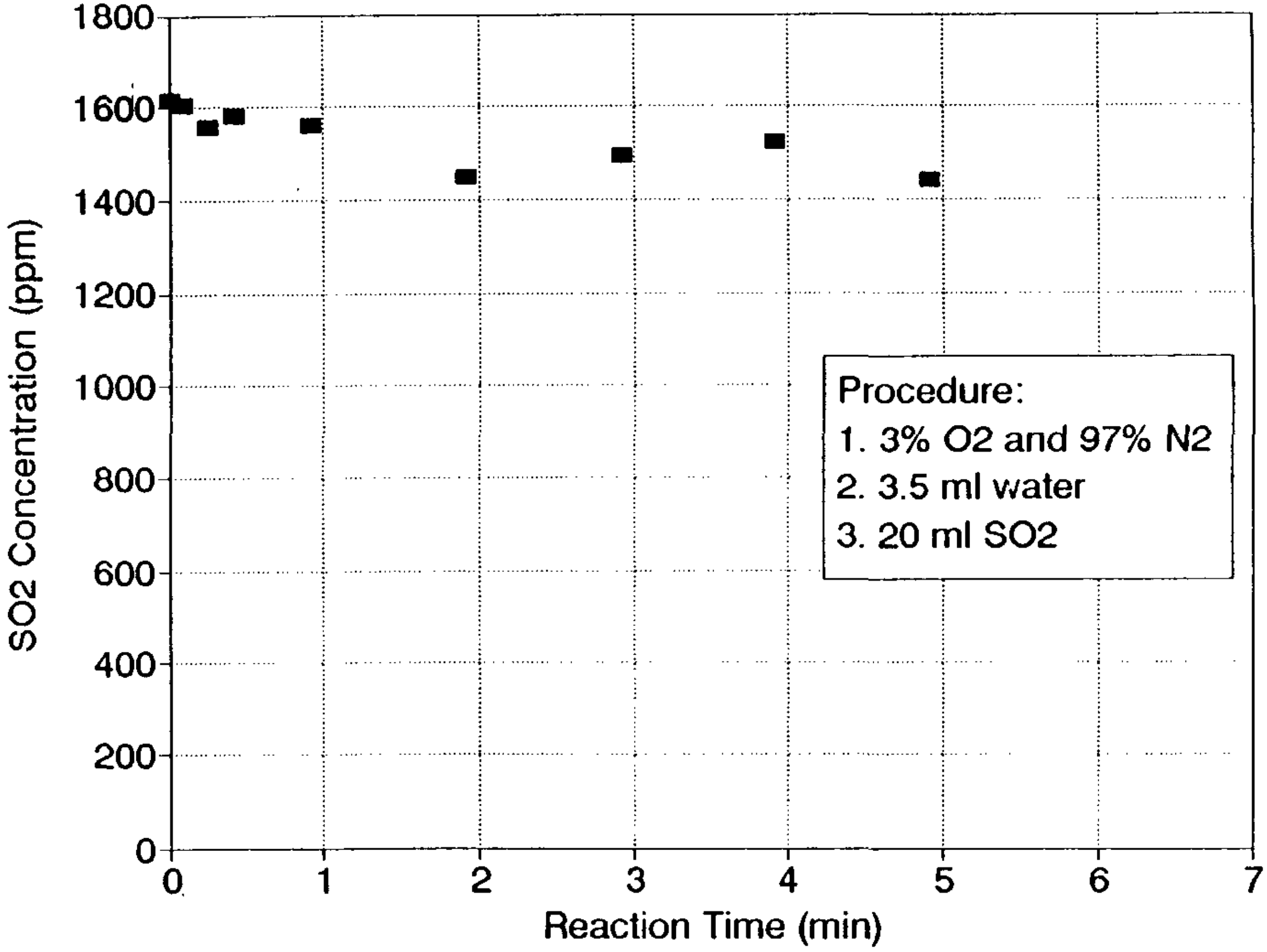


Figure A30. 08-07-93 : Blank test without NOx

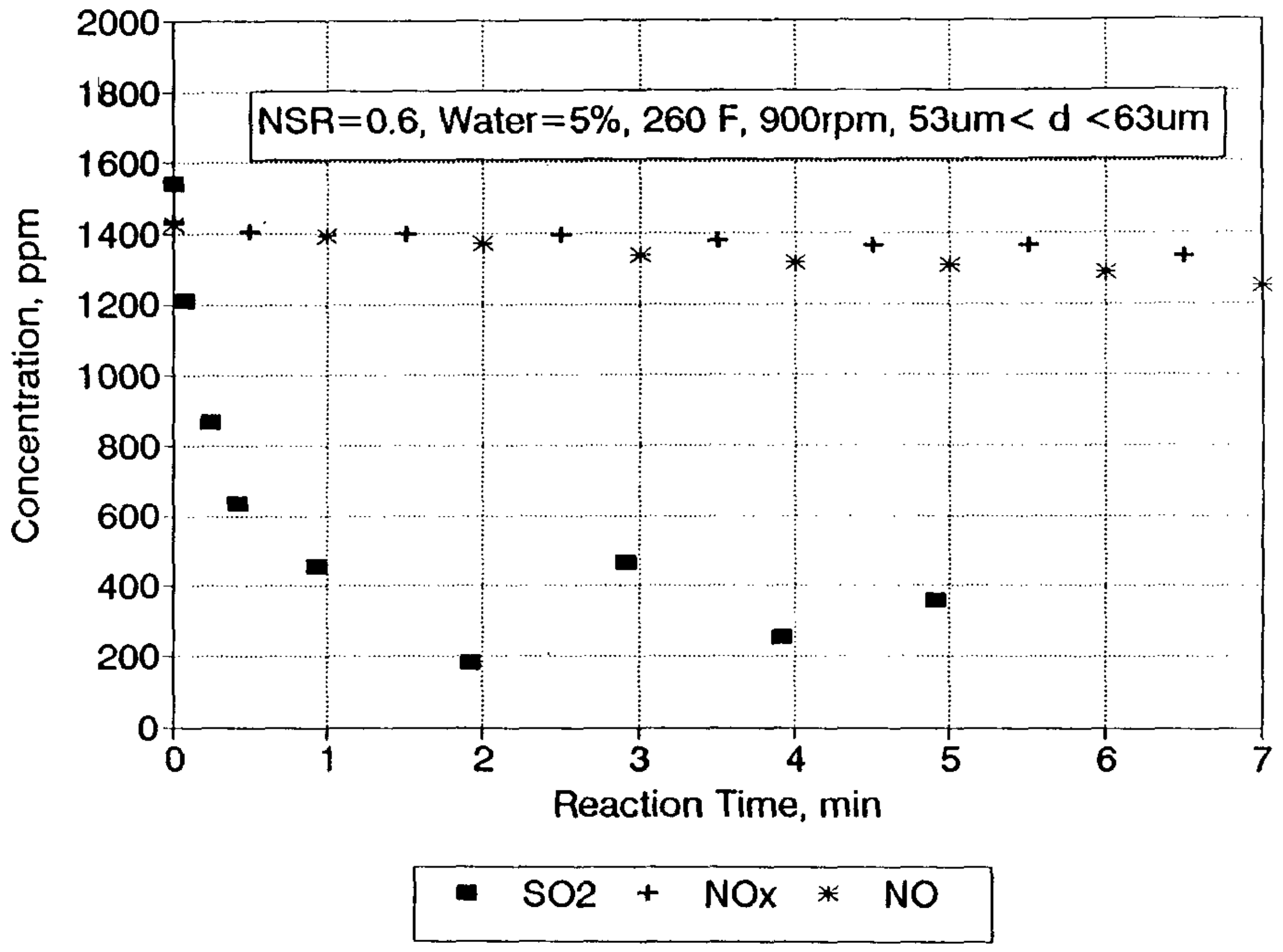


Figure A31. 08-07-93 : SO2 and NOx Removal by Sodium Bicarbonate

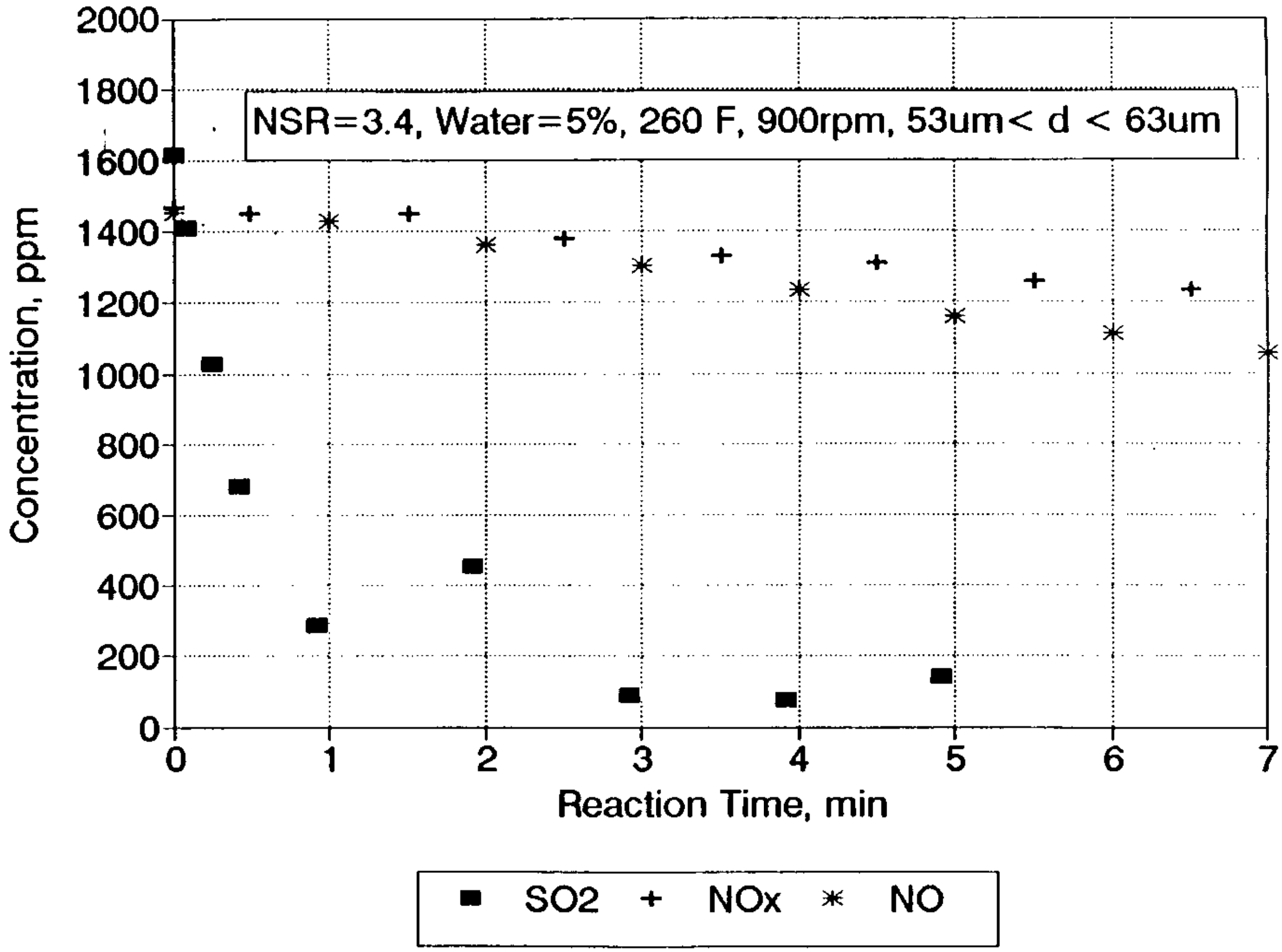
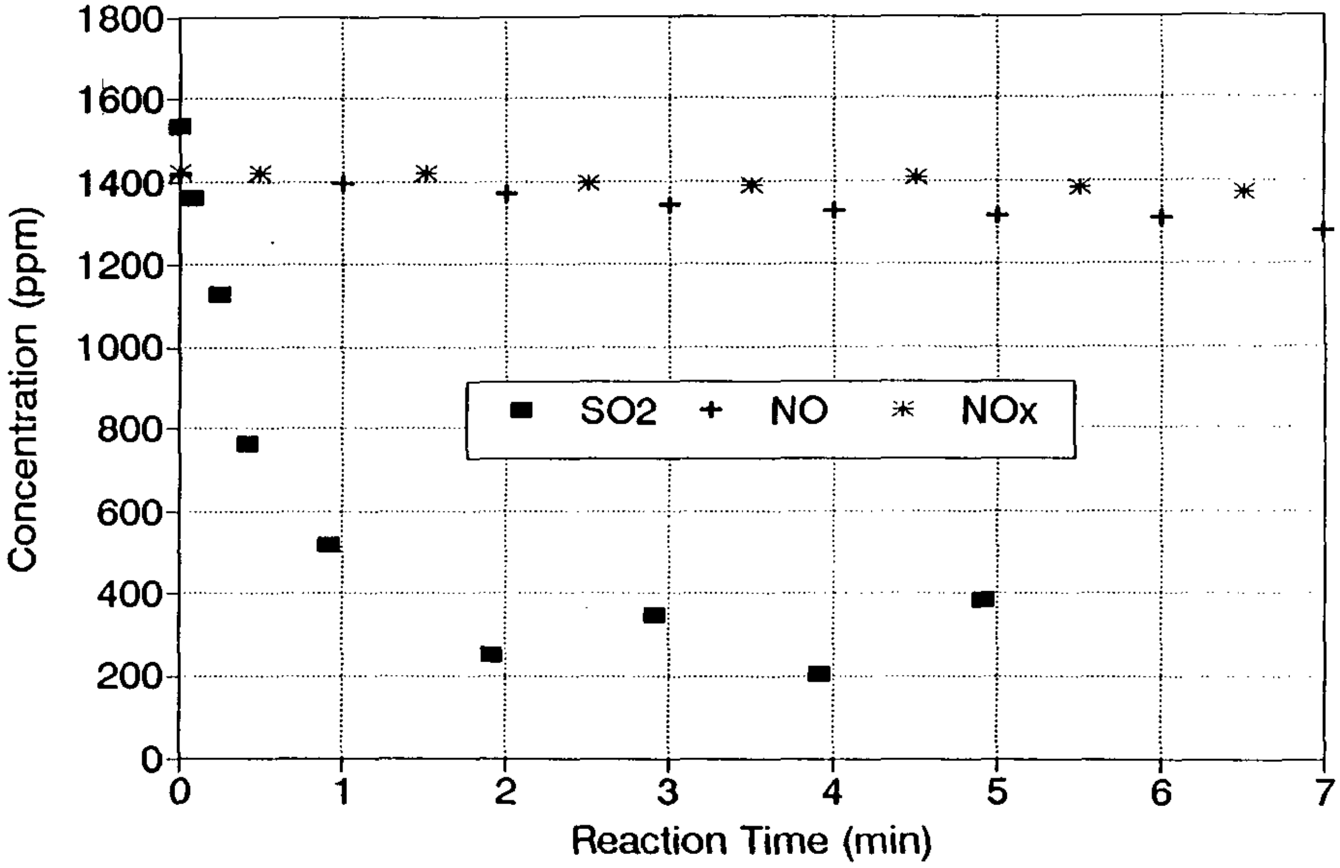


Figure A32. 08-08-93 : SO2 and NOx Removal by Sodium Bicarbonate



NSR=0, Water=5%, 260F, 700 rpm

Figure A33. 08-08-93 : SO2 and NOx Reduction without Dry Sorbent

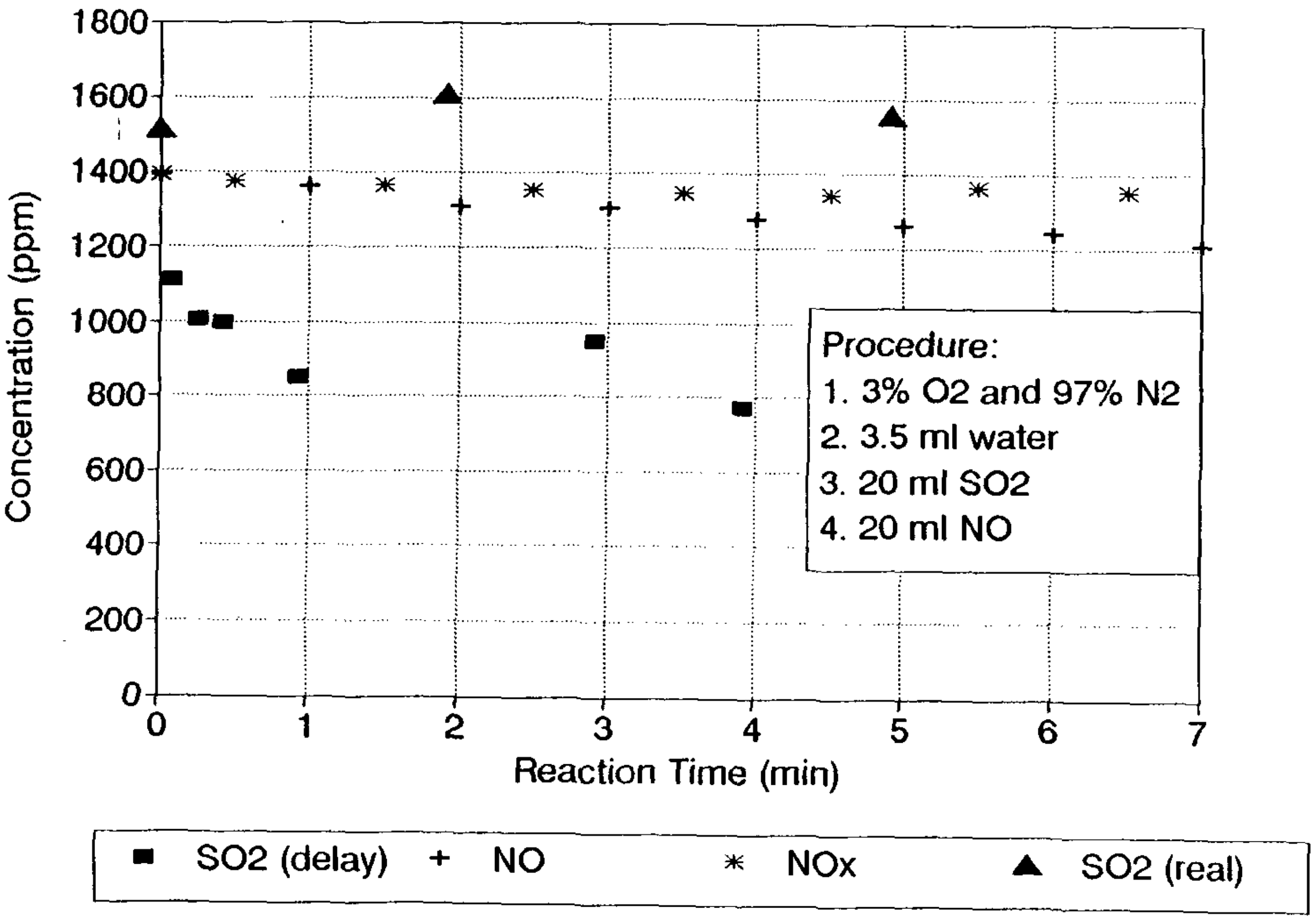
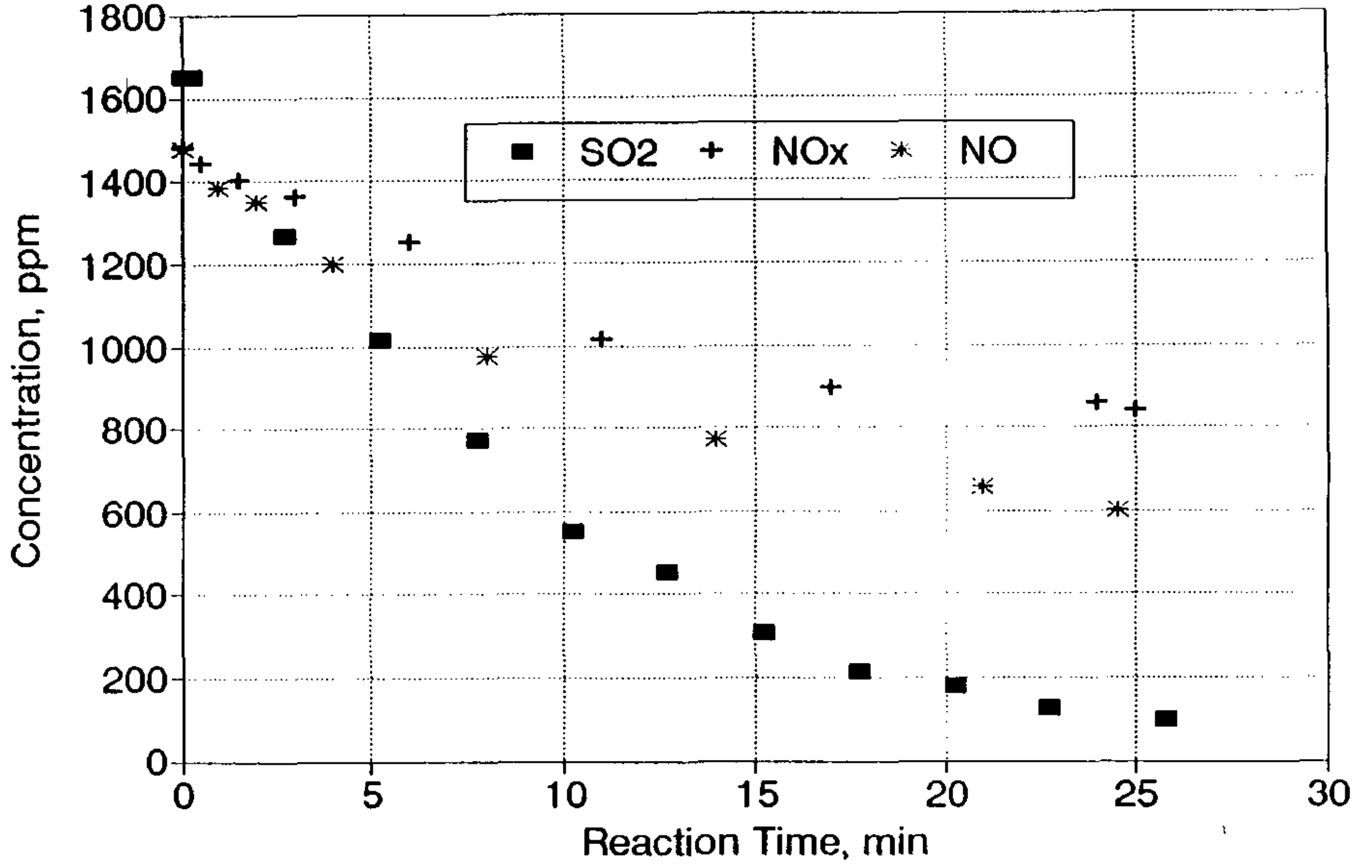


Figure A34. 08-10-93 : SO2 and NOx Reduction without Dry Sorbent



NSR=3.4, 260 F, 700rpm, 5% Water

Figure A35. 08-10-93 : SO2 and NOx Removed by Sodium Bicarbonate

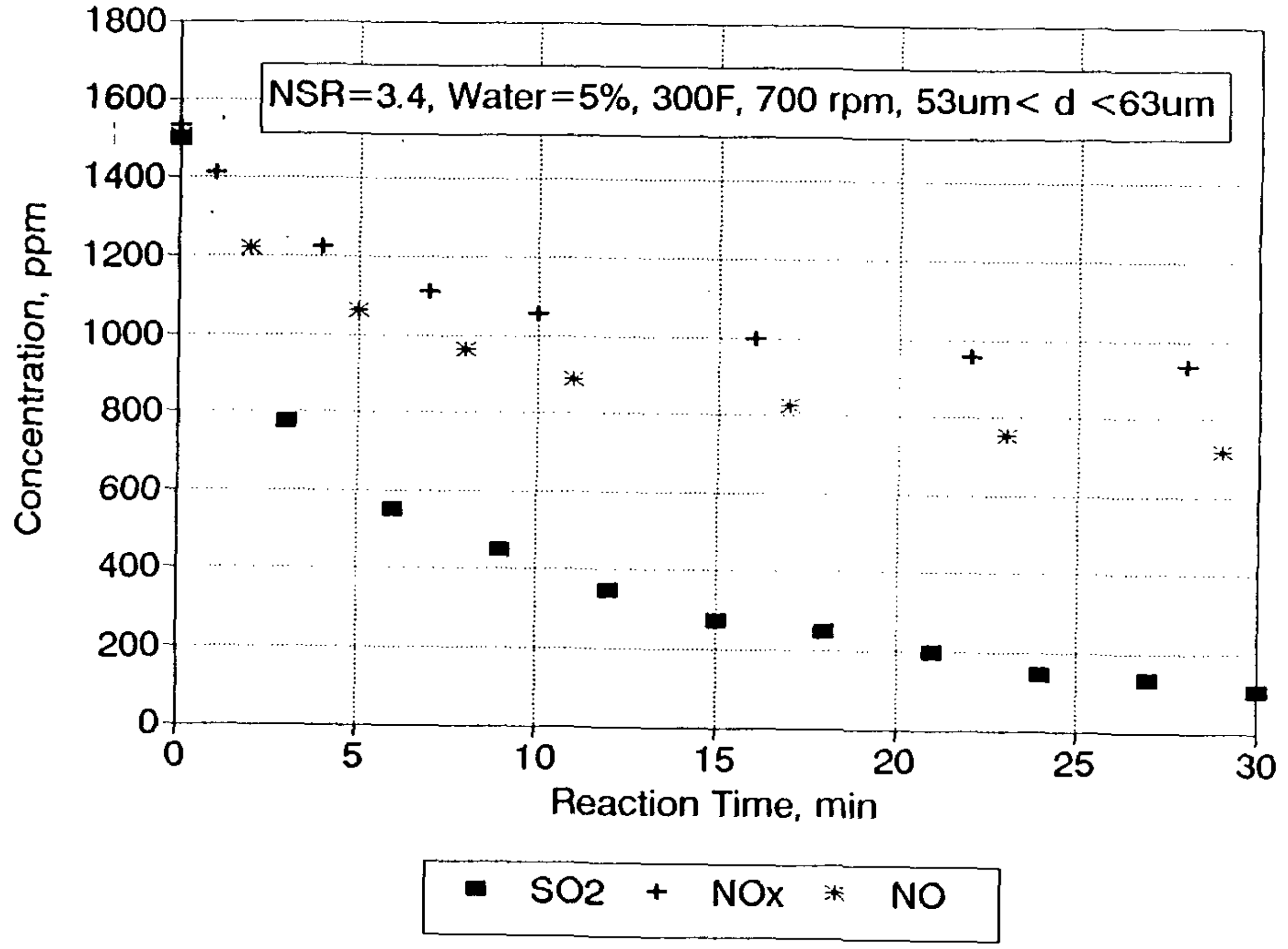


Figure A36. 09-20-93: SO2 and NOx Removal by Sodium Sesquicarbonate

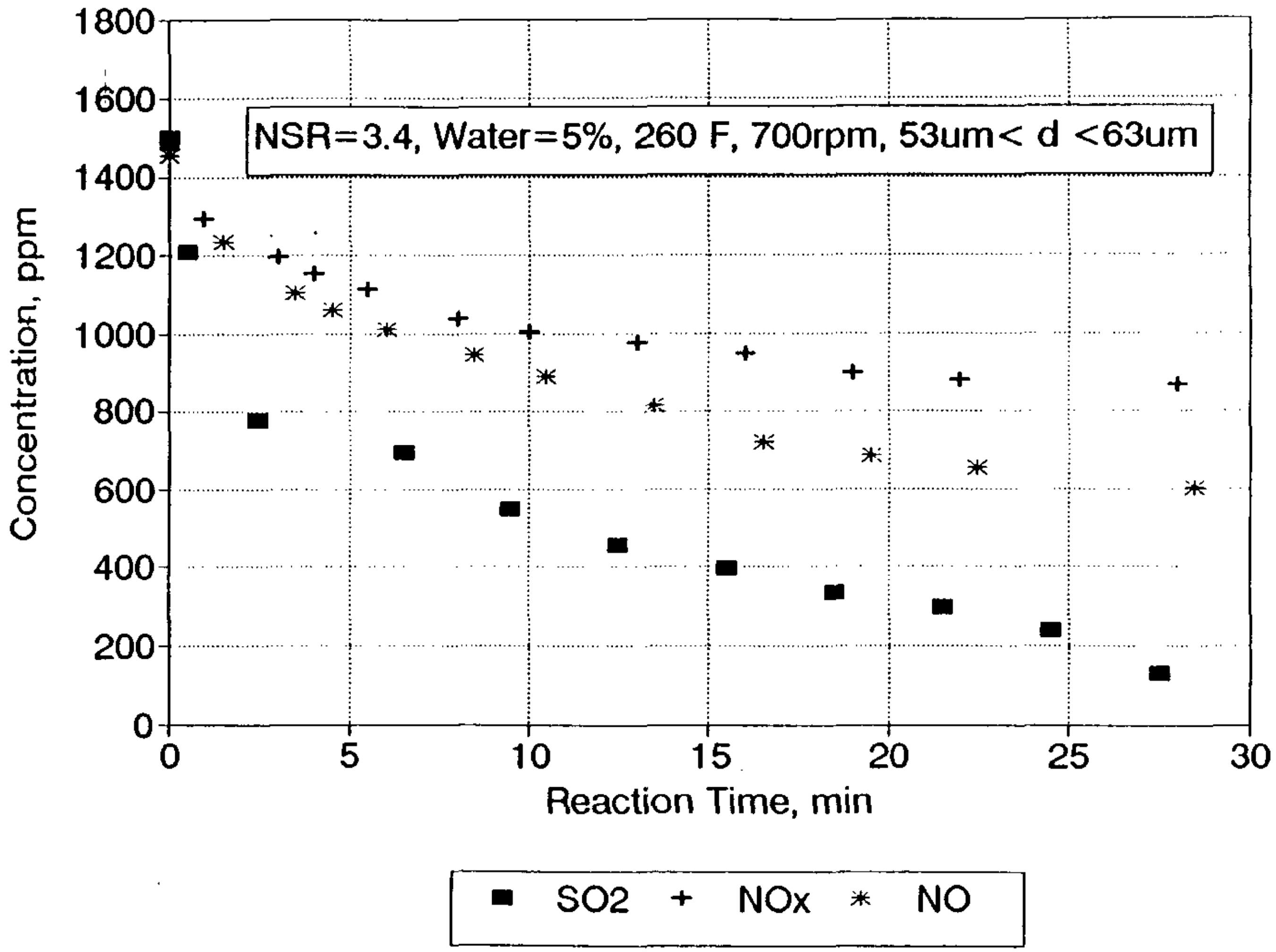


Figure A37. 10-21-93 : SO2 and NOx Removal by Sodium Sesquicarbonate

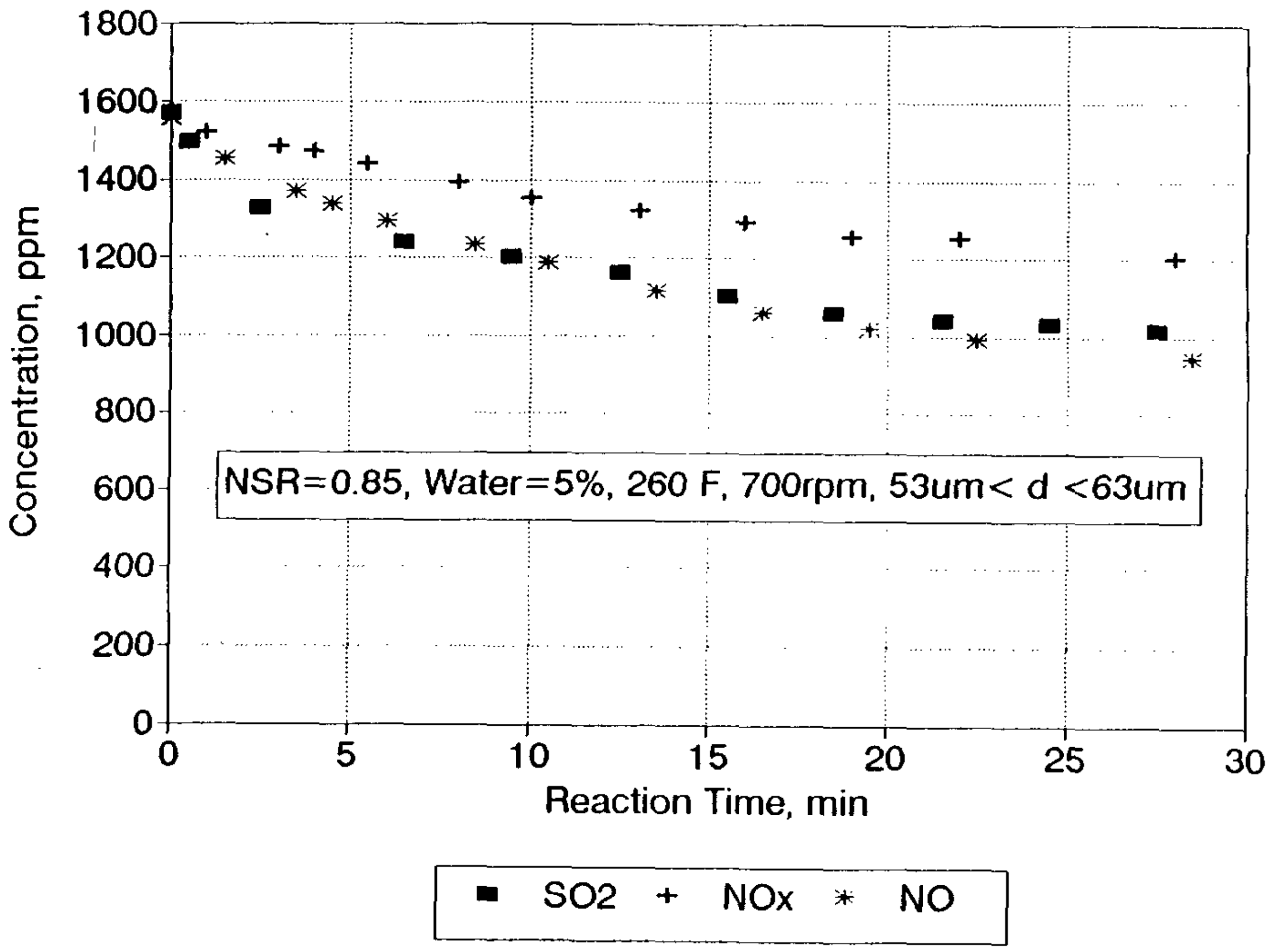


Figure A38. 10-22-93 : SO2 and NOx Removal by Sodium Sesquicarbonate

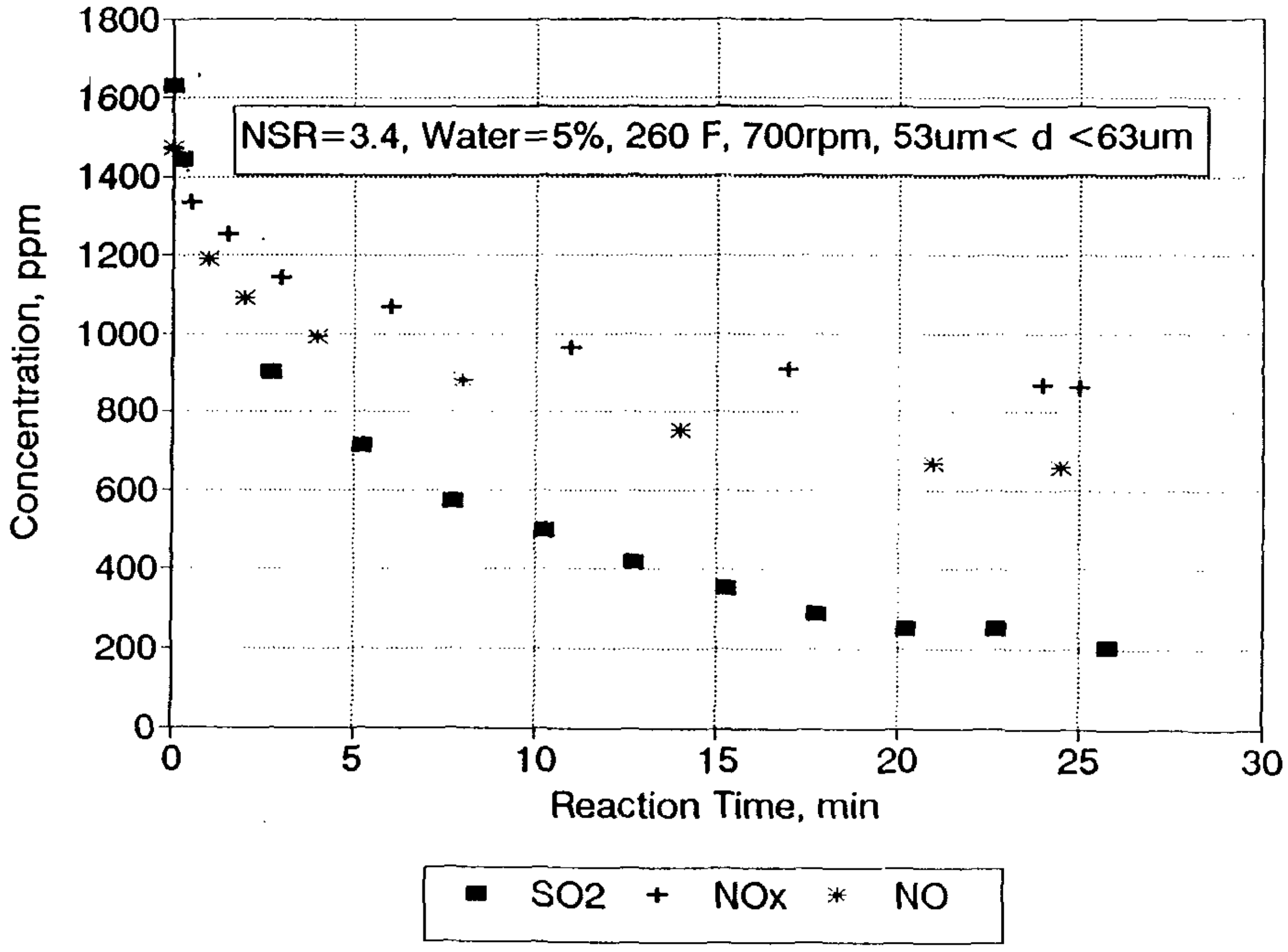


Figure A39. 10-24-93 : SO2 and NOx Removal by Sodium Sesquicarbonate

## Table A1: SO2 and NOx Removal by Sodium Bicarbonate

Date : 02-19-93
Sorbent: NaHCO3
Water(%) 3.5

Temp.(F) 300
rpm : 300
NSR : 13.5
Size(um) (53, 63)

| Time (min) | SO2/Air (Ratio) | SO2 (ppm) | NOx (Index) | NO (Index) | NOx (ppm) | NO (ppm) |
|---|---|---|---|---|---|---|
| 0 | 0.00395 | 1458.996 | 22.3 | 17.5 | 1311.835 | 976.0427 |
| 0.5 | 0.001731 | 652.0435 | | | | |
| 1 | | | 19 | | 1113.732 | |
| 1.5 | | | | 13.5 | | 745.999 |
| 2 | 0.001175 | 449.6815 | | | | |
| 2.5 | | | 17.5 | | 1023.685 | |
| 3 | | | | 12.5 | | 688.488 |
| 3.5 | 0.000113 | 63.39763 | | | | |
| 4 | | | | 11.8 | | 648.2304 |
| 4.5 | | | | 11.7 | | 642.4793 |
| 5 | 0.000226 | 104.5114 | | | | |
| 5.5 | | | 15.5 | | 903.6226 | |
| 6 | | | | 10 | | 544.7107 |
| 6.5 | 3.08E-05 | 33.67326 | | | | |
| 7 | | | 14.5 | | 843.5914 | |
| 8 | | | | 9.5 | | 515.9553 |
| 8.5 | 0 | 22.47273 | | | | |
| 9.5 | | | 14 | | 813.5758 | |
| 10 | | | | 8.7 | | 495.4103 |
| 12 | | | 13.5 | | 783.5602 | |
| 13 | | | | 8.5 | | 483.4041 |
| 15 | | | 13.5 | | 783.5602 | |
| 16 | | | | 8 | | 453.3885 |
| 24 | | | 12.8 | | 741.5383 | |
| 25 | | | | 7.5 | | 423.3729 |
| 36 | | | 12.5 | | | |

```
     43                          7.5       423.3729
     54                     12        693.5133
==========================================
```

Table A2. SO2 and NOx Removal by Sodium Bicarbonate

Date : 03-13-93
*Sorbent:* NaHCO3
Water(%) 3

Temp.(F) 300
*rpm :* *300*
NSR : 13.5
Size(um) (53, 63)

| Time (min) | SO2/Air (Ratio) | SO2 (ppm) | NOx (Index) | NO (Index) | NOx (ppm) | NO (ppm) |
|---|---|---|---|---|---|---|
| 0 | 0.004064 | 1500.323 | | | | |
| 0.5 | 0.001014 | 391.227 | | | | |
| 1 | 0.000359 | 153.0678 | | | | |
| 2 | 0 | 22.47273 | | | | |
| 15 | | | 26 | | 1533.95 | |
| 16 | | | | 26.7 | | 1505.143 |
| 20 | | | | 24.5 | | 1378.619 |
| 21 | | | 23.7 | | 1395.879 | |
| 23 | | | 23 | | 1353.857 | |
| 24 | | | | 22.6 | | 1269.348 |
| 25 | | | 22.3 | | 1311.835 | |
| 26 | | | | 22 | | 1234.842 |
| 28 | | | 21.4 | | 1257.807 | |
| 30 | | | | 20.7 | | 1160.078 |
| 32 | | | 20.5 | | 1203.779 | |
| 34 | | | | 19.9 | | 1114.069 |
| 36 | | | 20 | | 1173.763 | |
| 38 | | | | 19.3 | | 1079.562 |
| 40 | | | 19.6 | | 1149.751 | |

Table A3-1. Comparison between the NOx System with SO2 and the NOx System without SO2.

| | | | |
|---|---|---|---|
| Date : 03-21-93 | | Water(%): | 3.5 |
| Sorbent : | Blank | Temp(F) : | 300 |
| | | rpm : | 300 |

(1) RUN #1 (without SO2) :

| Time (min) | NO Index | NOx Index | NO ppm | NOx ppm | NO2 ppm |
|---|---|---|---|---|---|
| 0 | 24.5 | 23.4 | 1378.619 | 1377.869 | |
| 11 | 23.5 | 22.9 | 1321.108 | 1347.854 | |
| 20 | 22.3 | 22.6 | 1252.095 | 1329.844 | |
| 27 | 21.1 | 22.2 | 1183.082 | 1305.832 | |
| 32 | 20.5 | 21.9 | 1148.575 | 1287.822 | |
| 39 | 19.7 | 21.4 | 1102.567 | 1257.807 | |

Table A3-2. Comparison between the NOx System with SO2 and the NOx System without SO2.

(2) RUN #2 (with SO2) :

| Time (min) | NO Index | NOx Index | NO ppm | NOx ppm |
|---|---|---|---|---|
| 0 | 23.7 | 22.8 | 1332.61 | 1341.85 |
| 1 | 22.5 | | 1263.597 | |
| 3 | | 22.4 | | 1317.838 |
| 3.5 | 21.8 | | 1223.34 | |
| 9 | | 22 | | 1293.825 |
| 10 | 20.6 | | 1154.326 | |
| 15 | | 21.9 | | 1287.822 |
| 16 | 19.5 | | 1091.064 | |
| 17.5 | | 21.4 | | 1257.807 |
| 18.5 | | 21.4 | | 1257.807 |
| 19.5 | 19.1 | | 1068.06 | |
| 20.5 | | 21.2 | | 1245.801 |
| 21.5 | 18.7 | | 1045.056 | |
| 24 | | 20.9 | | 1227.791 |
| 25 | 18.1 | | 1010.549 | |
| 26.5 | 17.7 | | 987.5448 | |
| 29 | | 20.6 | | 1209.782 |
| 33 | | 20.4 | | 1197.776 |
| 35.5 | 16.3 | | 907.0295 | |
| 37 | | 20.2 | | 1185.769 |
| 39.5 | 15.8 | | 878.274 | |

Table A4. SO2 and NOx Removal by Sodium Bicarbonate

| | | | |
|---|---|---|---|
| Date : | 04-16-93 | Temp.(F) | 300 |
| Sorbent: | NaHCO3 | rpm : | 300 |
| Water(%) | 3.5 | NSR : | 13.5 |
| | | Size(um) | (53, 63) |

| Time (min) | SO2/Air (Ratio) | SO2 (ppm) | NOx (Index) | NO (Index) | NOx (ppm) | NO (ppm) |
|---|---|---|---|---|---|---|
| 0 | 0.00416 | 1535.272 | 22.5 | 21.8 | 1323.841 | 1223.34 |
| 0.33 | 0.002923 | 1085.521 | | | | |
| 0.5 | | | 21.5 | | 1263.81 | |
| 1 | 0.002186 | | | | | |
| 1.17 | | | | 18.5 | | 1033.554 |
| 2 | 0.001155 | 442.3976 | | | | |
| 3 | 0.000994 | 383.8403 | | | | |
| 3.5 | | | 16.5 | | 963.6538 | |
| 4 | 0.000257 | 115.9958 | | | | |
| 4.5 | | | | 12.5 | | 688.488 |
| 5 | 0 | 22.47273 | 15 | | 873.607 | |
| 6 | | | | 11.5 | | 630.9771 |
| 7 | | | 13.5 | | 783.5602 | |
| 8 | | | | 10.5 | | 573.4662 |
| 10 | | | 13 | | 753.5445 | |
| 12 | | | | 9.5 | | 515.9553 |
| 14 | | | 12.5 | | 723.5289 | |
| 16 | | | | 9.5 | | 515.9553 |
| 20 | | | 12 | | 693.5133 | |
| 25 | | | | 9 | | 487.1998 |
| 26 | | | 11.5 | | 663.4977 | |

Table A5. SO2 and NOx Removal by Sodium Bicarbonate

| | | | |
|---|---|---|---|
| Date : | 04-20-93 | Temp.(F) | 300 |
| Sorbent: | NaHCO3 | rpm : | 300 |
| Water(%) | 7 | NSR : | 13.5 |
| | | Size(um) | (53, 63) |

| Time (min) | SO2/Air (Ratio) | SO2 (ppm) | NOx (Index) | NO (Index) | NOx (ppm) | NO (ppm) |
|---|---|---|---|---|---|---|
| 0 | 0.003733 | 1379.881 | 26.5 | 27 | 1563.966 | 1522.396 |
| 0.50 | 0.002273 | 849.1706 | | | | |
| 0.67 | | | 24.5 | | 1443.904 | |
| 0.92 | 0.001545 | 584.1589 | | | | |
| 1.17 | | | | 23.8 | | 1338.362 |
| 1.42 | 0.001129 | 432.9685 | | | | |
| 1.67 | | | 23 | | 1353.857 | |
| 1.92 | 0.000753 | 296.1366 | | | | |
| 2.17 | | | | 22 | | 1234.842 |
| 2.42 | 0.000531 | 215.6276 | | | | |
| 2.67 | | | 21.8 | | 1281.819 | |
| 2.92 | 0.000354 | 151.2427 | | | | |
| 3.17 | | | | 20.2 | | 1131.322 |
| 3.42 | 0.000266 | 119.3193 | | | | |
| 3.67 | | | 20.6 | | 1209.782 | |
| 3.92 | 0.00025 | 113.3818 | | | | |
| 4.17 | | | | 18.7 | | 1045.056 |
| 4.67 | | | 19.2 | | 1125.738 | |
| 5.17 | | | | 17.7 | | 987.5449 |
| 5.67 | | | 18.8 | | 1101.726 | |
| 6.17 | | | | 17 | | 947.2872 |
| 6.67 | | | 18.5 | | 1083.716 | |
| 7.17 | | | | 16.7 | | 930.0339 |
| 7.67 | | | 18 | | 1053.701 | |
| 8.17 | | | | 16.5 | | 918.5317 |

Table A6. SO2 and NOx Removal by Sodium Bicarbonate

Date : 04-21-93
Sorbent: NaHCO3
Water(%) 7

Temp.(F) 300
rpm : 300
NSR : 13.5
Size(um) (53, 63)

| Time (min) | SO2/Air (Ratio) | SO2 (ppm) | NOx (Index) | NO (Index) | NOx (ppm) | NO (ppm) |
|---|---|---|---|---|---|---|
| 0 | 0.003735 | 1380.581 | 25.5 | 26 | 1503.935 | 1463.886 |
| 0.5 | | | 24.5 | | 1443.904 | |
| 0.75 | 0.002881 | 1070.065 | | | | |
| 1 | | | | 23.8 | | 1338.362 |
| 1.25 | 0.002346 | 875.6994 | | | | |
| 1.5 | | | 22.6 | | 1329.844 | |
| 1.75 | 0.002174 | 813.0347 | | | | |
| 2 | | | | 21.8 | | 1223.34 |
| 2.25 | 0.002264 | 845.624 | | | | |
| 2.5 | | | 21.3 | | 1251.804 | |
| 2.75 | 0.001929 | 723.8072 | | | | |
| 3 | | | | 19.3 | | 1079.562 |
| 3.25 | 0.001929 | 724.0124 | | | | |
| 3.5 | | | 19.3 | | 1131.741 | |
| 3.75 | 0.001833 | 688.9672 | | | | |
| 4 | | | | 17 | | 947.2872 |
| 4.25 | 0.001617 | 610.4084 | | | | |
| 4.5 | | | 18.3 | | 1071.71 | |
| 6 | | | | 15.5 | | 861.0208 |
| 6.5 | | | 16.7 | | 975.66 | |
| 7 | | | | 13.8 | | 763.2522 |
| 7.5 | | | 15.3 | | 891.6163 | |
| 8 | | | | 13.3 | | 734.4968 |

Table A7. SO2 and NOx Removal by Sodium Bicarbonate

Date : 04-23-93
Sorbent: NaHCO3
Water(%) 7

Temp.(F) 300
rpm : 300
NSR : 13.5
Size(um) (53, 63)

| Time (min) | SO2/Air (Ratio) | SO2 (ppm) | NOx (Index) | NO (Index) | NOx (ppm) | NO (ppm) |
|---|---|---|---|---|---|---|
| 0 | 0.004075 | 1504.223 | 26.5 | 27 | 1563.966 | 1522.396 |
| 0.25 | 0.002924 | 1085.661 | | | | |
| 0.5 | | | 25.3 | | 1491.929 | |
| 0.75 | 0.002102 | 786.8491 | | | | |
| 1 | | | | 23.5 | | 1321.108 |
| 1.25 | 0.001606 | 606.4316 | | | | |
| 1.5 | | | 24.3 | | 1431.897 | |
| 1.75 | 0.000947 | 366.6641 | | | | |
| 2 | | | | 22.5 | | 1263.597 |
| 2.25 | 0.000642 | 255.8223 | | | | |
| 2.5 | | | 22.8 | | 1341.85 | |
| 2.75 | 0.000683 | 270.8684 | | | | |
| 3 | | | | 21 | | 1177.331 |
| 3.25 | 0.000572 | 230.5899 | | | | |
| 3.5 | | | 21 | | 1233.794 | |
| 3.75 | 0.00045 | 186.1874 | | | | |
| 4 | | | | 19.5 | | 1091.065 |
| 4.25 | 0.000225 | 104.3301 | | | | |
| 5.5 | | | 19.7 | | 1155.754 | |
| 6 | | | | 17.5 | | 976.0427 |
| 7.5 | | | 19.5 | | 1143.747 | |
| 8 | | | | 14.5 | | 803.5099 |

Table A8. SO2 and NOx Removal by Sodium Bicarbonate

Date : 04-27-93
Sorbent: NaHCO3
Water(%) 2.9

Temp.(F) 300
rpm : 300
NSR : 13.5
Size(um) (53, 63)

| Time<br>(min) | SO2/Air<br>(Ratio) | SO2<br>(ppm) | NOx<br>(Index) | NO<br>(Index) | NOx<br>(ppm) | NO<br>(ppm) |
|---|---|---|---|---|---|---|
| 0 | 0.003981 | 1470.24 | 23.8 | 24.65 | 1401.882 | 1387.246 |
| 0.25 | 0.002966 | 1101.185 | | | | |
| 0.5 | | | 22 | | 1293.825 | |
| 0.75 | 0.002208 | 825.3321 | | | | |
| 1 | | | | 20.5 | | 1148.575 |
| 1.25 | 0.001684 | 635.0155 | | | | |
| 1.5 | | | 19.9 | | 1167.76 | |
| 1.75 | 0.00126 | 480.723 | | | | |
| 2 | | | | 17.8 | | 993.296 |
| 2.25 | 0.001047 | 403.3057 | | | | |
| 2.5 | | | 19.2 | | 1125.738 | |
| 2.75 | 0.000836 | 326.4855 | | | | |
| 3 | | | | 16.1 | | 895.5274 |
| 3.25 | 0.000735 | 289.6696 | | | | |
| 3.5 | | | 18 | | 1053.701 | |
| 3.75 | 0.000501 | 204.4952 | | | | |
| 4 | | | | 15.5 | | 861.0208 |
| 4.25 | 0.000174 | 85.6912 | | | | |
| 4.5 | | | 17.3 | | 1011.679 | |
| 5 | | | | 14.3 | | 792.0077 |
| 5.5 | | | 16.2 | | 945.6444 | |
| 6 | | | | 13.5 | | 745.999 |
| 6.5 | | | 15.5 | | 903.6226 | |
| 7 | | | | 12.9 | | 711.4924 |
| 7.5 | | | 14.8 | | 861.6007 | |
| 8 | | | | 12.4 | | 682.7369 |

Table A9. SO2 and NOx Removal by Sodium Bicarbonate

Date : 04-27-93
Sorbent: NaHCO3
Water(%) 3.5

Temp.(F) 300
rpm : 300
NSR : 13.5
Size(um) (53, 63)

| Time (min) | SO2/Air (Ratio) | SO2 (ppm) | NOx (Index) | NO (Index) | NOx (ppm) | NO (ppm) |
|---|---|---|---|---|---|---|
| 0 | 0.003803 | 1405.382 | 24.6 | 25.57 | 1449.907 | 1440.156 |
| 0.25 | 0.002704 | 1005.821 | | | | |
| 0.5 | | | 23.9 | | 1407.885 | |
| 0.75 | 0.002102 | 706.8491 | | | | |
| 1 | | | | 22.4 | | 1257.846 |
| 1.25 | 0.001606 | 526.4316 | | | | |
| 1.75 | 0.000947 | 316.6641 | | | | |
| 2.25 | 0.000642 | 225.8223 | | | | |
| 2.5 | | | 20.5 | | 1203.779 | |
| 2.75 | 0.000683 | 220.8684 | | | | |
| 3 | | | | 18.5 | | 1033.554 |
| 3.25 | 0.000572 | 190.5899 | | | | |
| 3.5 | | | 19.5 | | 1143.747 | |
| 3.75 | 0.00045 | 146.1874 | | | | |
| 4 | | | | 16.5 | | 918.5317 |
| 4.25 | 0.000225 | 94.33007 | | | | |
| 4.5 | | | 18 | | | |
| 5 | | | | 15.5 | | |
| 5.5 | | | 17 | | 993.6694 | |
| 6 | | | | 14.7 | | 815.0121 |
| 6.5 | | | 16.8 | | | |
| 7 | | | | 14 | | |
| 7.5 | | | 16.4 | | 957.6507 | |
| 8 | | | | 13.5 | | 745.999 |

Table A10. SO2 and NOx Removal by Sodium Bicarbonate

| | | | |
|---|---|---|---|
| Date : | 04-30-93 | Temp.(F) | 300 |
| Sorbent: | NaHCO3 | rpm : | 300 |
| Water(%) | 10 | NSR : | 13.5 |
| | | Size(um) | (53, 63) |

| Time (min) | SO2/Air (Ratio) | SO2 (ppm) | NOx (Index) | NO (Index) | NOx (ppm) | NO (ppm) |
|---|---|---|---|---|---|---|
| 0 | 0.004193 | 1547.247 | 25 | 26 | 1473.919 | 1464.886 |
| 0.166667 | 0.003168 | 1174.342 | | | | |
| 0.25 | | | 24 | | 1413.888 | |
| 0.416667 | 0.002262 | 844.9041 | | | | |
| 0.666667 | 0.001625 | 613.5531 | | | | |
| 0.75 | | | | 23.5 | | 1321.108 |
| 1 | 0.000945 | 365.9998 | | | | |
| 1.083333 | | | 23 | | 1353.857 | |
| 1.5 | 0.00058 | 233.4631 | | | | |
| 1.583333 | | | | 21.5 | | 1206.086 |
| 2 | 0.000464 | 191.265 | | | | |
| 2.083333 | | | 21 | | 1233.794 | |
| 2.5 | 0.000348 | 149.067 | | | | |
| 2.666667 | | | | 20 | | 1119.82 |
| 3 | 0.000244 | 111.0887 | | | | |
| 3.083333 | | | 19.8 | | 1161.757 | |
| 3.5 | | | | 18.5 | | 1033.554 |
| 4 | | | | 18 | | 1004.798 |
| 4.5 | | | | 17.5 | | 976.0427 |
| 5 | | | 18.5 | | 1083.716 | |
| 5.5 | | | | 16.5 | | 918.5317 |
| 6 | | | 18 | | 1053.701 | |
| 6.5 | | | | 15.8 | | 878.2741 |
| 7 | | | 17 | | 993.6694 | |
| 7.5 | | | | 15 | | 832.2654 |
| 8 | | | 16.5 | | 963.6538 | |

Table A11. SO2 and NOx Removal by Sodium Bicarbonate

| | | | |
|---|---|---|---|
| Date : | 05-03-93 | Temp.(F) | 300 |
| Sorbent: | NaHCO3 | rpm : | 300 |
| Water(%) | 3.5 | NSR : | 13.5 |
| | | Size(um) | (53, 63) |

| Time (min) | SO2/Air (Ratio) | SO2 (ppm) | NOx (Index) | NO (Index) | NOx (ppm) | NO (ppm) |
|---|---|---|---|---|---|---|
| 0 | | | 26.27 | 27.3 | 1550.159 | 1539.65 |
| 0.25 | | | 23 | | 1353.857 | |
| 0.75 | | | | 22 | | 1234.842 |
| 1.25 | | | 21.5 | | 1263.81 | |
| 1.75 | | | | 18.5 | | 1033.554 |
| 2.25 | | | 18.8 | | 1101.726 | |
| 2.75 | | | | 16.5 | | 918.5317 |
| 3.25 | | | 16.8 | | 981.6632 | |
| 3.75 | | | | 15 | | 832.2654 |
| 4.25 | | | 15.7 | | 915.6288 | |
| 4.75 | | | | 13.2 | | 728.7457 |
| 5.25 | | | 14.8 | | 861.6007 | |
| 5.75 | | | | 12.8 | | 705.7413 |
| 6.25 | | | 14.3 | | 831.5851 | |
| 6.75 | | | | 12 | | 659.7326 |
| 7.25 | | | 14 | | 813.5758 | |
| 7.75 | | | | 11.8 | | 648.2304 |

Table A12. SO2 and NOx Removal by Sodium Bicarbonate

| | | | |
|---|---|---|---|
| Date : | 05-07-93 | Temp.(F) | 240 |
| Sorbent: | NaHCO3 | rpm : | 300 |
| Water(%) | 6.7 | NSR : | 13.5 |
| | | Size(um) | (53, 63) |

| Time (min) | SO2/Air (Ratio) | SO2 (ppm) | NOx (Index) | NO (Index) | NOx (ppm) | NO (ppm) |
|---|---|---|---|---|---|---|
| 0 | 0.00445 | 1640.655 | 25.1 | 26.26 | 1479.922 | 1479.838 |
| 0.166667 | 0.0026 | 967.9273 | | | | |
| 0.25 | | | 24 | | 1413.888 | |
| 0.416667 | 0.00221 | 826.1091 | | | | |
| 0.666667 | 0.0018 | 677.0182 | | | | |
| 0.75 | | | | 24 | | 1349.864 |
| 1 | 0.00105 | 404.2909 | | | | |
| 1.25 | | | 22.7 | | 1335.847 | |
| 1.5 | 0.00097 | 375.2 | | | | |
| 1.75 | | | | 22 | | 1234.842 |
| 2 | 0.00096 | 371.5636 | | | | |
| 2.25 | | | 21.7 | | 1275.816 | |
| 2.5 | 0.00068 | 269.7455 | | | | |
| 2.75 | | | | 20.7 | | 1160.078 |
| 3 | 0.000433 | 179.9273 | | | | |
| 3.25 | | | 20.9 | | 1227.791 | |
| 3.75 | | | | 19.5 | | 1091.065 |
| 4.25 | | | 20.1 | | 1179.766 | |
| 4.75 | | | | 18 | | 1004.798 |
| 5.25 | | | 19.2 | | 1125.738 | |
| 5.75 | | | | 17.5 | | 976.0427 |
| 6.25 | | | 18.3 | | 1071.71 | |
| 6.75 | | | | 18 | | 1004.798 |
| 7.25 | | | 15.2 | | 885.6132 | |
| 7.75 | | | | 17.3 | | 964.5405 |

Table A13. SO2 and NOx Removal by Sodium Sesquicarbonate

| | | | |
|---|---|---|---|
| Date : | 05-10-93 | Temp.(F) | 240 |
| Sorbent: | Sodium Sesquicarbonate | rpm : | 300 |
| Water(%) | 6.7 | NSR : | 13.5 |
| | | Size(um) | (53, 63) |

| Time (min) | SO2/Air (Ratio) | SO2 (ppm) | NOx (Index) | NO (Index) | NOx (ppm) | NO (ppm) |
|---|---|---|---|---|---|---|
| 0 | 0.004145 | 1529.745 | 26.27 | 27.05 | 1550.159 | 1525.272 |
| 0.166667 | 0.0037 | 1367.927 | | | | |
| 0.25 | | | 23.5 | | 1383.872 | |
| 0.416667 | 0.00229 | 855.2 | | | | |
| 0.666667 | 0.0016 | 604.2909 | | | | |
| 0.75 | | | | 23.1 | | 1298.104 |
| 1 | 0.00097 | 375.2 | | | | |
| 1.25 | | | 21.5 | | 1263.81 | |
| 1.5 | 0.00059 | 237.0182 | | | | |
| 1.75 | | | | 21 | | 1177.331 |
| 2 | 0.000481 | 197.3818 | | | | |
| 2.25 | | | 19.5 | | 1143.747 | |
| 2.5 | 0.000463 | 190.8364 | | | | |
| 2.75 | | | | 18.8 | | 1050.807 |
| 3 | 0.000241 | 110.1091 | | | | |
| 3.25 | | | 18.2 | | 1065.707 | |
| 3.75 | | | | 17.6 | | 981.7938 |
| 4.25 | | | 16.8 | | 981.6632 | |
| 4.75 | | | | 16.4 | | 912.7807 |
| 5.25 | | | 16.5 | | 963.6538 | |
| 5.75 | | | | 15.3 | | 849.5186 |
| 6.75 | | | | 16.3 | | 907.0296 |
| 7.25 | | | 14.5 | | 843.5914 | |
| 7.75 | | | | 15.3 | | 849.5186 |

Table A14. SO2 and NOx Removal by Sodium Bicarbonate

|  |  |  |  |
|---|---|---|---|
| Date : | 05-20-93 | Temp.(F) | 260 |
| Sorbent: | Sodium Bicarbonate | rpm : | 300 |
| Water(%) | 5 | NSR : | 3.4 |
|  |  | Size(um) | (53, 63) |

| Time (min) | SO2/Air (Ratio) | SO2 (ppm) | NOx (Index) | NO (Index) | NOx (ppm) | NO (ppm) |
|---|---|---|---|---|---|---|
| 0 | 0.004366 | 1610.263 | 24.95 | 25.8 | 1470.918 | 1453.383 |
| 0.166667 | 0.003493 | 1292.676 |  |  |  |  |
| 0.25 |  |  | 24.5 |  | 1443.904 |  |
| 0.416667 | 0.002641 | 982.7314 |  |  |  |  |
| 0.666667 | 0.001295 | 493.5472 |  |  |  |  |
| 0.75 |  |  |  | 23.2 |  | 1303.855 |
| 1 | 0.001083 | 416.3293 |  |  |  |  |
| 1.25 |  |  | 23.5 |  | 1383.872 |  |
| 1.5 | 0.00093 | 360.7973 |  |  |  |  |
| 1.75 |  |  |  | 22.8 |  | 1280.851 |
| 2 | 0.001012 | 390.3396 |  |  |  |  |
| 2.25 |  |  | 22.5 |  | 1323.841 |  |
| 2.5 | 0.000657 | 261.3252 |  |  |  |  |
| 2.75 |  |  |  | 22.3 |  | 1252.095 |
| 3 | 0.00046 | 189.6695 |  |  |  |  |
| 3.25 |  |  | 21.8 |  | 1281.819 |  |
| 3.75 |  |  |  | 21.3 |  | 1194.584 |
| 4.25 |  |  | 21.8 |  | 1281.819 |  |
| 4.75 |  |  |  | 20 |  | 1119.82 |
| 5.25 |  |  | 20.6 |  | 1209.782 |  |
| 5.75 |  |  |  | 19.3 |  | 1079.562 |
| 6.25 |  |  | 20.8 |  | 1221.788 |  |
| 6.75 |  |  |  | 18.7 |  | 1045.056 |
| 7.25 |  |  | 20.3 |  | 1191.772 |  |
| 7.75 |  |  |  | 18.3 |  | 1022.051 |

Table A15. SO2 and NOx Removal by Sodium Pyrosulfite

Date : 05-24-93
Sorbent: Sodium Pyrosulfite
Water(%) 5

Temp.(F) 260
rpm : 300
NSR : 2
Size(um) (53, 63)

| Time<br>(min) | SO2/Air<br>(Ratio) | SO2<br>(ppm) | NOx<br>(Index) | NO<br>(Index) | NOx<br>(ppm) | NO<br>(ppm) |
|---|---|---|---|---|---|---|
| 0 | 0 | 0 | 24.8 | 26.3 | 1461.913 | 1482.139 |
| 0.25 | | | 23.4 | | 1377.869 | |
| 0.75 | | | | 21.5 | | 1206.086 |
| 1 | 0 | 11.23636 | | 23.6 | | |
| 1.25 | | | 22.2 | | 1305.832 | |
| 1.75 | | | | 22.3 | | 1252.095 |
| 2 | 0 | 22.47273 | | | | |
| 2.25 | | | 21.6 | | 1269.813 | |
| 2.75 | | | | 21.7 | | 1217.589 |
| 3 | 0.000157 | 79.44483 | | | | |
| 3.25 | | | 21.6 | | 1269.813 | |
| 3.75 | | | | 20.4 | | 1142.824 |
| 4 | 0.000313 | 136.4169 | | | | |
| 4.25 | | | 20.6 | | 1209.782 | |
| 4.75 | | | | 19.6 | | 1096.816 |
| 5 | 0.000399 | 167.7025 | | | | |
| 5.25 | | | 19.8 | | 1161.757 | |
| 5.75 | | | | 19.2 | | 1073.811 |
| 6 | 0.000485 | 198.9881 | | | | |
| 6.25 | | | 19.7 | | 1155.754 | |
| 6.75 | | | | 18.5 | | 1033.554 |
| 7 | 0.000498 | 225 | | | | |
| 7.25 | | | 19.6 | | 1149.751 | |
| 7.75 | | | | 18.1 | | 1010.549 |
| 8 | 0.000285 | 243 | | | | |

## Table A16. Typical Result of SO2 and NOx Removal by Sodium Bicarbonate

Date : 05-25-93
Sorbent: Sodium Bicarbonate
Water(%) 5

Temp.(F) 260
rpm : 700
NSR : 3.4
Size(um) (53, 63)

| Time (min) | SO2/Air (Ratio) | SO2 (ppm) | NOx (Index) | NO (Index) | NOx (ppm) | NO (ppm) |
|---|---|---|---|---|---|---|
| 0 | 0.004274 | 1576.537 | 25.11 | 26.2 | 1480.523 | 1476.388 |
| 0.166667 | 0.003402 | 1259.431 | | | | |
| 0.25 | | | 24.2 | | 1425.894 | |
| 0.416667 | 0.002633 | 980.0017 | | | | |
| 0.666667 | 0.0022 | 822.4727 | | | | |
| 0.75 | | | | 24.4 | | 1372.868 |
| 1 | 0.002022 | 757.7006 | | | | |
| 1.25 | | | 23.8 | | 1401.882 | |
| 1.5 | 0.001912 | 717.6988 | | | | |
| 1.75 | | | | 23.2 | | 1303.855 |
| 2 | 0.001521 | 575.3917 | | | | |
| 2.25 | | | 23.4 | | 1377.869 | |
| 2.5 | 0.001304 | 496.5845 | | | | |
| 2.75 | | | | 22.1 | | 1240.593 |
| 3 | 0.001151 | 440.9603 | | | | |
| 3.25 | | | 22.3 | | | |
| 3.75 | | | | 21.4 | | 1200.335 |
| 4.25 | | | 21.9 | | 1287.822 | |
| 4.75 | | | | 20.3 | | |
| 5.25 | | | 20.9 | | 1227.791 | |
| 5.75 | | | | 19.3 | | 1079.562 |
| 6.25 | | | 20.8 | | 1221.788 | |
| 6.75 | | | | 18.9 | | 1056.558 |
| 7.25 | | | 19.6 | | 1149.751 | |
| 7.75 | | | | 18.6 | | 1039.305 |

Table A17. SO2 and NOx Removal by Sodium Sesquicarbonate

|  |  |  |  |
|---|---|---|---|
| Date : | 05-27-93 | Temp.(F) | 260 |
| Sorbent: | Sodium Sesquicarbonate | rpm : | 700 |
| Water(%) | 5 | NSR : | 3.4 |
|  |  | Size(um) | (53, 63) |

| Time<br>(min) | SO2/Air<br>(Ratio) | SO2<br>(ppm) | NOx<br>(Index) | NO<br>(Index) | NOx<br>(ppm) | NO<br>(ppm) |
|---|---|---|---|---|---|---|
| 0 | 0.004174 | 1540.471 | 23.3 | 21.5 | 1371.866 | 1206.086 |
| 0.166667 | 0.003249 | 1204.021 |  |  |  |  |
| 0.25 |  |  |  |  |  |  |
| 0.416667 | 0.002137 | 799.5758 |  |  |  |  |
| 0.75 |  |  | 19.5 |  | 1143.747 |  |
| 1 | 0.001317 | 501.4798 |  |  |  |  |
| 1.25 |  |  |  | 18.7 |  | 1045.056 |
| 1.5 | 0.001603 | 605.3356 |  |  |  |  |
| 2 | 0.001247 | 475.8105 |  |  |  |  |
| 2.25 |  |  | 17.7 |  | 1035.691 |  |
| 2.5 | 0.000831 | 324.7872 |  |  |  |  |
| 2.75 |  |  |  | 17.6 |  | 981.7938 |
| 3 | 0.000456 | 188.1536 |  |  |  |  |
| 3.25 |  |  | 17.9 |  | 1047.698 |  |
| 3.75 |  |  |  | 16.6 |  | 924.2828 |
| 4.25 |  |  | 17.7 |  | 1035.691 |  |
| 4.75 |  |  |  | 16 |  | 889.7763 |
| 5.25 |  |  | 17 |  | 993.6694 |  |
| 5.75 |  |  |  | 15.6 |  | 866.7719 |
| 6.25 |  |  | 16.5 |  | 963.6538 |  |
| 6.75 |  |  |  | 14.8 |  | 820.7632 |
| 7.25 |  |  | 16.5 |  | 963.6538 |  |
| 7.75 |  |  |  | 14.3 |  | 792.0077 |

Table A18. SO2 and NOx Removal by Sodium Bicarbonate

| | | | |
|---|---|---|---|
| Date : | 05-30-93 | Temp.(F) | 260 |
| Sorbent: | Sodium Bicarbonate | rpm : | 700 |
| Water(%) | 5 | NSR : | 3.4 |
| | | Size(um) | (53, 63) |

| Time (min) | SO2/Air (Ratio) | SO2 (ppm) | NOx (Index) | NO (Index) | NOx (ppm) | NO (ppm) |
|---|---|---|---|---|---|---|
| 0 | 0.004003 | 1478.112 | 24.5 | 25.7 | 1443.904 | 1447.632 |
| 0.166667 | 0.002571 | 957.4882 | | | | |
| 0.25 | | | 23.8 | | 1401.882 | |
| 0.416667 | 0.001959 | 734.8266 | | | | |
| 0.666667 | 0.001502 | 568.6783 | | | | |
| 0.75 | | | | 23.9 | | 1344.113 |
| 1 | 0.001488 | 563.4668 | | | | |
| 1.25 | | | 23.1 | | 1359.86 | |
| 1.5 | 0.001234 | 471.1341 | | | | |
| 1.75 | | | | 22.6 | | 1269.348 |
| 2 | 0.000828 | 323.7213 | | | | |
| 2.25 | | | 22.8 | | 1341.85 | |
| 2.5 | 0 | 22.47273 | | | | |
| 2.75 | | | | 22.4 | | 1257.846 |
| 3 | 0 | 22.47273 | | | | |
| 3.75 | | | | 21 | | 1177.331 |
| 4.25 | | | 21.7 | | 1275.816 | |
| 5.25 | | | 21.3 | | 1251.804 | |
| 5.75 | | | | 19.5 | | 1091.065 |
| 6.25 | | | 21.3 | | 1251.804 | |
| 6.75 | | | | 18.9 | | 1056.558 |
| 7.25 | | | 20.7 | | 1215.785 | |
| 7.75 | | | | 18.2 | | 1016.3 |

Table A19. SO2 and NOx Removal by Sodium Sesquicarbonate.

Date : 06-17-93
Sorbent Sodium Sesquicarbonate
Water(%) 5

Temp.(F) 260
rpm : 700
NSR : 1.7
Size(um) : (53, 63)

| Time (min) | SO2/Air (Ratio) | SO2 (ppm) | NOx (Index) | NO (Index) | NOx (ppm) | NO (ppm) |
|---|---|---|---|---|---|---|
| 0 | 0.004392 | 1619.731 | 23.5 | 24 | 1383.872 | 1349.864 |
| 0.25 | 0.004169 | 1538.593 | | | | |
| 0.366667 | | | 22.9 | | 1347.854 | |
| 0.75 | 0.002468 | 920.0678 | | | | |
| 0.866667 | | | | 22.7 | | 1275.099 |
| 1.25 | 0.0018 | 677.0572 | | | | |
| 1.366667 | | | 22.5 | | 1323.841 | |
| 1.75 | 0.00194 | 727.8779 | | | | |
| 1.866667 | | | | 21.4 | | 1200.335 |
| 2.25 | 0.001164 | 445.7158 | | | | |
| 2.366667 | | | 22.3 | | 1311.835 | |
| 2.75 | 0.000776 | 304.6348 | | | | |
| 2.866667 | | | | 21.6 | | 1211.837 |
| 3.25 | 0.000333 | 143.5686 | | | | |
| 3.366667 | | | | 21.3 | | 1194.584 |
| 3.833333 | | | | 21.1 | | 1183.082 |
| 4.333333 | | | 21.5 | | 1263.81 | |
| 4.833333 | | | | 20.7 | | 1160.078 |
| 5.333333 | | | 20.9 | | 1227.791 | |
| 5.833333 | | | 21.5 | | 1263.81 | |
| 6.333333 | | | | 19.5 | | 1091.064 |
| 6.833333 | | | 20.3 | | 1191.772 | |
| 7.333333 | | | | 18.5 | | 1033.554 |
| 7.833333 | | | 19.1 | | 1119.735 | |

Table A20. SO2 and NOx Removal by Sodium Sesquicarbonate.

Date : 06-18-93
Sorbent Sodium Sesquicarbonate
Water(%) 5
Temp.(F) 260
rpm : 700
NSR : 0.85
Size(um) : (53, 63)

| Time (min) | SO2/Air (Ratio) | SO2 (ppm) | NOx (Index) | NO (Index) | NOx (ppm) | NO (ppm) |
|---|---|---|---|---|---|---|
| 0 | 0.004411 | 1626.588 | 23.5 | 23.8 | 1383.872 | 1338.361 |
| 0.116667 | 0.003974 | 1467.522 | | | | |
| 0.333333 | 0.002947 | 1094.212 | | | | |
| 0.5 | | | 22.3 | | 1311.835 | |
| 0.883333 | 0.001918 | 720.107 | | | | |
| 1 | | | | 23.2 | | 1303.855 |
| 1.383333 | 0.001201 | 459.0374 | | | | |
| 1.5 | | | 22.3 | | 1311.835 | |
| 1.883333 | 0.001678 | 632.5084 | | | | |
| 2 | | | | | | |
| 2.383333 | 0.000907 | 352.4679 | | | | |
| 2.5 | | | 22.3 | | 1311.835 | |
| 2.883333 | 0.000353 | 150.7693 | | | | |
| 3 | | | | 21.5 | | 1206.086 |
| 3.383333 | 0.000222 | 103.1797 | | | | |
| 3.5 | | | 22.2 | | 1305.832 | |
| 4 | | | | 21.1 | | 1183.082 |
| 4.5 | | | 21.2 | | 1245.801 | |
| 5 | | | | 20.2 | | 1131.322 |
| 5.5 | | | 21.1 | | 1239.797 | |
| 6 | | | | 19.5 | | 1091.064 |
| 6.5 | | | 20.3 | | 1191.772 | |
| 7 | | | | 19.2 | | 1073.811 |

Table A21. SO2 and NOx Removal by Sodium Sesquicarbonate.

| | | | |
|---|---|---|---|
| Date : | 06-21-93 | Temp.(F) | 260 |
| Sorbent | Sodium Sesquicarbonate | rpm : | 700 |
| Water(%) | 5 | NSR : | 1.7 |
| | | Size(um) : | (53, 63) |

| Time (min) | SO2/Air (Ratio) | SO2 (ppm) | NOx (Index) | NO (Index) | NOx (ppm) | NO (ppm) |
|---|---|---|---|---|---|---|
| 0 | 0.004189 | 1545.661 | 24.9 | 26 | 1467.916 | 1464.885 |
| 0.133333 | 0.003392 | 1255.987 | | | | |
| 0.25 | 0.002489 | 927.4801 | | | | |
| 0.416667 | 0.001324 | 504.0373 | | | | |
| 0.5 | | | 23.5 | | 1383.872 | |
| 0.916667 | 0.000918 | 356.2894 | | | | |
| 1 | | | | 23.5 | | 1321.108 |
| 1.5 | | | 23.3 | | 1371.866 | |
| 1.916667 | 0.000596 | 239.135 | | | | |
| 2 | | | | 23 | | 1292.353 |
| 2.5 | | | 22.5 | | 1323.841 | |
| 2.916667 | 0.000357 | 152.4701 | | | | |
| 3 | | | | 21.8 | | 1223.34 |
| 3.5 | | | 21.9 | | 1287.822 | |
| 3.916667 | 0.000238 | 109.1376 | | | | |
| 4 | | | | 21.1 | | 1183.082 |
| 4.5 | | | 21.9 | | 1287.822 | |
| 5 | | | | 20.6 | | 1154.326 |
| 5.5 | | | 21.9 | | 1287.822 | |
| 6 | | | | 20.1 | | 1125.571 |
| 6.5 | | | 20.9 | | 1227.791 | |
| 7 | | | | 19.8 | | 1108.318 |

Table A22. SO2 and NOx Removal by Sodium Sesquicarbonate.

Date : 06-22-93
Sorbent Sodium Sesquicarbonate
Water(%) 5
Temp.(F) 260
rpm : 700
NSR : 0.85
Size(um) : (53, 63)

| Time (min) | SO2/Air (Ratio) | SO2 (ppm) | NOx (Index) | NO (Index) | NOx (ppm) | NO (ppm) |
|---|---|---|---|---|---|---|
| 0 | 0.004875 | 1795.104 | 25.4 | 26.3 | 1497.932 | 1482.139 |
| 0.116667 | 0.004308 | 1588.87 | | | | |
| 0.25 | 0.002771 | 1030.255 | | | | |
| 0.416667 | 0.002334 | 871.2405 | | | | |
| 0.5 | | | 24.5 | | 1443.904 | |
| 0.916667 | 0.001029 | 396.5503 | | | | |
| 1 | | | | 24.5 | | 1378.619 |
| 1.416667 | 0.000423 | 176.4006 | | | | |
| 1.5 | | | 23.9 | | 1407.885 | |
| 2 | | | | 23.5 | | 1321.108 |
| 2.5 | | | 23.4 | | 1377.869 | |
| 2.916667 | 0.000746 | 293.8349 | | | | |
| 3 | | | | 22.5 | | 1263.597 |
| 3.5 | | | 22.4 | | 1317.838 | |
| 3.916667 | 0.000249 | 112.9268 | | | | |
| 4 | | | | 22.1 | | 1240.593 |
| 4.5 | | | 22.3 | | 1311.835 | |
| 4.916667 | 0.00101 | 389.8713 | | | | |
| 5 | | | | 21.3 | | 1194.584 |
| 5.5 | | | 22.3 | | 1311.835 | |
| 6 | | | | 21.1 | | 1183.082 |
| 6.5 | | | 22.2 | | 1305.832 | |
| 7 | | | | 20.9 | | 1171.58 |

Table A23. SO2 and NOx Removal by Sodium Sesquicarbonate

| | | | |
|---|---|---|---|
| Date | : 06-23-93 | Temp.(F) | 260 |
| Sorbent | : Sodium Sesquicarbonate | rpm : | 700 |
| Water(%) | 5 | NSR : | 3.4 |
| | | Size(um) : | (15, 32) |

| Time (min) | SO2/Air (Ratio) | SO2 (ppm) | NOx (Index) | NO (Index) | NOx (ppm) | NO (ppm) |
|---|---|---|---|---|---|---|
| 0 | 0.004734 | 1743.767 | 25 | 26.3 | 1473.919 | 1482.139 |
| 0.083333 | 0.003856 | 1424.75 | | | | |
| 0.25 | 0.002548 | 948.8925 | | | | |
| 0.416667 | 0.001886 | 708.4329 | | | | |
| 0.5 | | | 22.3 | | 1311.835 | |
| 0.916667 | 0.00134 | 509.5697 | | | | |
| 1 | | | | 22.2 | | 1246.344 |
| 1.5 | | | 21.6 | | 1269.813 | |
| 1.916667 | 0.000447 | 184.8384 | | | | |
| 2 | | | | 20.6 | | 1154.326 |
| 2.5 | | | 20.9 | | 1227.791 | |
| 2.916667 | 0.000466 | 191.7788 | | | | |
| 3 | | | | 19.6 | | 1096.816 |
| 3.5 | | | 20.3 | | 1191.772 | |
| 3.916667 | 0 | 22.47273 | | | | |
| 4 | | | | 18.6 | | 1039.305 |
| 4.5 | | | 19.5 | | 1143.747 | |
| 4.916667 | 0 | 22.47273 | | | | |
| 5 | | | | 18.1 | | 1010.549 |
| 5.5 | | | 18.9 | | 1107.729 | |
| 6 | | | | 17.5 | | 976.0426 |
| 6.5 | | | 18.4 | | 1077.713 | |
| 7 | | | | 17.4 | | 970.2915 |

Table A24. SO2 and NOx Removal by Sodium Sesquicarbonate

| | | | |
|---|---|---|---|
| Date : | 06-23-93 | Temp.(F) | 260 |
| Sorbent : | Sodium Sesquicarbonate | rpm : | 700 |
| Water(%) | 5 | NSR : | 3.4 |
| | | Size(um) : | (45, 53) |

| Time (min) | SO2/Air (Ratio) | SO2 (ppm) | NOx (Index) | NO (Index) | NOx (ppm) | NO (ppm) |
|---|---|---|---|---|---|---|
| 0 | 0.004757 | 1752.279 | 25.2 | 25.3 | 1485.925 | 1424.628 |
| 0.083333 | 0.003612 | 1335.812 | | | | |
| 0.25 | 0.00219 | 818.7002 | | | | |
| 0.416667 | 0.001591 | 601.0655 | | | | |
| 0.5 | | | 22.3 | | 1311.835 | |
| 0.916667 | 0.001501 | 568.3182 | | | | |
| 1 | | | | 21.1 | | 1183.082 |
| 1.5 | | | 21.1 | | 1239.797 | |
| 1.916667 | 0.0005 | 204.4212 | | | | |
| 2 | | | | 19.5 | | 1091.064 |
| 2.5 | | | 19.1 | | 1119.735 | |
| 2.916667 | 0 | 22.47273 | | | | |
| 3 | | | | 18.2 | | 1016.3 |
| 3.5 | | | 18.5 | | 1083.716 | |
| 3.916667 | 0 | 22.47273 | | | | |
| 4 | | | | 17.2 | | 958.7893 |
| 4.5 | | | 18.1 | | 1059.704 | |
| 4.916667 | 0 | 22.47273 | | | | |
| 5 | | | | 17.1 | | 953.0382 |
| 5.5 | | | 17.8 | | 1041.694 | |
| 6 | | | | 16.6 | | 924.2828 |
| 6.5 | | | 17.6 | | 1029.688 | |
| 7 | | | | 15.6 | | 866.7719 |

Table A25. SO2 and NOx Removed by Sodium Sulfite

Date : 06-25-93
Sorbent : Sodium Sulfite
Water(%) 5

Temp.(F) 260
rpm : 700
NSR : 2
Size(um) : (53, 63)

| Time (min) | SO2/Air (Ratio) | SO2 (ppm) | NOx (Index) | NO (Index) | NOx (ppm) | NO (ppm) |
|---|---|---|---|---|---|---|
| 0 | | | 24.43 | 25.48 | 1439.701 | 1434.98 |
| 0.116667 | | | | | | |
| 0.25 | | | | | | |
| 0.416667 | | | | | | |
| 0.5 | | | 24.1 | | 1419.891 | |
| 0.916667 | | | | | | |
| 1 | | | | 24.8 | | 1395.872 |
| 1.416667 | | | | | | |
| 1.5 | | | 23.6 | | 1389.875 | |
| 2 | | | | 24.3 | | 1367.117 |
| 2.5 | | | 23.2 | | 1365.863 | |
| 2.916667 | | | | | | |
| 3 | | | | 23.9 | | 1344.113 |
| 3.5 | | | 22.8 | | 1341.85 | |
| 3.916667 | | | | | | |
| 4 | | | | 23.5 | | 1321.108 |
| 4.5 | | | 22.4 | | 1317.838 | |
| 4.916667 | | | | | | |
| 5 | | | | 22.8 | | 1280.851 |
| 5.5 | | | 22.2 | | 1305.832 | |
| 6 | | | | 21.8 | | 1223.34 |
| 6.5 | | | 21.8 | | 1281.819 | |
| 7 | | | | 21.6 | | 1211.837 |

Table A26: SO2 and NOx Removal by Sodium Sesquicarbonate

Date : 07-22-93
Sorbent: Sesqui-
Water(%) : 0
Temp.(F) : 300
rpm : 300
NSR : 3.4
Size(um) : (53, 63)

| Time (min) | SO2/Air (Ratio) | SO2 (ppm) | NOx (Index) | NO (Index) | NOx (ppm) | NO (ppm) |
|---|---|---|---|---|---|---|
| 0 | 0.004152 | 1515.869 | 25 | 25.5 | 1473.919 | 1436.13 |
| 0.083333 | 0.00375 | 1369.745 | | | | |
| 0.25 | 0.00346 | 1264.291 | | | | |
| 0.416667 | 0.003244 | 1185.795 | | | | |
| 0.5 | | | 22.8 | | 1341.85 | |
| 0.916667 | 0.00275 | 1006.109 | | | | |
| 1 | | | | 22.4 | | 1257.846 |
| 1.5 | | | 21.7 | | 1275.816 | |
| 1.916667 | 0.002093 | 767.2527 | | | | |
| 2 | | | | 21 | | 1177.331 |
| 2.5 | | | 21.4 | | 1257.807 | |
| 2.916667 | 0.001226 | 452.0241 | | | | |
| 3 | | | | 20 | | 1119.82 |
| 3.5 | | | 21.2 | | 1245.801 | |
| 3.916667 | 0.001943 | 712.6754 | | | | |
| 4 | | | | 19.2 | | 1073.811 |
| 4.5 | | | 20.6 | | 1209.782 | |
| 4.916667 | 0.000945 | 349.7347 | | | | |
| 5 | | | | 19.1 | | 1068.06 |
| 5.5 | | | 20.2 | | 1185.769 | |
| 6 | | | | 18.5 | | 1033.554 |
| 6.5 | | | 20 | | 1173.763 | |
| 7 | | | | 18.3 | | 1022.051 |

Table A27: SO2 and NOx Removal by Sodium Sesquicarbonate

| | | | |
|---|---|---|---|
| Date : | 07-22-93 | Temp.(F) : | 300 |
| Sorbent: | Sesqui- | rpm : | 300 |
| Water(%) : | 10 | NSR : | 3.4 |
| | | Size(um) : | (53, 63) |

| Time (min) | SO2/Air (Ratio) | SO2 (ppm) | NOx (Index) | NO (Index) | NOx (ppm) | NO (ppm) |
|---|---|---|---|---|---|---|
| 0 | 0.004014 | 1465.837 | 24.8 | 25.4 | 1461.913 | 1430.379 |
| 0.083333 | 0.003259 | 1191.3 | | | | |
| 0.25 | 0.002604 | 953.1268 | | | | |
| 0.416667 | 0.0021 | 769.7455 | | | | |
| 0.5 | | | 23 | | 1353.857 | |
| 0.916667 | 0.001863 | 683.402 | | | | |
| 1 | | | | 22.3 | | 1252.095 |
| 1.5 | | | 21.8 | | 1281.819 | |
| 1.916667 | 0.001567 | 575.9798 | | | | |
| 2 | | | | 20.5 | | 1148.575 |
| 2.5 | | | 21.3 | | 1251.804 | |
| 2.916667 | 0.00109 | 402.327 | | | | |
| 3 | | | | 19.5 | | 1091.064 |
| 3.5 | | | 21.2 | | 1245.801 | |
| 3.916667 | 0.00103 | 380.655 | | | | |
| 4 | | | | 19.2 | | 1073.811 |
| 4.5 | | | 20.3 | | 1191.772 | |
| 4.916667 | 0.000535 | 200.5435 | | | | |
| 5 | | | | 18.8 | | 1050.807 |
| 5.5 | | | 19.6 | | 1149.751 | |
| 6 | | | | 18.4 | | 1027.802 |
| 6.5 | | | 18.8 | | 1101.726 | |
| 7 | | | | 18 | | 1004.798 |

Table A28. SO2 and NOx Removal by Sodium Sulfite

Date : 07-24-93

Sorbent : Sodium Sulfite

Water(%) 5

Temp.(F) 260

rpm : 700

NSR : 2

Size(um) : (53, 63)

| Time (min) | SO2/Air (Ratio) | SO2 (ppm) | NOx (Index) | NO (Index) | NOx (ppm) | NO (ppm) |
|---|---|---|---|---|---|---|
| 0 | | | 24.2 | 25.3 | 1425.894 | 1424.628 |
| 0.116667 | | | | | | |
| 0.25 | | | | | | |
| 0.416667 | | | | | | |
| 0.5 | | | 23.3 | | 1371.866 | |
| 0.916667 | | | | | | |
| 1 | | | | 23.6 | | 1326.859 |
| 1.416667 | | | | | | |
| 1.5 | | | 22.7 | | 1335.847 | |
| 2 | | | | 23 | | 1292.353 |
| 2.5 | | | 22.6 | | 1329.844 | |
| 2.916667 | | | | | | |
| 3 | | | | 23.1 | | 1298.104 |
| 3.5 | | | 22.3 | | 1311.835 | |
| 3.916667 | | | | | | |
| 4 | | | | 22.7 | | 1275.099 |
| 4.5 | | | 22.2 | | 1305.832 | |
| 4.916667 | | | | | | |
| 5 | | | | 22.4 | | 1257.846 |
| 5.5 | | | 21.9 | | 1287.822 | |
| 6 | | | | 21.9 | | 1229.091 |
| 6.5 | | | 21.8 | | 1281.819 | |
| 7 | | | | 21.6 | | 1211.837 |

Table A29. Blank Test at 300 F, 500 rpm, 5% Water
High Concentration (1500 ppm-Method II)
N2-Air-Water-NO System :

| Time (min) | SO2/N2 Ratio) | SO2/N2 (ppm) | NO (Index) | NOx (Index) | NO (ppm) | NOx (ppm) |
|---|---|---|---|---|---|---|
| 0 | | | 24.3 | 23 | 1350 | 1353.857 |
| 0.5 | | | | 22.8 | | 1341.85 |
| 1 | | | 24.3 | | 1339 | |
| 1.5 | | | | 22 | | 1327 |
| 2 | | | 23.4 | | 1315.357 | |
| 2.5 | | | | 22 | | 1320 |
| 3 | | | 23.1 | | 1298.104 | |
| 3.5 | | | | 22.4 | | 1317.838 |
| 4 | | | 22.8 | | 1280.851 | |
| 4.5 | | | | 21.5 | | 1314 |
| 5 | | | 22.4 | | 1257.846 | |
| 5.5 | | | | 22.3 | | 1311.835 |
| 6 | | | 21.9 | | 1229.091 | |
| 6.5 | | | | 21.4 | | 1307 |
| 7 | | | 21.3 | | 1194.584 | |

Table A30. Blank Test at 300 F, 500 rpm, 5% Water
(Water-SO2-Air)

| Time (min) | SO2/N2 (Ratio) | SO2/N2 (ppm) | NO (Index) | NOx (Index) | NO (ppm) | NOx (ppm) |
|---|---|---|---|---|---|---|
| 0 | 0.00438 | 1615.159 | | | | |
| 0.083333 | 0.004357 | 1606.937 | | | | |
| 0.25 | 0.004221 | 1557.3 | | | | |
| 0.416667 | 0.004281 | 1579.069 | | | | |
| 0.5 | | | | | | |
| 0.916667 | 0.00423 | 1560.545 | | | | |
| 1 | | | | | | |
| 1.5 | | | | | | |
| 1.916667 | 0.003927 | 1450.446 | | | | |
| 2 | | | | | | |
| 2.5 | | | | | | |
| 2.916667 | 0.00405 | 1495.192 | | | | |
| 3 | | | | | | |
| 3.5 | | | | | | |
| 3.916667 | 0.004127 | 1523.051 | | | | |
| 4 | | | | | | |
| 4.5 | | | | | | |
| 4.916667 | 0.0039 | 1440.697 | | | | |
| 5 | | | | | | |
| 5.5 | | | | | | |
| 6 | | | | | | |
| 6.5 | | | | | | |
| 7 | | | | | | |

Table A31. SO2 and NOx Removal by Sodium Bicarbonate.

Date : 08-07-93
Sorbent : Sodium Bicarbonate
Water(%) 5

Temp.(F) 260
rpm : 700
NSR : 0.6
Size(um) : (53, 63)

| Time<br>(min) | SO2/Air<br>(Ratio) | SO2<br>(ppm) | NOx<br>(Index) | NO<br>(Index) | NOx<br>(ppm) | NO<br>(ppm) |
|---|---|---|---|---|---|---|
| 0 | 0.004182 | 1543.255 | 24.3 | 25.4 | 1431.897 | 1430.379 |
| 0.083333 | 0.003274 | 1212.844 | | | | |
| 0.25 | 0.002331 | 870.0159 | | | | |
| 0.416667 | 0.001694 | 638.6191 | | | | |
| 0.5 | | | 23.9 | | 1407.885 | |
| 0.916667 | 0.0012 | 458.7337 | | | | |
| 1 | | | | 24.7 | | 1390.121 |
| 1.5 | | | 23.8 | | 1401.882 | |
| 1.916667 | 0.000441 | 182.6561 | | | | |
| 2 | | | | 24.4 | | 1372.868 |
| 2.5 | | | 23.7 | | 1395.879 | |
| 2.916667 | 0.00122 | 466.0569 | | | | |
| 3 | | | | 23.8 | | 1338.361 |
| 3.5 | | | 23.4 | | 1377.869 | |
| 3.916667 | 0.000645 | 257.0106 | | | | |
| 4 | | | | 23.4 | | 1315.357 |
| 4.5 | | | 23.2 | | 1365.863 | |
| 4.916667 | 0.000928 | 359.8556 | | | | |
| 5 | | | | 23.3 | | 1309.606 |
| 5.5 | | | 23.2 | | 1365.863 | |
| 6 | | | | 22.9 | | 1286.602 |
| 6.5 | | | 22.7 | | 1335.847 | |
| 7 | | | | 22.3 | | 1252.095 |

Table A32. SO2 and NOx Removal by Sodium Bicarbonate.

| | | | |
|---|---|---|---|
| Date : | 08-08-93 | Temp.(F) | 260 |
| Sorbent : | Sodium Bicarbonate | rpm : | 700 |
| Water(%) | 5 | NSR : | 3.4 |
| | | Size(um) : | (53, 63) |

| Time (min) | SO2/Air (Ratio) | SO2 (ppm) | NOx (Index) | NO (Index) | NOx (ppm) | NO (ppm) |
|---|---|---|---|---|---|---|
| 0 | 0.004386 | 1617.223 | 24.9 | 25.8 | 1467.916 | 1453.383 |
| 0.083333 | 0.003822 | 1412.391 | | | | |
| 0.25 | 0.00276 | 1025.967 | | | | |
| 0.416667 | 0.001816 | 682.9426 | | | | |
| 0.5 | | | 24.6 | | 1449.907 | |
| 0.916667 | 0.000728 | 287.0852 | | | | |
| 1 | | | | 25.4 | | 1430.379 |
| 1.5 | | | 24.6 | | 1449.907 | |
| 1.916667 | 0.001191 | 455.5698 | | | | |
| 2 | | | | 24.2 | | 1361.366 |
| 2.5 | | | 23.4 | | 1377.869 | |
| 2.916667 | 0.000192 | 92.14259 | | | | |
| 3 | | | | 23.2 | | 1303.855 |
| 3.5 | | | 22.7 | | 1335.847 | |
| 3.916667 | 0.000151 | 77.51855 | | | | |
| 4 | | | | 22 | | 1234.842 |
| 4.5 | | | 22.3 | | 1311.835 | |
| 4.916667 | 0.000333 | 143.6824 | | | | |
| 5 | | | | 20.7 | | 1160.078 |
| 5.5 | | | 21.4 | | 1257.807 | |
| 6 | | | | 19.8 | | 1108.318 |
| 6.5 | | | 21 | | 1233.794 | |
| 7 | | | | 18.9 | | 1056.558 |

|  |  |  |  |  |  |  |
|---|---|---|---|---|---|---|
| 19.5 |  |  |  | 18.3 |  | 1022.051 |
| 21.5 | 0.00285 | 1042.473 |  |  |  |  |
| 22 |  |  | 21.3 |  | 1251.804 |  |
| 22.5 |  |  |  | 17.8 |  | 993.2959 |
| 24.5 | 0.002823 | 1032.621 |  |  |  |  |
| 25 |  |  | 21.2 |  |  |  |
| 25.5 |  |  |  | 17.7 |  |  |
| 27.5 | 0.002777 | 1015.881 |  |  |  |  |
| 28 |  |  | 20.5 |  | 1203.779 |  |
| 28.5 |  |  |  | 17 |  | 947.2872 |

====================================

Table A39. SO2 and NOx Removal by Sodium Sesquicarbonate

Date : 10-24-93
Sorbent Sodium Sesquicarbonate
Water(%) 5

Temp.(F) 260
rpm : 700
NSR : 3.4
Size(um) : (53, 63)

| Time (min) | SO2/Air (Ratio) | SO2 (ppm) | NOx (Index) | NO (Index) | NOx (ppm) | NO (ppm) |
|---|---|---|---|---|---|---|
| 0 | 0.004462 | 1628.628 | 25 | 26.15 | 1473.919 | 1473.512 |
| 0.25 | 0.003957 | 1444.873 | | | | |
| 0.5 | | | 22.7 | | 1335.847 | |
| 1 | | | | 21.3 | | 1194.584 |
| 1.5 | | | 21.3 | | 1251.804 | |
| 2 | | | | 19.5 | | 1091.064 |
| 2.75 | 0.002467 | 903.0249 | | | | |
| 3 | | | 19.5 | | 1143.747 | |
| 4 | | | | 17.8 | | 993.2959 |
| 5.25 | 0.001947 | 713.9838 | | | | |
| 6 | | | 18.3 | | 1071.71 | |
| 7.75 | 0.001569 | 576.7865 | | | | |
| 8 | | | | 15.8 | | 878.274 |
| 10.25 | 0.001365 | 502.3186 | | | | |
| 11 | | | 16.5 | | 963.6538 | |
| 12.75 | 0.00114 | 420.6867 | | | | |
| 14 | | | | 13.6 | | 751.75 |
| 15.25 | 0.000966 | 357.2379 | | | | |
| 17 | | | 15.6 | | 909.6257 | |
| 17.75 | 0.000784 | 291.2502 | | | | |
| 20.25 | 0.000672 | 250.4137 | | | | |
| 21 | | | | 12.2 | | 671.2347 |
| 22.75 | 0.000672 | 250.3218 | | | | |
| 24 | | | 14.9 | | 867.6039 | |
| 24.5 | | | | 12 | | 659.7325 |

```
      25                            14.8             861.6007
   25.75  0.000549  205.7772
=========================================================================
```

# APPENDIX B

Table B1-1. Corrected Results from the case of Sodium Bicarbonate with NSR = 0.85 (Figure 23)

CORRECTED DATA

| Time<br>(min) | SO2<br>(ppm) | NOx<br>(ppm) | NO<br>(ppm) |
|---|---|---|---|
| 0 | 1758.467 | 1473.919 | 1470.637 |
| 0.25 | 1731.227 | | |
| 0.5 | | 1435.597 | |
| 1 | | | 1357.264 |
| 1.5 | | 1418.985 | |
| 2 | | | 1307.153 |
| 2.5 | | | |
| 2.75 | 1628.402 | | |
| 3 | | 1388.063 | |
| 3.5 | | | |
| 4 | | | 1275.944 |
| 4.5 | | | |
| 5 | | | |
| 5.25 | 1540.655 | | |
| 5.5 | | | |
| 6 | | 1362.238 | |
| 7 | | | |
| 7.75 | 1446.109 | | |
| 8 | | | 1184.771 |
| 9 | | | |
| 10 | | | |
| 10.25 | 1378.948 | | |
| 10.5 | | | |
| 11 | | 1351.213 | |
| 12 | | | |

| | | | |
|---|---|---|---|
| 12.75 | 1340.655 | | |
| 13 | | | |
| 14 | | | 1142.905 |
| 15 | | | |
| 15.25 | 1318.836 | | |
| 15.5 | | | |
| 16 | | | |
| 17 | | 1329.579 | |
| 17.75 | 1297.018 | | |
| 18 | | | |
| 19 | | | |
| 20 | | | |
| 20.25 | 1275.2 | | |
| 20.5 | | | |
| 21 | | | 1056.678 |
| 22 | | | |
| 22.75 | 1258.711 | | |
| 23 | | | |
| 24 | | 1333.354 | |
| 24.5 | | | 1065.325 |
| 25 | | 1310.738 | |
| 25.75 | 1257.018 | | |
| 26 | | | |
| 27 | | | |

====================================

Table B1-2. Simulation Results from the Case of Sodium Bicarbonate with NSR = 0.85 (Figure 23)

SIMULATION (with kA=7.65, kB=1.06E8, and x=0.70)

| SO2 (ppm) | NO (ppm) | NOx (ppm) | R (um) | R(um) X 100 |
|---|---|---|---|---|
| 1758.47 | 1470.64 | 1473.92 | 29 | 2900 |
| 1747.11 | 1463.6 | 1469.34 | 28.9062 | 2890.62 |
| 1735.9 | 1456.68 | 1464.85 | 28.8131 | 2881.31 |
| 1713.9 | 1443.21 | 1456.09 | 28.6289 | 2862.89 |
| 1692.45 | 1430.19 | 1447.63 | 28.4473 | 2844.73 |
| 1671.54 | 1417.61 | 1439.45 | 28.2682 | 2826.82 |
| 1651.14 | 1405.45 | 1431.55 | 28.0916 | 2809.16 |
| 1641.13 | 1399.52 | 1427.69 | 28.0042 | 2800.42 |
| 1631.24 | 1393.68 | 1423.9 | 27.9173 | 2791.73 |
| 1611.82 | 1382.3 | 1416.5 | 27.7454 | 2774.54 |
| 1592.87 | 1371.27 | 1409.33 | 27.5757 | 2757.57 |
| 1574.36 | 1360.6 | 1402.39 | 27.4082 | 2740.82 |
| 1556.29 | 1350.25 | 1395.67 | 27.2429 | 2724.29 |
| 1547.41 | 1345.19 | 1392.38 | 27.161 | 2716.1 |
| 1538.64 | 1340.22 | 1389.15 | 27.0796 | 2707.96 |
| 1521.4 | 1330.49 | 1382.82 | 26.9184 | 2691.84 |
| 1488.08 | 1311.89 | 1370.74 | 26.6017 | 2660.17 |
| 1464.07 | 1298.65 | 1362.13 | 26.3692 | 2636.92 |
| 1456.24 | 1294.37 | 1359.34 | 26.2926 | 2629.26 |
| 1425.79 | 1277.82 | 1348.59 | 25.9906 | 2599.06 |
| 1396.65 | 1262.19 | 1338.43 | 25.6955 | 2569.55 |
| 1389.56 | 1258.41 | 1335.97 | 25.6227 | 2562.27 |
| 1382.54 | 1254.69 | 1333.55 | 25.5503 | 2555.03 |
| 1368.74 | 1247.39 | 1328.81 | 25.4067 | 2540.67 |

| | | | | |
|---|---|---|---|---|
| 1341.98 | 1233.37 | 1319.7 | 25.1242 | 2512.42 |
| 1322.64 | 1223.34 | 1313.17 | 24.9162 | 2491.62 |
| 1316.33 | 1220.08 | 1311.05 | 24.8476 | 2484.76 |
| 1291.7 | 1207.45 | 1302.85 | 24.5766 | 2457.66 |
| 1268.06 | 1195.45 | 1295.05 | 24.3111 | 2431.11 |
| 1262.29 | 1192.54 | 1293.16 | 24.2455 | 2424.55 |
| 1256.58 | 1189.67 | 1291.29 | 24.1802 | 2418.02 |
| 1245.33 | 1184.03 | 1287.62 | 24.0507 | 2405.07 |
| 1223.49 | 1173.15 | 1280.55 | 23.7952 | 2379.52 |
| 1207.65 | 1165.33 | 1275.47 | 23.6068 | 2360.68 |
| 1202.48 | 1162.79 | 1273.82 | 23.5445 | 2354.45 |
| 1182.25 | 1152.89 | 1267.39 | 23.2984 | 2329.84 |
| 1162.77 | 1143.45 | 1261.24 | 23.0566 | 2305.66 |
| 1158.02 | 1141.15 | 1259.75 | 22.9969 | 2299.69 |
| 1153.3 | 1138.88 | 1258.28 | 22.9373 | 2293.73 |
| 1144.01 | 1134.42 | 1255.38 | 22.8191 | 2281.91 |
| 1125.92 | 1125.78 | 1249.76 | 22.5855 | 2258.55 |
| 1112.78 | 1119.55 | 1245.71 | 22.413 | 2241.3 |
| 1108.48 | 1117.52 | 1244.39 | 22.3559 | 2235.59 |
| 1091.65 | 1109.6 | 1239.25 | 22.13 | 2213 |
| 1083.46 | 1105.77 | 1236.75 | 22.0184 | 2201.84 |
| 1075.41 | 1102.01 | 1234.31 | 21.9077 | 2190.77 |
| 1063.59 | 1096.53 | 1230.75 | 21.7433 | 2174.33 |
| 1059.72 | 1094.74 | 1229.58 | 21.6889 | 2168.89 |
| 1044.57 | 1087.75 | 1225.04 | 21.4734 | 2147.34 |

==================================

Table B2-1. Corrected Results from the Case of Sodium Bicarbonate with NSR = 3.37 (Figure 24) :

CORRECTED DATA

| Time (min) | SO2 (ppm) | NOx (ppm) | NO (ppm) |
|---|---|---|---|
| 0 | 1660.945 | 1545.957 | 1533.899 |
| 0.25 | 1629.602 | | |
| 0.5 | | 1477.619 | |
| 1 | | | 1357.264 |
| 1.5 | | 1424.988 | |
| 2 | | | 1324.406 |
| 2.5 | | | |
| 2.75 | 1354.878 | | |
| 3 | | 1340.038 | |
| 3.5 | | | |
| 4 | | | 1206.931 |
| 4.5 | | | |
| 5 | | | |
| 5.25 | 1037.27 | | |
| 5.5 | | | |
| 6 | | 1296.204 | |
| 7 | | | |
| 7.75 | 829.3276 | | |
| 8 | | | 1063.998 |
| 9 | | | |
| 10 | | | |
| 10.25 | 616.3675 | | |
| 10.5 | | | |

| | | | |
|---|---|---|---|
| 11 | | 1171.119 | |
| 12 | | | |
| 12.75 | 394.5502 | | |
| 13 | | | |
| 14 | | | 901.3587 |
| 15 | | | |
| 15.25 | 292.2909 | | |
| 15.5 | | | |
| 16 | | | |
| 17 | | 1131.476 | |
| 17.75 | 212.9872 | | |
| 18 | | | |
| 19 | | | |
| 20 | | | |
| 20.25 | 197.7455 | | |
| 20.5 | | | |
| 21 | | | 832.3858 |
| 22 | | | |
| 22.75 | 182.3518 | | |
| 23 | | | |
| 24 | | 1093.229 | |
| 24.5 | | | 846.7836 |
| 25 | | 1094.626 | |
| 25.75 | 159.5636 | | |
| 26 | | | |
| 27 | | | |

Table B2-2. Simulation Results from the Case of Sodium Bicarbonate with NSR = 3.37 (Figure 24) :

SIMULATION (with kA=7.65, kB=1.06E8, and x=0.70)

| SO2 (ppm) | NO (ppm) | NOx (ppm) | R(um) | R(um) X 100 |
|---|---|---|---|---|
| 1661 | 1534 | 1546 | 29 | 2900 |
| 1615.32 | 1506.21 | 1527.94 | 28.9172 | 2891.72 |
| 1571.15 | 1479.82 | 1510.78 | 28.837 | 2883.7 |
| 1487.06 | 1430.85 | 1478.95 | 28.6836 | 2868.36 |
| 1408.28 | 1386.43 | 1450.08 | 28.5391 | 2853.91 |
| 1334.37 | 1346.03 | 1423.82 | 28.4028 | 2840.28 |
| 1264.98 | 1309.16 | 1399.85 | 28.2743 | 2827.43 |
| 1231.87 | 1291.92 | 1388.65 | 28.2127 | 2821.27 |
| 1199.76 | 1275.43 | 1377.93 | 28.1529 | 2815.29 |
| 1138.41 | 1244.49 | 1357.82 | 28.0381 | 2803.81 |
| 1080.64 | 1216.05 | 1339.33 | 27.9295 | 2792.95 |
| 1026.21 | 1189.85 | 1322.3 | 27.8267 | 2782.67 |
| 974.88 | 1165.65 | 1306.57 | 27.7294 | 2772.94 |
| 950.31 | 1154.25 | 1299.16 | 27.6827 | 2768.27 |
| 926.44 | 1143.27 | 1292.03 | 27.6372 | 2763.72 |
| 880.7 | 1122.53 | 1278.55 | 27.5497 | 2754.97 |
| 796.62 | 1085.39 | 1254.4 | 27.388 | 2738.8 |
| 739.41 | 1060.82 | 1238.43 | 27.2773 | 2727.73 |
| 721.36 | 1053.19 | 1233.47 | 27.2423 | 2724.23 |
| 653.88 | 1025.12 | 1215.23 | 27.1106 | 2711.06 |
| 593.24 | 1000.54 | 1199.25 | 26.9917 | 2699.17 |
| 579.06 | 994.88 | 1195.57 | 26.9637 | 2696.37 |
| 565.24 | 989.39 | 1192.01 | 26.9365 | 2693.65 |

| | | | | |
|---|---|---|---|---|
| 538.66 | 978.93 | 1185.2 | 26.8839 | 2688.39 |
| 489.47 | 959.84 | 1172.8 | 26.7863 | 2678.63 |
| 455.74 | 946.97 | 1164.43 | 26.7191 | 2671.91 |
| 445.06 | 942.93 | 1161.81 | 26.6978 | 2669.78 |
| 404.92 | 927.91 | 1152.04 | 26.6174 | 2661.74 |
| 368.61 | 914.52 | 1143.34 | 26.5444 | 2654.44 |
| 360.08 | 911.4 | 1141.31 | 26.5272 | 2652.72 |
| 351.75 | 908.37 | 1139.34 | 26.5104 | 2651.04 |
| 335.71 | 902.56 | 1135.56 | 26.478 | 2647.8 |
| 305.89 | 891.85 | 1128.6 | 26.4176 | 2641.76 |
| 285.35 | 884.55 | 1123.86 | 26.3759 | 2637.59 |
| 278.83 | 882.24 | 1122.36 | 26.3626 | 2636.26 |
| 254.25 | 873.61 | 1116.75 | 26.3125 | 2631.25 |
| 231.93 | 865.84 | 1111.69 | 26.2669 | 2626.69 |
| 226.67 | 864.02 | 1110.51 | 26.2561 | 2625.61 |
| 221.53 | 862.24 | 1109.36 | 26.2456 | 2624.56 |
| 211.62 | 858.83 | 1107.14 | 26.2253 | 2622.53 |
| 193.15 | 852.5 | 1103.03 | 26.1874 | 2618.74 |
| 180.39 | 848.16 | 1100.2 | 26.1611 | 2616.11 |
| 176.33 | 846.78 | 1099.31 | 26.1528 | 2615.28 |
| 161.02 | 841.61 | 1095.95 | 26.1212 | 2612.12 |
| 153.88 | 839.21 | 1094.39 | 26.1065 | 2610.65 |
| 147.06 | 836.92 | 1092.9 | 26.0924 | 2609.24 |
| 137.41 | 833.7 | 1090.8 | 26.0724 | 2607.24 |
| 134.34 | 832.67 | 1090.14 | 26.0661 | 2606.61 |
| 122.75 | 828.82 | 1087.63 | 26.0421 | 2604.21 |

============================

Table B3-1. Corrected Results from the Case of Sodium Bicarbonate with NSR = 3.37 (Figure 25) :

CORRECTED DATA

| Time (min) | SO2 (ppm) | NOx (ppm) | NO (ppm) |
|---|---|---|---|
| 0 | 1652.04 | 1485.925 | 1476.388 |
| 0.25 | 1652.04 | | |
| 0.5 | | 1447.604 | |
| 1 | | | 1391.77 |
| 1.5 | | 1412.982 | |
| 2 | | | 1364.664 |
| 2.5 | | | |
| 2.75 | 1266.887 | | |
| 3 | | 1382.06 | |
| 3.5 | | | |
| 4 | | | 1229.935 |
| 4.5 | | | |
| 5 | | | |
| 5.25 | 1018.684 | | |
| 5.5 | | | |
| 6 | | 1296.204 | |
| 7 | | | |
| 7.75 | 775.0761 | | |
| 8 | | | 1035.243 |
| 9 | | | |
| 10 | | | |
| 10.25 | 553.2198 | | |
| 10.5 | | | |
| 11 | | 1099.082 | |

| | | | |
|---|---|---|---|
| 12 | | | |
| 12.75 | 454.2929 | | |
| 13 | | | |
| 14 | | | 878.3544 |
| 15 | | | |
| 15.25 | 309.4106 | | |
| 15.5 | | | |
| 16 | | | |
| 17 | | 1023.419 | |
| 17.75 | 212.9872 | | |
| 18 | | | |
| 19 | | | |
| 20 | | | |
| 20.25 | 179.7919 | | |
| 20.5 | | | |
| 21 | | | 815.1325 |
| 22 | | | |
| 22.75 | 128.0145 | | |
| 23 | | | |
| 24 | | 1039.201 | |
| 24.5 | | | 783.5216 |
| 25 | | 1028.591 | |
| 25.75 | 98.53301 | | |
| 26 | | | |
| 27 | | | |

========================

Table B3-2. Simulated Results from the Case of Sodium with NSR = 3.37 (Figure 25) :

SIMULATION (with kA=7.65, kB=1.06E8, x=0.70)

| SO2 (ppm) | NO (ppm) | NOx (ppm) | R (um) | R X100 |
|---|---|---|---|---|
| 1652.04 | 1476.39 | 1485.93 | 29 | 2900 |
| 1606.62 | 1448.33 | 1467.69 | 28.9129 | 2891.29 |
| 1562.7 | 1421.71 | 1450.39 | 28.8284 | 2882.84 |
| 1479.14 | 1372.39 | 1418.33 | 28.667 | 2866.7 |
| 1400.88 | 1327.76 | 1389.32 | 28.515 | 2851.5 |
| 1327.5 | 1287.24 | 1362.98 | 28.3718 | 2837.18 |
| 1258.63 | 1250.32 | 1338.99 | 28.2366 | 2823.66 |
| 1225.78 | 1233.09 | 1327.79 | 28.1718 | 2817.18 |
| 1193.92 | 1216.61 | 1317.07 | 28.1089 | 2810.89 |
| 1133.07 | 1185.73 | 1297 | 27.9882 | 2798.82 |
| 1075.78 | 1157.38 | 1278.57 | 27.8741 | 2787.41 |
| 1021.81 | 1131.29 | 1261.62 | 27.766 | 2776.6 |
| 970.93 | 1107.23 | 1245.98 | 27.6636 | 2766.36 |
| 946.58 | 1095.9 | 1238.61 | 27.6145 | 2761.45 |
| 922.92 | 1085 | 1231.53 | 27.5666 | 2756.66 |
| 877.59 | 1064.42 | 1218.15 | 27.4746 | 2747.46 |
| 794.26 | 1027.6 | 1194.22 | 27.3045 | 2730.45 |
| 737.57 | 1003.29 | 1178.41 | 27.188 | 2718.8 |
| 719.69 | 995.73 | 1173.5 | 27.1511 | 2715.11 |
| 652.8 | 967.99 | 1155.47 | 27.0125 | 2701.25 |
| 592.7 | 943.72 | 1139.7 | 26.8871 | 2688.71 |
| 578.63 | 938.13 | 1136.06 | 26.8577 | 2685.77 |
| 564.94 | 932.72 | 1132.55 | 26.8289 | 2682.89 |

| | | | | |
|---|---|---|---|---|
| 538.58 | 922.4 | 1125.83 | 26.7735 | 2677.35 |
| 489.79 | 903.58 | 1113.6 | 26.6706 | 2667.06 |
| 456.33 | 890.89 | 1105.36 | 26.5996 | 2659.96 |
| 445.73 | 886.91 | 1102.77 | 26.5771 | 2657.71 |
| 405.88 | 872.11 | 1093.15 | 26.4921 | 2649.21 |
| 369.81 | 858.92 | 1084.57 | 26.4149 | 2641.49 |
| 361.34 | 855.85 | 1082.58 | 26.3967 | 2639.67 |
| 353.07 | 852.87 | 1080.64 | 26.3789 | 2637.89 |
| 337.12 | 847.14 | 1076.92 | 26.3446 | 2634.46 |
| 307.46 | 836.59 | 1070.06 | 26.2806 | 2628.06 |
| 287.03 | 829.4 | 1065.39 | 26.2364 | 2623.64 |
| 280.54 | 827.13 | 1063.91 | 26.2223 | 2622.23 |
| 256.07 | 818.62 | 1058.38 | 26.1691 | 2616.91 |
| 233.81 | 810.96 | 1053.4 | 26.1207 | 2612.07 |
| 228.57 | 809.17 | 1052.24 | 26.1092 | 2610.92 |
| 223.45 | 807.42 | 1051.1 | 26.098 | 2609.8 |
| 213.56 | 804.06 | 1048.91 | 26.0764 | 2607.64 |
| 195.12 | 797.82 | 1044.86 | 26.0361 | 2603.61 |
| 182.38 | 793.53 | 1042.07 | 26.0081 | 2600.81 |
| 178.32 | 792.18 | 1041.19 | 25.9992 | 2599.92 |
| 163.01 | 787.07 | 1037.87 | 25.9655 | 2596.55 |
| 155.87 | 784.7 | 1036.33 | 25.9498 | 2594.98 |
| 149.05 | 782.44 | 1034.86 | 25.9348 | 2593.48 |
| 139.38 | 779.25 | 1032.79 | 25.9134 | 2591.34 |
| 136.31 | 778.24 | 1032.13 | 25.9066 | 2590.66 |
| 124.68 | 774.42 | 1029.65 | 25.8809 | 2588.09 |

Table B4-1. Corrected Results from the Case of Sodium Bicarbonate with NSR = 13.5 (Figure 26)

Corrected Data

| Time (min) | (SO2) (ppm) | (NOx) (ppm) | (NO) (ppm) |
|---|---|---|---|
| 0 | 1745.43 | 1497.93 | 1482.14 |
| 0.25 | 1652.04 | | |
| 0.5 | | 1338.24 | |
| 1 | | | 1124.61 |
| 1.5 | | | |
| 2 | | | 956.858 |
| 2.5 | | 933.596 | |
| 2.75 | 1065.02 | | |
| 3 | | | |
| 3.5 | | 884.353 | |
| 4 | | | 805.398 |
| 4.5 | | 853.12 | |
| 5 | | | 764.175 |
| 5.25 | 578.817 | | |
| 5.5 | | | |
| 6 | | | 705.698 |
| 6.5 | | 826.672 | |
| 7 | | | 681.728 |
| 7.5 | | 789.435 | |
| 7.75 | 250.059 | | |
| 8 | | | 652.007 |
| 8.5 | | 764.205 | |
| 9 | | | |
| 9.5 | | | |
| 10 | | | |
| 10.25 | 83.2901 | | |
| 10.5 | | | |

```
    11
    12
 12.75    6.10909
    13
=====================
```

Table B4-2. Simulation Results from the Case of Sodium Bicarbonate with NSR = 13.5 (Figure 26)

Simulated Data (with kA=7.65, kB=1.06E8, and x=0.70)

| (SO2) (ppm) | (NOx) (ppm) | (NO) (ppm) | R (um) | R*100 (um) |
|---|---|---|---|---|
| 1745.43 | 1482.14 | 1497.93 | 29 | 2900 |
| 1561.21 | 1376.78 | 1401.25 | 28.9174 | 2891.74 |
| 1397.26 | 1289.34 | 1321.01 | 28.8442 | 2884.42 |
| 1120.92 | 1154.34 | 1197.13 | 28.7216 | 2872.16 |
| 900.74 | 1056.97 | 1107.78 | 28.6244 | 2862.44 |
| 724.76 | 985.09 | 1041.82 | 28.5471 | 2854.71 |
| 583.78 | 931.04 | 992.22 | 28.4852 | 2848.52 |
| 524.11 | 909.07 | 972.06 | 28.4591 | 2845.91 |
| 470.62 | 889.82 | 954.39 | 28.4357 | 2843.57 |
| 379.65 | 858 | 925.2 | 28.3959 | 2839.59 |
| 306.43 | 833.23 | 902.46 | 28.3639 | 2836.39 |
| 247.44 | 813.78 | 884.62 | 28.3381 | 2833.81 |
| 199.88 | 798.44 | 870.54 | 28.3173 | 2831.73 |
| 179.66 | 792.01 | 864.64 | 28.3085 | 2830.85 |
| 161.5 | 786.27 | 859.37 | 28.3006 | 2830.06 |
| 130.52 | 776.58 | 850.48 | 28.287 | 2828.7 |
| 105.5 | 768.85 | 843.38 | 28.2761 | 2827.61 |
| 85.29 | 762.65 | 837.7 | 28.2673 | 2826.73 |
| 68.96 | 757.68 | 833.14 | 28.2602 | 2826.02 |
| 62.01 | 755.58 | 831.21 | 28.2571 | 2825.71 |
| 55.77 | 753.69 | 829.48 | 28.2544 | 2825.44 |
| 45.1 | 750.48 | 826.53 | 28.2498 | 2824.98 |
| 36.47 | 747.9 | 824.16 | 28.246 | 2824.6 |
| 29.5 | 745.81 | 822.25 | 28.243 | 2824.3 |
| 23.86 | 744.13 | 820.7 | 28.2405 | 2824.05 |
| 21.46 | 743.41 | 820.05 | 28.2394 | 2823.94 |
| 19.3 | 742.77 | 819.46 | 28.2385 | 2823.85 |

|  |  |  |  |  |
|---|---|---|---|---|
| 15.61 | 741.68 | 818.45 | 28.2369 | 2823.69 |
| 10.21 | 740.08 | 816.98 | 28.2345 | 2823.45 |
| 7.43 | 739.25 | 816.23 | 28.2333 | 2823.33 |
| 6.68 | 739.03 | 816.03 | 28.233 | 2823.3 |

================================

Table B5-1. Corrected Results from the Case of Sodium Sesquicarbonate with NSR = 0.85 (Figure 27)

CORRECTED DATA

| Time<br>(min) | SO2<br>(ppm) | NOx<br>(ppm) | NO<br>(ppm) |
|---|---|---|---|
| 0 | 1725.517 | 1491.929 | 1487.89 |
| 0.25 | 1620.329 | | |
| 0.5 | | 1465.613 | |
| 1 | | | 1397.521 |
| 1.5 | | 1424.988 | |
| 2 | | | 1358.913 |
| 2.5 | | | |
| 2.75 | 1528.297 | | |
| 3 | | 1388.063 | |
| 3.5 | | | |
| 4 | | | 1321.953 |
| 4.5 | | | |
| 5 | | | |
| 5.25 | 1433.181 | | |
| 5.5 | | | |
| 6 | | 1350.232 | |
| 7 | | | |
| 7.75 | | | |
| 8 | | | 1213.526 |
| 9 | | | |
| 10 | | | |
| 10.25 | 1343.537 | | |
| 10.5 | | | |

|  |  |  |  |
|---|---|---|---|
| 11 |  | 1309.191 |  |
| 12 |  |  |  |
| 12.75 | 1326.151 |  |  |
| 13 |  |  |  |
| 14 |  |  | 1160.158 |
| 15 |  |  |  |
| 15.25 | 1320.908 |  |  |
| 15.5 |  |  |  |
| 16 |  |  |  |
| 17 |  | 1299.563 |  |
| 17.75 | 1293.54 |  |  |
| 18 |  |  |  |
| 19 |  |  |  |
| 20 |  |  |  |
| 20.25 | 1287.445 |  |  |
| 20.5 |  |  |  |
| 21 |  |  | 1160.198 |
| 22 |  |  |  |
| 22.75 | 1275.983 |  |  |
| 23 |  |  |  |
| 24 |  | 1339.357 |  |
| 24.5 |  |  | 1082.578 |
| 25 |  | 1316.741 |  |
| 26 |  |  |  |

Table B5-2. Simulation Results from the Case of Sodium Sesquicarbonate with NSR = 0.85 (Figure 27)

SIMULATION (with kA=8.77, kB=1.24E8, and x=0.55)

| SO2 (ppm) | NO (ppm) | NOx (ppm) | R(um) | R(um) X 100 |
|---|---|---|---|---|
| 1725.52 | 1487.89 | 1491.93 | 29 | 2900 |
| 1711.94 | 1479.2 | 1485.63 | 28.899 | 2889.9 |
| 1698.55 | 1470.69 | 1479.46 | 28.7989 | 2879.89 |
| 1672.37 | 1454.19 | 1467.5 | 28.6014 | 2860.14 |
| 1646.94 | 1438.33 | 1456 | 28.4074 | 2840.74 |
| 1622.23 | 1423.09 | 1444.95 | 28.2166 | 2821.66 |
| 1598.21 | 1408.43 | 1434.32 | 28.029 | 2802.9 |
| 1586.45 | 1401.31 | 1429.16 | 27.9364 | 2793.64 |
| 1574.85 | 1394.33 | 1424.1 | 27.8445 | 2784.45 |
| 1552.14 | 1380.74 | 1414.25 | 27.6631 | 2766.31 |
| 1530.04 | 1367.65 | 1404.76 | 27.4845 | 2748.45 |
| 1508.54 | 1355.03 | 1395.61 | 27.3088 | 2730.88 |
| 1487.6 | 1342.85 | 1386.78 | 27.1357 | 2713.57 |
| 1477.34 | 1336.93 | 1382.48 | 27.0502 | 2705.02 |
| 1467.21 | 1331.1 | 1378.26 | 26.9654 | 2696.54 |
| 1447.35 | 1319.76 | 1370.03 | 26.7976 | 2679.76 |
| 1409.14 | 1298.19 | 1354.4 | 26.4694 | 2646.94 |
| 1381.73 | 1282.95 | 1343.35 | 26.2295 | 2622.95 |
| 1372.82 | 1278.03 | 1339.78 | 26.1507 | 2615.07 |
| 1338.27 | 1259.14 | 1326.08 | 25.8408 | 2584.08 |
| 1305.36 | 1241.4 | 1313.23 | 25.5394 | 2553.94 |
| 1297.38 | 1237.14 | 1310.13 | 25.4653 | 2546.53 |
| 1289.5 | 1232.94 | 1307.09 | 25.3917 | 2539.17 |

| | | | | |
|---|---|---|---|---|
| 1274 | 1224.73 | 1301.14 | 25.246 | 2524.6 |
| 1244.07 | 1209.03 | 1289.76 | 24.9602 | 2496.02 |
| 1222.52 | 1197.85 | 1281.65 | 24.7505 | 2475.05 |
| 1215.5 | 1194.23 | 1279.03 | 24.6815 | 2468.15 |
| 1188.18 | 1180.25 | 1268.89 | 24.4097 | 2440.97 |
| 1162.06 | 1167.04 | 1259.31 | 24.1444 | 2414.44 |
| 1155.71 | 1163.84 | 1257 | 24.0791 | 2407.91 |
| 1149.42 | 1160.7 | 1254.71 | 24.0141 | 2401.41 |
| 1137.06 | 1154.52 | 1250.24 | 23.8854 | 2388.54 |
| 1113.1 | 1142.66 | 1241.64 | 23.6322 | 2363.22 |
| 1107.27 | 1139.79 | 1239.56 | 23.5698 | 2356.98 |
| 1090.14 | 1131.41 | 1233.48 | 23.3847 | 2338.47 |
| 1068.11 | 1120.72 | 1225.73 | 23.1426 | 2314.26 |
| 1046.96 | 1110.55 | 1218.36 | 22.9057 | 2290.57 |
| 1041.81 | 1108.08 | 1216.57 | 22.8473 | 2284.73 |
| 1036.71 | 1105.65 | 1214.8 | 22.7891 | 2278.91 |
| 1026.65 | 1100.86 | 1211.34 | 22.6738 | 2267.38 |
| 1007.13 | 1091.64 | 1204.65 | 22.4466 | 2244.66 |
| 992.98 | 1085 | 1199.84 | 22.2791 | 2227.91 |
| 988.36 | 1082.84 | 1198.27 | 22.2239 | 2222.39 |
| 970.29 | 1074.44 | 1192.18 | 22.0056 | 2200.56 |
| 961.51 | 1070.38 | 1189.24 | 21.898 | 2189.8 |
| 952.9 | 1066.41 | 1186.36 | 21.7914 | 2179.14 |
| 936.14 | 1058.74 | 1180.8 | 21.5813 | 2158.13 |

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Table B6-1. Corrected Results from the Case of Sodium Sesquicarbonate with NSR = 0.85 (Figure 32)

| CORRECTED DATA | | | |
|---|---|---|---|
| Time (min) | SO2 (ppm) | NOx (ppm) | NO (ppm) |
| 0 | 1569.756 | 1581.975 | 1556.903 |
| 0.5 | 1497.018 | | |
| 1 | | 1529.344 | |
| 1.5 | | | 1464.483 |
| 2 | | | |
| 2.5 | 1326.406 | | |
| 3 | | 1508.125 | |
| 3.5 | | | 1393.017 |
| 4 | | 1503.519 | |
| 4.5 | | | 1371.661 |
| 5 | | | |
| 5.5 | | 1478.6 | |
| 6 | | | 1336.753 |
| 6.5 | 1242.473 | | |
| 7 | | | |
| 8 | | 1455.079 | |
| 8.5 | | | 1297.742 |
| 9 | | | |
| 9.5 | 1206.109 | | |
| 10 | | 1427.857 | |
| 10.5 | | | 1266.533 |
| 11 | | | |
| 12 | | | |

| | | | |
|---|---|---|---|
| 12.5 | 1163.304 | | |
| 13 | | 1420.041 | |
| 13.5 | | | 1219.72 |
| 14 | | | |
| 15 | | | |
| 15.5 | 1103.927 | | |
| 16 | | 1412.225 | |
| 16.5 | | | 1184.409 |
| 17 | | | |
| 18 | | | |
| 18.5 | 1060.655 | | |
| 19 | | 1398.407 | |
| 19.5 | | | 1166.351 |
| 20 | | | |
| 20.5 | | | |
| 21 | | | |
| 21.5 | 1042.473 | | |
| 22 | | 1414.604 | |
| 22.5 | | | 1159.796 |
| 23 | | | |
| 24 | | | |
| 24.5 | 1032.621 | | |
| 25 | | | |
| 25.5 | | | |
| 26 | | | |
| 27 | | | |
| 27.5 | 1015.881 | | |
| 28 | | 1410.979 | |
| 28.5 | | | 1158.187 |
| 29 | | | |

Table B6-2. Simulation Results from the Case of Sodium Sesquicarbonate with NSR = 0.85 (Figure 32)

SIMULATION (with kA=8.77, kB=1.24E8, x=0.55)

| SO2 (ppm) | NO (ppm) | NOx (ppm) | R(um) | R(um) X 100 |
|---|---|---|---|---|
| 1569.76 | 1556.9 | 1581.98 | 29 | 2900 |
| 1545.21 | 1540.51 | 1570.1 | 28.8155 | 2881.55 |
| 1521.35 | 1524.75 | 1558.67 | 28.6342 | 2863.42 |
| 1498.15 | 1509.57 | 1547.67 | 28.4561 | 2845.61 |
| 1475.58 | 1494.96 | 1537.07 | 28.2809 | 2828.09 |
| 1453.63 | 1480.88 | 1526.86 | 28.1088 | 2810.88 |
| 1432.25 | 1467.3 | 1517.02 | 27.9394 | 2793.94 |
| 1411.44 | 1454.19 | 1507.52 | 27.7728 | 2777.28 |
| 1391.18 | 1441.54 | 1498.35 | 27.6089 | 2760.89 |
| 1371.44 | 1429.33 | 1489.49 | 27.4476 | 2744.76 |
| 1352.2 | 1417.52 | 1480.93 | 27.2888 | 2728.88 |
| 1333.45 | 1406.11 | 1472.66 | 27.1325 | 2713.25 |
| 1315.16 | 1395.07 | 1464.66 | 26.9785 | 2697.85 |
| 1297.33 | 1384.39 | 1456.91 | 26.8268 | 2682.68 |
| 1279.94 | 1374.05 | 1449.41 | 26.6774 | 2667.74 |
| 1246.4 | 1354.33 | 1435.12 | 26.3851 | 2638.51 |
| 1230.23 | 1344.92 | 1428.3 | 26.2421 | 2624.21 |
| 1214.44 | 1335.8 | 1421.68 | 26.1011 | 2610.11 |
| 1199.02 | 1326.95 | 1415.26 | 25.962 | 2596.2 |
| 1183.95 | 1318.36 | 1409.04 | 25.8249 | 2582.49 |
| 1169.23 | 1310.02 | 1402.99 | 25.6896 | 2568.96 |
| 1154.84 | 1301.92 | 1397.12 | 25.5561 | 2555.61 |
| 1127.02 | 1286.4 | 1385.86 | 25.2945 | 2529.45 |

| | | | | |
|---|---|---|---|---|
| 1113.57 | 1278.96 | 1380.47 | 25.1662 | 2516.62 |
| 1100.42 | 1271.73 | 1375.23 | 25.0396 | 2503.96 |
| 1087.54 | 1264.69 | 1370.13 | 24.9145 | 2491.45 |
| 1074.95 | 1257.84 | 1365.16 | 24.7911 | 2479.11 |
| 1050.55 | 1244.68 | 1355.62 | 24.5487 | 2454.87 |
| 1038.74 | 1238.36 | 1351.04 | 24.4297 | 2442.97 |
| 1027.17 | 1232.2 | 1346.57 | 24.3122 | 2431.22 |
| 1015.83 | 1226.19 | 1342.22 | 24.196 | 2419.6 |
| 1004.73 | 1220.34 | 1337.97 | 24.0812 | 2408.12 |
| 983.19 | 1209.06 | 1329.8 | 23.8556 | 2385.56 |
| 972.74 | 1203.63 | 1325.86 | 23.7447 | 2374.47 |
| 962.5 | 1198.32 | 1322.01 | 23.6351 | 2363.51 |
| 952.46 | 1193.15 | 1318.26 | 23.5267 | 2352.67 |
| 942.61 | 1188.1 | 1314.6 | 23.4195 | 2341.95 |
| 932.96 | 1183.16 | 1311.02 | 23.3135 | 2331.35 |
| 923.48 | 1178.34 | 1307.52 | 23.2086 | 2320.86 |
| 914.19 | 1173.63 | 1304.11 | 23.1049 | 2310.49 |
| 905.07 | 1169.02 | 1300.77 | 23.0022 | 2300.22 |
| 896.13 | 1164.52 | 1297.51 | 22.9007 | 2290.07 |
| 887.34 | 1160.12 | 1294.32 | 22.8001 | 2280.01 |
| 870.26 | 1151.61 | 1288.15 | 22.6022 | 2260.22 |
| 861.95 | 1147.49 | 1285.16 | 22.5048 | 2250.48 |
| 853.79 | 1143.47 | 1282.24 | 22.4083 | 2240.83 |
| 845.78 | 1139.52 | 1279.38 | 22.3128 | 2231.28 |
| 837.91 | 1135.66 | 1276.58 | 22.2182 | 2221.82 |
| 822.58 | 1128.18 | 1271.16 | 22.0318 | 2203.18 |
| 815.11 | 1124.56 | 1268.53 | 21.9399 | 2193.99 |
| 807.78 | 1121.01 | 1265.96 | 21.849 | 2184.9 |
| 800.57 | 1117.53 | 1263.44 | 21.7588 | 2175.88 |
| 793.48 | 1114.12 | 1260.96 | 21.6696 | 2166.96 |

==================================

Table B7-1. Corrected Results from the Case of Sodium Sesquicarbonate with NSR = 3.38 (Figure 28)

CORRECTED DATA

| Time<br>(min) | SO2<br>(ppm) | NOx<br>(ppm) | NO<br>(ppm) |
|---|---|---|---|
| 0 | 1507.547 | 1533.95 | 1487.89 |
| 0.5 | | | |
| 1 | | 1457.307 | |
| 1.5 | | | |
| 2 | | | 1261.144 |
| 2.5 | | | |
| 3 | 851.4231 | | |
| 3.5 | | | |
| 4 | | 1257.391 | |
| 4.5 | | | |
| 5 | | | 1059.051 |
| 5.5 | | | |
| 6 | 633.1955 | | |
| 7 | | 1219.56 | |
| 8 | | | 994.985 |
| 9 | 515.4968 | | |
| 10 | | 1181.729 | |
| 10.5 | | | |
| 11 | | | 959.674 |
| 12 | 421.9122 | | |
| 13 | | | |
| 14 | | | |
| 15 | 357.7891 | | |
| 15.5 | | | |

| | | | |
|---|---|---|---|
| 16 | | 1118.073 | |
| 17 | | | 935.0609 |
| 18 | 291.1866 | | |
| 19 | | | |
| 20 | | | |
| 20.5 | | | |
| 21 | 245.9431 | | |
| 22 | | 1126.454 | |
| 23 | | | 893.1945 |
| 24 | 142.529 | | |
| 25 | | | |
| 26 | | | |
| 27 | 164.3607 | | |
| 28 | | 1110.823 | |
| 29 | | | 874.3325 |
| 30 | 124.0352 | | |

Table B7-2. Simulation Results from the Case of Sodium Sesquicarbonate with NSR = 3.38 (Figure 28)

SIMULATION (with kA=8.77, kB=1.24, and x=0.55)

| SO2 (ppm) | NO (ppm) | NOx (ppm) | R (um) | R(um) X100 |
|---|---|---|---|---|
| 1507.55 | 1487.89 | 1533.95 | 29 | 2900 |
| 1420.11 | 1432.85 | 1494.05 | 28.8286 | 2882.86 |
| 1338.66 | 1383.41 | 1458.2 | 28.6681 | 2866.81 |
| 1262.68 | 1338.84 | 1425.89 | 28.5177 | 2851.77 |
| 1191.72 | 1298.5 | 1396.64 | 28.3765 | 2837.65 |
| 1125.38 | 1261.89 | 1370.1 | 28.244 | 2824.4 |
| 1063.28 | 1228.56 | 1345.94 | 28.1193 | 2811.93 |
| 1005.09 | 1198.13 | 1323.87 | 28.002 | 2800.2 |
| 950.53 | 1170.27 | 1303.68 | 27.8915 | 2789.15 |
| 899.31 | 1144.72 | 1285.15 | 27.7873 | 2778.73 |
| 851.19 | 1121.22 | 1268.11 | 27.6891 | 2768.91 |
| 805.95 | 1099.56 | 1252.41 | 27.5963 | 2759.63 |
| 763.38 | 1079.57 | 1237.92 | 27.5088 | 2750.88 |
| 685.56 | 1043.96 | 1212.1 | 27.3478 | 2734.78 |
| 616.4 | 1013.29 | 1189.87 | 27.2038 | 2720.38 |
| 554.81 | 986.74 | 1170.62 | 27.0747 | 2707.47 |
| 499.84 | 963.64 | 1153.87 | 26.9589 | 2695.89 |
| 474.59 | 953.2 | 1146.3 | 26.9055 | 2690.55 |
| 450.7 | 943.44 | 1139.22 | 26.8548 | 2685.48 |
| 406.7 | 925.71 | 1126.37 | 26.7612 | 2676.12 |
| 367.25 | 910.1 | 1115.05 | 26.6768 | 2667.68 |
| 331.82 | 896.31 | 1105.05 | 26.6008 | 2660.08 |
| 299.98 | 884.09 | 1096.2 | 26.5322 | 2653.22 |
| 285.28 | 878.5 | 1092.15 | 26.5005 | 2650.05 |

|  |  |  |  |  |
|---|---|---|---|---|
| 271.33 | 873.24 | 1088.33 | 26.4703 | 2647.03 |
| 245.52 | 863.58 | 1081.32 | 26.4144 | 2641.44 |
| 222.26 | 854.96 | 1075.08 | 26.3638 | 2636.38 |
| 201.27 | 847.26 | 1069.49 | 26.3181 | 2631.81 |
| 182.33 | 840.37 | 1064.5 | 26.2767 | 2627.67 |
| 173.55 | 837.2 | 1062.2 | 26.2575 | 2625.75 |
| 165.22 | 834.19 | 1060.02 | 26.2392 | 2623.92 |
| 149.75 | 828.65 | 1056 | 26.2053 | 2620.53 |
| 135.76 | 823.67 | 1052.39 | 26.1746 | 2617.46 |
| 123.11 | 819.19 | 1049.14 | 26.1467 | 2614.67 |
| 111.66 | 815.16 | 1046.22 | 26.1215 | 2612.15 |
| 101.29 | 811.52 | 1043.58 | 26.0986 | 2609.86 |
| 91.9 | 808.24 | 1041.21 | 26.0779 | 2607.79 |
| 83.39 | 805.28 | 1039.06 | 26.0591 | 2605.91 |
| 75.68 | 802.61 | 1037.12 | 26.042 | 2604.2 |
| 68.7 | 800.2 | 1035.37 | 26.0265 | 2602.65 |

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Table B8-1. Corrected Results from the Case of Sodium Sesquicarbonate with NSR = 3.38 (Figure 29)

CORRECTED DATA

| Time<br>(min) | SO2<br>(ppm) | NOx<br>(ppm) | NO<br>(ppm) |
|---|---|---|---|
| 0 | 1498.712 | 1533.95 | 1505.143 |
| 0.5 | | | |
| 1 | | 1421.288 | |
| 1.5 | | | |
| 2 | | | 1238.14 |
| 2.5 | | | |
| 3 | 779.2395 | | |
| 3.5 | | | |
| 4 | | 1257.391 | |
| 4.5 | | | |
| 5 | | | 1099.309 |
| 5.5 | | | |
| 6 | 554.2251 | | |
| 7 | | 1165.532 | |
| 8 | | | 1023.74 |
| 9 | 451.2955 | | |
| 10 | | 1133.704 | |
| 10.5 | | | |
| 11 | | | 971.1762 |
| 12 | 349.0822 | | |
| 13 | | | |
| 14 | | | |
| 15 | 275.2263 | | |

| | | | |
|---|---|---|---|
| 15.5 | | | |
| 16 | | 1118.073 | |
| 17 | | | 952.3142 |
| 18 | 249.0683 | | |
| 19 | | | |
| 20 | | | |
| 20.5 | | | |
| 21 | 201.1042 | | |
| 22 | | 1120.451 | |
| 23 | | | 927.7011 |
| 24 | 146.1053 | | |
| 25 | | | |
| 26 | | | |
| 27 | 131.2129 | | |
| 28 | | 1140.838 | |
| 29 | | | 931.8434 |
| 30 | 105.6567 | | |

========================

Table B8-2. Simulation Results from the Case of Sodium Sesquicarbonate with NSR = 3.38 (Figure 29)

SIMULATION (with kA=8.77, kB=1.24E8, and x=0.55)

| SO2 (ppm) | NO (ppm) | NOx (ppm) | R(um) | R(um) X 100 |
|---|---|---|---|---|
| 1533.95 | 1505.14 | 1533.95 | 29 | 2900 |
| 1444.99 | 1442.32 | 1486.64 | 28.8253 | 2882.53 |
| 1362.14 | 1391.72 | 1449.95 | 28.6619 | 2866.19 |
| 1284.87 | 1346.12 | 1416.9 | 28.5087 | 2850.87 |
| 1212.71 | 1304.9 | 1387.01 | 28.3649 | 2836.49 |
| 1145.26 | 1267.5 | 1359.89 | 28.2299 | 2822.99 |
| 1082.13 | 1233.47 | 1335.22 | 28.1029 | 2810.29 |
| 1022.98 | 1202.42 | 1312.71 | 27.9834 | 2798.34 |
| 967.52 | 1174.01 | 1292.12 | 27.8709 | 2787.09 |
| 915.46 | 1147.96 | 1273.23 | 27.7648 | 2776.48 |
| 866.56 | 1124.02 | 1255.87 | 27.6648 | 2766.48 |
| 820.59 | 1101.96 | 1239.87 | 27.5704 | 2757.04 |
| 777.33 | 1081.6 | 1225.12 | 27.4812 | 2748.12 |
| 698.24 | 1045.35 | 1198.83 | 27.3172 | 2731.72 |
| 627.96 | 1014.15 | 1176.22 | 27.1705 | 2717.05 |
| 565.36 | 987.15 | 1156.64 | 27.039 | 2703.9 |
| 509.5 | 963.66 | 1139.61 | 26.9209 | 2692.09 |
| 483.83 | 953.06 | 1131.92 | 26.8665 | 2686.65 |
| 459.55 | 943.13 | 1124.73 | 26.8148 | 2681.48 |
| 414.81 | 925.12 | 1111.67 | 26.7193 | 2671.93 |
| 374.69 | 909.26 | 1100.17 | 26.6333 | 2663.33 |
| 338.66 | 895.25 | 1090.01 | 26.5557 | 2655.57 |

| | | | | |
|---|---|---|---|---|
| 306.27 | 882.83 | 1081.01 | 26.4857 | 2648.57 |
| 291.31 | 877.16 | 1076.9 | 26.4533 | 2645.33 |
| 277.12 | 871.81 | 1073.02 | 26.4225 | 2642.25 |
| 250.85 | 861.99 | 1065.9 | 26.3654 | 2636.54 |
| 227.17 | 853.24 | 1059.55 | 26.3137 | 2631.37 |
| 205.8 | 845.41 | 1053.88 | 26.267 | 2626.7 |
| 186.5 | 838.41 | 1048.8 | 26.2246 | 2622.46 |
| 177.56 | 835.18 | 1046.46 | 26.205 | 2620.5 |
| 169.06 | 832.13 | 1044.25 | 26.1863 | 2618.63 |
| 153.3 | 826.49 | 1040.16 | 26.1516 | 2615.16 |
| 139.04 | 821.43 | 1036.49 | 26.1202 | 2612.02 |
| 126.13 | 816.87 | 1033.19 | 26.0917 | 2609.17 |
| 114.45 | 812.77 | 1030.21 | 26.0658 | 2606.58 |
| 103.86 | 809.07 | 1027.53 | 26.0424 | 2604.24 |
| 94.27 | 805.73 | 1025.11 | 26.0211 | 2602.11 |
| 85.58 | 802.72 | 1022.93 | 26.0018 | 2600.18 |
| 77.7 | 800 | 1020.95 | 25.9843 | 2598.43 |
| 70.56 | 797.54 | 1019.17 | 25.9684 | 2596.84 |

Table B9-1. Corrected Results from the Case of Sodium Sesquicarbonate with NSR = 3.38 (Figure 30)

CORRECTED DATA

| Time (min) | SO2 (ppm) | NOx (ppm) | NO (ppm) |
|---|---|---|---|
| 0 | 1497.735 | 1473.919 | 1453.383 |
| 0.5 | 1210.789 | | |
| 1 | | 1301.225 | |
| 1.5 | | | 1245.942 |
| 2 | | | |
| 2.5 | 779.2395 | | |
| 3 | | 1219.976 | |
| 3.5 | | | 1128.467 |
| 4 | | 1185.354 | |
| 4.5 | | | 1095.609 |
| 5 | | | |
| 5.5 | | 1154.432 | |
| 6 | | | 1054.949 |
| 6.5 | 697.5384 | | |
| 7 | | | |
| 8 | | 1100.894 | |
| 8.5 | | | 1010.187 |
| 9 | | | |
| 9.5 | 551.3629 | | |
| 10 | | 1079.676 | |
| 10.5 | | | 967.4762 |
| 11 | | | |
| 12 | | | |
| 12.5 | 458.3382 | | |

| | | | |
|---|---|---|---|
| 13 | | 1071.86 | |
| 13.5 | | | 914.912 |
| 14 | | | |
| 15 | | | |
| 15.5 | 397.4017 | | |
| 16 | | 1070.048 | |
| 16.5 | | | 845.0945 |
| 17 | | | |
| 18 | | | |
| 18.5 | 338.9096 | | |
| 19 | | 1038.219 | |
| 19.5 | | | 832.788 |
| 20 | | | |
| 20.5 | | | |
| 21 | | | |
| 21.5 | 302.3264 | | |
| 22 | | 1042.41 | |
| 22.5 | | | 820.4814 |
| 23 | | | |
| 24 | | | |
| 24.5 | 242.6758 | | |
| 25 | | | |
| 25.5 | | | |
| 26 | | | |
| 27 | | | |
| 27.5 | 131.2129 | | |
| 28 | | 1074.804 | |
| 28.5 | | | 813.1216 |
| 29 | | | |

Table B9-2. Simulation Results from the Case of Sodium Sesquicarbonate with NSR = 3.38 (Figure 30)

SIMULATION (with kA=8.77, kB=1.24E8, and x=0.55)

| SO2 (ppm) | NO (ppm) | NOx (ppm) | R(um) | R(um) X 100 |
|---|---|---|---|---|
| 1533.95 | 1505.14 | 1533.95 | 29 | 2900 |
| 1410.86 | 1399.96 | 1435.19 | 28.8304 | 2883.04 |
| 1329.93 | 1351.95 | 1400.39 | 28.6716 | 2867.16 |
| 1254.42 | 1308.66 | 1369 | 28.5228 | 2852.28 |
| 1183.9 | 1269.47 | 1340.59 | 28.3831 | 2838.31 |
| 1117.96 | 1233.89 | 1314.79 | 28.2519 | 2825.19 |
| 1056.23 | 1201.5 | 1291.3 | 28.1285 | 2812.85 |
| 998.39 | 1171.91 | 1269.85 | 28.0124 | 2801.24 |
| 944.15 | 1144.82 | 1250.22 | 27.903 | 2790.3 |
| 893.23 | 1119.97 | 1232.2 | 27.7999 | 2779.99 |
| 845.39 | 1097.11 | 1215.62 | 27.7026 | 2770.26 |
| 800.42 | 1076.04 | 1200.35 | 27.6108 | 2761.08 |
| 758.1 | 1056.59 | 1186.25 | 27.5241 | 2752.41 |
| 718.26 | 1038.6 | 1173.21 | 27.4422 | 2744.22 |
| 680.73 | 1021.93 | 1161.12 | 27.3647 | 2736.47 |
| 611.97 | 992.09 | 1139.48 | 27.2222 | 2722.22 |
| 580.48 | 978.71 | 1129.78 | 27.1566 | 2715.66 |
| 550.74 | 966.24 | 1120.75 | 27.0944 | 2709.44 |
| 522.65 | 954.61 | 1112.31 | 27.0356 | 2703.56 |
| 496.1 | 943.75 | 1104.44 | 26.9798 | 2697.98 |
| 471 | 933.59 | 1097.07 | 26.9269 | 2692.69 |
| 447.25 | 924.09 | 1090.18 | 26.8768 | 2687.68 |
| 403.52 | 906.83 | 1077.67 | 26.7841 | 2678.41 |

|  |  |  |  |  |
|---|---|---|---|---|
| 383.38 | 898.99 | 1071.99 | 26.7413 | 2674.13 |
| 364.31 | 891.63 | 1066.65 | 26.7006 | 2670.06 |
| 346.24 | 884.71 | 1061.64 | 26.662 | 2666.2 |
| 329.11 | 878.2 | 1056 92 | 26.6254 | 2662.54 |
| 297.47 | 866.31 | 1048.29 | 26.5575 | 2655.75 |
| 282.86 | 860.87 | 1044.35 | 26.5261 | 2652.61 |
| 269 | 855.74 | 1040.63 | 26.4963 | 2649.63 |
| 255.85 | 850.9 | 1037.12 | 26.4679 | 2646.79 |
| 243.37 | 846.34 | 1033.81 | 26.441 | 2644.1 |
| 220.27 | 837.95 | 1027.73 | 26.391 | 2639.1 |
| 209.58 | 834.1 | 1024.94 | 26.3678 | 2636.78 |
| 199.43 | 830.46 | 1022.3 | 26.3457 | 2634.57 |
| 189.78 | 827.01 | 1019.8 | 26.3248 | 2632.48 |
| 180.62 | 823.75 | 1017.44 | 26.3048 | 2630.48 |
| 171.91 | 820.66 | 1015.2 | 26.2859 | 2628.59 |
| 163.63 | 817.74 | 1013.08 | 26.2678 | 2626.78 |
| 155.76 | 814.97 | 1011.07 | 26.2506 | 2625.06 |
| 148.28 | 812.35 | 1009.17 | 26.2343 | 2623.43 |
| 141.17 | 809.86 | 1007.37 | 26.2188 | 2621.88 |
| 134.4 | 807.5 | 1005.66 | 26.2039 | 2620.39 |
| 121.85 | 803.14 | 1002.5 | 26.1765 | 2617.65 |
| 116.03 | 801.13 | 1001.04 | 26.1637 | 2616.37 |
| 110.49 | 799.22 | 999.66 | 26.1515 | 2615.15 |
| 105.22 | 797.41 | 998.34 | 26.14 | 2614 |
| 100.21 | 795.69 | 997.09 | 26.1289 | 2612.89 |
| 90.9 | 792.5 | 994.78 | 26.1085 | 2610.85 |
| 86.58 | 791.03 | 993.71 | 26.099 | 2609.9 |
| 82.47 | 789.62 | 992.7 | 26.0899 | 2608.99 |
| 78.55 | 788.29 | 991.73 | 26.0813 | 2608.13 |
| 74.82 | 787.03 | 990.81 | 26.0731 | 2607.31 |

==============================

Table B10-1. Corrected Results from the Case of Sodium Sesquicarbonate with NSR = 3.38 (Figure 31)

CORRECTED DATA

| Time (min) | SO2 (ppm) | NOx (ppm) | NO (ppm) |
|---|---|---|---|
| 0 | 1628.628 | 1473.919 | 1473.512 |
| 0.25 | 1444.873 | | |
| 0.5 | | 1339.547 | |
| 1 | | | 1201.984 |
| 1.5 | | 1262.904 | |
| 2 | | | 1105.864 |
| 2.5 | | | |
| 2.75 | 903.0249 | | |
| 3 | | 1165.947 | |
| 3.5 | | | |
| 4 | | | 1022.896 |
| 4.5 | | | |
| 5 | | | |
| 5.25 | 713.9838 | | |
| 5.5 | | | |
| 6 | | 1116.11 | |
| 7 | | | |
| 7.75 | 576.7865 | | |
| 8 | | | 937.474 |
| 9 | | | |
| 10 | | | |
| 10.25 | 502.3186 | | |
| 10.5 | | | |

| | | | |
|---|---|---|---|
| 11 | | 1045.054 | |
| 12 | | | |
| 12.75 | 420.6867 | | |
| 13 | | | |
| 14 | | | 855.35 |
| 15 | | | |
| 15.25 | 357.2379 | | |
| 15.5 | | | |
| 16 | | | |
| 17 | | 1035.426 | |
| 17.75 | 291.2502 | | |
| 18 | | | |
| 19 | | | |
| 20 | | | |
| 20.25 | 250.4137 | | |
| 20.5 | | | |
| 21 | | | 826.6347 |
| 22 | | | |
| 22.75 | 250.3218 | | |
| 23 | | | |
| 24 | | 1045.204 | |
| 24.5 | | | 841.0325 |
| 25 | | 1046.601 | |
| 25.75 | 205.7772 | | |
| 26 | | | |

=========================

Table B10-2. Simulation Results from the Case of Sodium Sesquicarbonate with NSR = 3.38 (Figure 31)

SIMULATION (with kA=8.77, kB=1.24E8, x=0.55)

| SO2 (ppm) | NO (ppm) | NOx (ppm) | R(um) | R(um) X 100 |
|---|---|---|---|---|
| 1628.63 | 1473.51 | 1473.92 | 29 | 2900 |
| 1580.56 | 1443.29 | 1452.01 | 28.906 | 2890.6 |
| 1534.21 | 1414.74 | 1431.31 | 28.8152 | 2881.52 |
| 1446.33 | 1362.15 | 1393.18 | 28.6422 | 2864.22 |
| 1364.42 | 1314.89 | 1358.92 | 28.4802 | 2848.02 |
| 1287.97 | 1272.26 | 1328.01 | 28.3282 | 2832.82 |
| 1216.53 | 1233.68 | 1300.04 | 28.1854 | 2818.54 |
| 1182.56 | 1215.74 | 1287.04 | 28.1172 | 2811.72 |
| 1149.69 | 1198.64 | 1274.64 | 28.0511 | 2805.11 |
| 1087.1 | 1166.73 | 1251.5 | 27.9247 | 2792.47 |
| 1028.41 | 1137.58 | 1230.37 | 27.8057 | 2780.57 |
| 973.34 | 1110.89 | 1211.02 | 27.6935 | 2769.35 |
| 921.62 | 1086.4 | 1193.26 | 27.5876 | 2758.76 |
| 896.93 | 1074.9 | 1184.93 | 27.5369 | 2753.69 |
| 873 | 1063.87 | 1176.93 | 27.4877 | 2748.77 |
| 827.26 | 1043.1 | 1161.87 | 27.3933 | 2739.33 |
| 743.63 | 1006.16 | 1135.09 | 27.2196 | 2721.96 |
| 687.08 | 981.93 | 1117.53 | 27.1014 | 2710.14 |
| 669.31 | 974.44 | 1112.09 | 27.0641 | 2706.41 |
| 603.1 | 947.02 | 1092.22 | 26.9247 | 2692.47 |
| 544 | 923.2 | 1074.94 | 26.7994 | 2679.94 |
| 530.23 | 917.73 | 1070.98 | 26.7701 | 2677.01 |

| | | | | |
|---|---|---|---|---|
| 516.84 | 912.45 | 1067.15 | 26.7415 | 2674.15 |
| 491.14 | 902.4 | 1059.86 | 26.6867 | 2668.67 |
| 443.77 | 884.16 | 1046.64 | 26.5851 | 2658.51 |
| 411.47 | 871.93 | 1037.78 | 26.5156 | 2651.56 |
| 401.27 | 868.11 | 1035 | 26.4936 | 2649.36 |
| 363.08 | 853.93 | 1024.73 | 26.4109 | 2641.09 |
| 328.72 | 841.38 | 1015.62 | 26.3362 | 2633.62 |
| 320.67 | 838.47 | 1013.51 | 26.3187 | 2631.87 |
| 312.84 | 835.64 | 1011.46 | 26.3016 | 2630.16 |
| 297.77 | 830.23 | 1007.54 | 26.2687 | 2626.87 |
| 269.86 | 820.3 | 1000.34 | 26.2077 | 2620.77 |
| 250.73 | 813.56 | 995.46 | 26.1657 | 2616.57 |
| 244.67 | 811.44 | 993.92 | 26.1524 | 2615.24 |
| 221.93 | 803.52 | 988.18 | 26.1023 | 2610.23 |
| 201.37 | 796.43 | 983.04 | 26.0569 | 2605.69 |
| 196.54 | 794.78 | 981.84 | 26.0462 | 2604.62 |
| 191.84 | 793.17 | 980.67 | 26.0358 | 2603.58 |
| 182.77 | 790.07 | 978.43 | 26.0157 | 2601.57 |
| 165.94 | 784.36 | 974.29 | 25.9784 | 2597.84 |
| 154.37 | 780.46 | 971.46 | 25.9527 | 2595.27 |
| 150.7 | 779.23 | 970.56 | 25.9445 | 2594.45 |
| 136.89 | 774.6 | 967.21 | 25.9138 | 2591.38 |
| 130.48 | 772.46 | 965.66 | 25.8995 | 2589.95 |
| 124.37 | 770.43 | 964.19 | 25.8859 | 2588.59 |
| 115.76 | 767.58 | 962.12 | 25.8667 | 2586.67 |
| 113.02 | 766.67 | 961.46 | 25.8606 | 2586.06 |

=============================

# APPENDIX C

```
C============  PURPOSE OF THE PROGRAM  ============
C
C  THE FOLLOWING PROGRAM IS AN EXAMPLE PROGRAM TO
C  DEMONSTRATE THE SIMULATION PROCESS USING SOLVAY'S
C  MODEL.  DATA ARE TAKEN FROM TABLE 22, OR FIGURE 28,
C  FOR THE CASE OF SODIUM SESQUICARBONATE WITH NSR=3.4.
C  KINETIC PARAMETERS KA, KB, AND X WERE OBTAINED FROM
C  QPRO SOFTWARE FIRST, WITH WHICH THE CONCENTRATIONS
C  OF SO2, NO, AND NOX AND THE SHRINKING CORE RADIUS VS
C  REACTION TIME COULD BE PREDICTED.
C
C=========       ==========       ===========

C******** DEFINITION OF VARIABLES & EXPERIMENTAL DATA *******
C
C      V: REACTOR VOLUME = 12864 ml  = 12864 cm^3
C      M: MOLECULAR WEIGHT OF SODIUM SESQUICARBONATE :
C       226.04 g/mol
C      D: DENSITY OF SODIUM SESQUICARBONATE :
C       2.112 g/ml ( g/cm^3 )
C      W: WEIGHT OF SODIUM SESQUICARBONATE INJECTED :
C           W = 0.36 g
C      R: MEAN RADIUS OF SHRINKING PARTICLES.
C     RO: INITIAL MEAN RADIUS OF PARTICLES
C            Ro = 58/2 um = 0.0029 cm
C      N: TOTAL NUMBER OF NaHCO3 PARTICLES INJECTED
C             N = W/(4/3*3.14159*Ro^3*D)
C     X: CONSTANT USED TO SIMPLIFY THE RATE EXPRESSION
C           X = 4*PI*N/V
C      A: CONCENTRATION OF SO2
C     AO: INITIAL CONCENTRALTION OF SO2
C            Ao = 1507.55 ppm
C      B: CONCENTRATION OF NO
C     BO: INITIAL CONCENTRATION OF NO
C            Bo = 1487.89 ppm
C      C: CONCENTRATION OF NO2
C     CO: INITIAL CONCENTRATION OF NO2
C            Co = (NO2)o =46.06 ppm
C   NOX: INITIAL CONCENTRATION OF NOX
```

```
C           NOX = 1533.95 ppm
C     XXX: CONCENTRATION OF NOX AT TIME TIME
C           XXX = A + B
C      KA: RATE CONSTANT FOR SO2 REMOVAL = 8.77 cm/min
C      KB: RATE CONSTANT FOR NO REMOVAL = 1.24E8 cm^4/(min)(mol)
C     XX: SELECTIVITY COEFFICIENT DEFINED IN EQUATION (3-20)
C           XX = 0.55
C      RA: DISAPPEARANCE RATE OF SO2
C             RA = dA/dt = -N*(4*3.14159*R^2)*KA*A / V
C      RB: DISAPPEARANCE RATE OF NO
C             RB = dB/dt = -N*(4*3.14159*R^2)*KB*A*B / V
C      RC: GENERATION RATE OF NO2
C             RC = dC/dt = - XX/2 RB
C     RR: RADIUS SHRINKING RATE OF PARTICLES
C           RR = -Y*(KA*A+KB*(1-XX/2)/2*A*B)
C      Y: CONSTANT USED TO SIMPLIFY THE RR EQUATION
C            Y = 0.666667*M/D
C     RG: IDEAL GAS LAW CONSTANT
C           RG = 0.082 atm L/mol K
C      T: REACTION TEMPERATURE
C            T = 260 F
C      P: REACTOR PRESSURE
C            P = 1 atm
C    TIME: REACTION TIME, min
C   DTIME: TIME DIVISION USED IN THE NUMERICAL METHOD FOR
C        SOLVING SIMULTANEOUS ORDINARY DIFFERENTIAL EQUATIONS
C         DTIME = 0.0005 min
C   KRA: A CONSTANT  ( KRA=KA*X )
C   KRB: A CONSTANT  ( KRB=KB*X )
C    FLAG: ACCUMULATED RUNNING TIME CORRESPONDING TO THE
C        TIME DIVISION, DTIME
C---------------------------------------------------------------------
C    DA, DB, DC, DR : PARAMETERS USED IN RUNGE-KUTTA METHOD
C---------------------------------------------------------------------
C    FA, FB, FC, FR, ADA, ADB, ADC, ADR, FPA, FPB, FPC, FPR,
C   PA, PB, PC, PR : PARAMETERS USED IN ADAMS-BASHFORTH-MOULTON
C                METHOD
C
C**********************************************************************
```

```
      REAL*8 A, B, C, R, AO, BO, CO, RO, KA, KB, V, M, D
      REAL*8 W, N, VG, MOL, PI, RAO, RBO, RCO,X,Y, XX, NOX
      REAL*8 KRA, KRB, TIME, DTIME, DA(4), DB(4), DC(4), DR(4)
      REAL*8 FA(4),FB(4),FC(4),FR(4),ADA(4),ADB(4),ADC(4),ADR(4)
      REAL*8 FPA, FPB, FPC, FPR, PA, PB, PC, PR, CCC
      INTEGER FLAG
      RA(A, R)=-KRA*A*R**2
      RB(A, B, R)=-KRB*A*B*R**2
      RC(A, B, R)=KRB/2*XX*A*B*R**2
      RR(A, B) = -Y*(KA*A+KB*(1-XX/2)/2*A*B)
      DATA V,M,D,W,RO,XX/12864, 226.04, 2.112, 0.36, 0.0029, 0.55/
      DATA AO,BO,CO,PI/ 1507.55, 1487.89, 46.06, 3.14159/
      DATA RG, T, P, DTIME/ 0.082, 260, 1., 0.0005/


C***** CALCULATION FOR THE NUMBER OF PARTICLES *****
C*************************************************************
      N=W/4*3/PI/RO**3/D


C***** UNIT CONVERSION FROM ppm TO mol/cc FOR AO, BO AND CO *****
C****************************************************************************
      VG=AO*1.0E-9
      T=(T+460)/1.8
      MOL=P*VG/RG/T
      AO=MOL
      VG=BO*1.0E-9
      MOL=P*VG/RG/T
      BO=MOL
      VG=CO*1.0E-9
      MOL=P*VG/RG/T
      CO=MOL


C***** CACULATION OF X, Y, KRA AND KRB *****
C****************************************************
      X=4*PI*N/V
      Y=0.666667*M/D
```

```
      KA=8.77
      KB=1.24E8
      KRA=KA*X
      KRB=KB*X


C*****  INITIALIZE A, B, C, R, AND TIME  *****
C**********************************************
      A=AO
      B=BO
      C=CO
      R=RO
      TIME=0


C*****  OUTPUT FILE SETUP FOR A PROGRAMMED RESULTS *****
C***********************************************************
      OPEN(4, FILE='S31',STATUS='NEW',FORM='FORMATTED',ERR=902)
      WRITE(4,*) '-------------------------------------------'
      WRITE(4,*) '  TIME     (SO2)    (NO)     (NOx)      R'
      WRITE(4,*) '  (min)    (ppm)    (ppm)    (ppm)     (um)'
      WRITE(4,*) '-------------------------------------------'
      WRITE(4,*) '   0.0   1507.55   1487.89   1533.95   29.0000'


C*****  RUNGE KUTTA METHOD APPLIED IN 1ST 4 POINTS     ******
C***************************************************************
      DO 10 I=1, 4
      FA(I)=A
      FB(I)=B
      FC(I)=C
      FR(I)=R
      TIME=TIME+DTIME
      DA(1)=DTIME*RA(A,R)
      DB(1)=DTIME*RB(A,B,R)
      DC(1)=DTIME*RC(A,B,R)
      DR(1)=DTIME*RR(A,B)
      DA(2)=DTIME*RA(A+DA(1)/2,R+DR(1)/2)
      DB(2)=DTIME*RB(A+DA(1)/2,B+DB(1)/2,R+DR(1)/2)
```

```
      DC(2)=DTIME*RC(A+DA(1)/2,B+DB(1)/2,R+DR(1)/2)
      DR(2)=DTIME*RR(A+DA(1)/2,B+DB(1)/2)
      DA(3)=DTIME*RA(A+DA(2)/2,R+DR(2)/2)
      DB(3)=DTIME*RB(A+DA(2)/2,B+DB(2)/2,R+DR(2)/2)
      DC(3)=DTIME*RC(A+DA(2)/2,B+DB(2)/2,R+DR(2)/2)
      DR(3)=DTIME*RR(A+DA(2)/2,B+DB(2)/2)
      DA(4)=DTIME*RA(A+DA(3),R+DR(3))
      DB(4)=DTIME*RB(A+DA(3),B+DB(3),R+DR(3))
      DC(4)=DTIME*RC(A+DA(3),B+DB(3),R+DR(3))
      DR(4)=DTIME*RR(A+DA(3),B+DB(3))
      A=A+(DA(1)+2*DA(2)+2*DA(3)+DA(4))/6
      B=B+(DB(1)+2*DB(2)+2*DB(3)+DB(4))/6
      C=C+(DC(1)+2*DC(2)+2*DC(3)+DC(4))/6
      R=R+(DR(1)+2*DR(2)+2*DR(3)+DR(4))/6
10     CONTINUE

      FLAG=3


C*****  MARK FOR THE NEXT TIME DIVISION CALCULATION ******
C**********************************************************
5      FLAG=FLAG+1
      TIME=FLAG*DTIME


C*****  ADAMS-BASHFORTH-MOULTON METHOD APPLIED FOR THE REST
C************************************************************
      ADA(1)=RA(FA(1), FR(1))
      ADB(1)=RB(FA(1), FB(1), FR(1))
      ADC(1)=RC(FA(1), FB(1), FR(1))
      ADR(1)=RR(FA(1), FB(1))
      ADA(2)=RA(FA(2), FR(2))
      ADB(2)=RB(FA(2), FB(2), FR(2))
      ADC(2)=RC(FA(2), FB(2), FR(2))
      ADR(2)=RR(FA(2), FB(2))
      ADA(3)=RA(FA(3), FR(3))
      ADB(3)=RB(FA(3), FB(3), FR(3))
      ADC(3)=RC(FA(3), FB(3), FR(3))
      ADR(3)=RR(FA(3), FB(3))
```