

# The Use of Rice Hulls for Sustainable Control of NO<sub>x</sub> Emissions in Deep Space Missions

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## Abstract

The use of the activated carbon produced from rice hulls to control NO<sub>x</sub> emissions for the future deep space missions has been demonstrated. The optimal carbonization temperature range was found to be between 600°C and 750°C. The burnoff of 61.8% was found at 700°C in pyrolysis and 750°C in activation. The BET surface area of the activated carbon from rice hulls was determined to be 172 m<sup>2</sup>/g when prepared at 700°C. The presence of oxygen in flue gas is essential for effective adsorption of NO by the activated carbon. On the contrary, water vapor inhibits the adsorption efficiency of NO. Consequently, water vapor in flue gas should be removed by drying agents before adsorption to ensure high NO adsorption efficiency. All of NO in the flue gas was removed for more than one and a half hours when 10% oxygen was present and using a ratio of the carbon weight to the flue gas flow rate (W/F) of 15.4 g-min/L. The reduction of the adsorbed NO to form N<sub>2</sub> can be effectively accomplished under anaerobic conditions at 550°C. For NO saturated activated carbon, the loss of carbon mass was determined to be about 0.16% of the activated carbon per cycle of regeneration. The reduction of the adsorbed NO also regenerates the activated carbon. The regenerated activated carbon exhibits improved NO adsorption efficiency.

## Introduction

Human space travel depends upon the operation of life support systems. In deep space missions, such as the mission to Mars, life support cannot depend upon storage alone, it requires a fully regenerative system as well, i.e. waste must be reclaimed for reuse.

A number of solid waste reclamation technologies are under investigation for space applications (Fisher et.al., 1998). Technologies such as incineration, supercritical water oxidation, steam reformation, and electrochemical oxidation are at various stages of

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development for use in space. Incineration is perhaps the most promising technology because it rapidly and completely converts the waste to carbon dioxide, water, and minerals. Incineration also lends itself to experiment more affordably than most of the other technologies, and it is already the most thoroughly developed technology for use in a terrestrial environment. The major difficulty with the use of incineration, particularly in a closed environment, is the emission of pollutants that can build up, thus necessitating a flue gas cleanup system.

Incineration of the inedible portion of crops and wastes, such as human feces, produces mostly carbon dioxide, water, and ash. However the incineration also produces NO<sub>x</sub> and SO<sub>2</sub>; pollutants that need to be removed from flue gas and recovered for reuse. NO<sub>x</sub> is produced from nitrogen in the waste or fuel and from the nitrogen in the air. Similarly, the sulfur in the waste is converted to SO<sub>2</sub> during incineration.

To conserve the nutrients for life support, NO<sub>x</sub> should be converted to N<sub>2</sub>, NH<sub>3</sub>, and/or nitrates. The N<sub>2</sub> can be used to replace cabin N<sub>2</sub> leakage and/or the loss of N<sub>2</sub> during combustion, while NH<sub>3</sub> and nitrates can be recycled as part of the plant hydroponics nutrient solution. The SO<sub>2</sub> can be converted to either elemental sulfur or sulfate because elemental sulfur can be safely stored or converted to sulfate, where sulfate can be recycled as part of the plant hydroponics nutrient solution as well.

Many flue-gas clean up technologies have been developed to remove NO<sub>x</sub> and SO<sub>2</sub> from terrestrial incineration (Sada et. al., 1980; Martin, A.E., 1981; Tsai et. al., 1989). Most of the technologies require expendables, making them unsuitable for a space application. Processes that use catalyst (Jin et. al., 1997; Yu et. al. 1997) may have problems because catalyst poisoning is an issue that limits the life-span of a catalyst. The poisoning of the catalyst by soot, alkali metals, and chlorides in the flue gases can occur, and wet processes (Chang and Liu, 1990; Chang and Lee, 1992; Pham and Chang, 1994; Shi et. al., 1996) that handle liquids, like using spray absorbers, pose difficulty because of the micro-gravity situation. What also need to be addressed are the issue of safety and energy requirements of the technology. Using potential hazardous high-pressure systems and/or systems that require an excessive amount of electric energy is unwarranted for space missions.

In view of the aforementioned constraints and requirements, we are investigating an approach involving the use of rice hulls, an inedible biomass that can be continuously produced in a space vehicle, to clean up flue gas pollutants generated during incineration. We have found that flue gas from the incineration of biomass contains an insignificant amount of SO<sub>2</sub>, and that most of the sulfur in the biomass has ended up as sulfate in flyash. Presumably, SO<sub>2</sub> has reacted with the alkali metal in the biomass, thus, this study focuses on the control of NO<sub>x</sub> emissions. The approach involves the carbonization of the rice hulls to produce activated carbon for the adsorption of NO<sub>x</sub> and a subsequent reduction of the adsorbed NO<sub>x</sub> by carbon to N<sub>2</sub>. The optimal conditions for the production of activated carbon from rice hulls for the adsorption of NO<sub>x</sub> has been determined. Parametric studies on the adsorption of NO<sub>x</sub> by the carbon have been

performed. The effectiveness of this approach to control NO<sub>x</sub> emissions in deep space missions has also been assessed.

### **Experimental Section**

**Materials.** The following materials were used: NO (5% with N<sub>2</sub> as balance, Scott Co.), standard NO (500ppm with N<sub>2</sub> as balance, Scott Co.), CO<sub>2</sub>, N<sub>2</sub>, O<sub>2</sub> (Airgas Co.), and rice hulls (field grown).

**Experimental Setup.** A schematic diagram of the experimental set-up used for the preparation of char from inedible biomass, the adsorption of NO<sub>x</sub> on a char bed, and the reduction of NO<sub>x</sub> by carbon at elevated temperatures to form N<sub>2</sub>, is shown in Fig. 1. The main component of the system is a 2" I.D. for char preparation, which is switched to a 3/4" I.D. stainless steel tube (all 30" length) reactor for adsorption, de-adsorption and regeneration. The tubular reactors are put into a tube furnace (Thermolyne, Type F121100) for heating. The furnace has the function of running an automatic set point ramping program.

**Preparation of Carbon.** Approximately 55.0 g of rice hull was tightly packed into a cylinder for activation. Nitrogen and Carbon dioxide were used as the pyrolysis and activation gases, respectively. The gas flow rate for pyrolysis was 0.5-1.0 L nitrogen per minute and activation was 0.25L carbon dioxide per minute. Pyrolysis and activation times (between 0.5 hr and 6 hr), and temperatures (between 300°C and 950°C) were varied during carbonization in order to obtain optimal activation conditions. The activation temperature was usually 50°C higher than the pyrolysis temperature. The notation of the activated carbon "RH-2-600-1-650" implies that the activated carbon was prepared from rice hulls with a 2 hrs pyrolysis time at 600°C followed by 1 hr of activation at 650°C. Once activation was complete, CO<sub>2</sub> was supplied to the sample until it could be sealed in a container.

**Characterization.** Specific surface areas of samples were determined by gas adsorption using an automated adsorption apparatus (Micromeritics, ASAP 2010). Nitrogen adsorption/desorption was measured isothermally at -196°C. Before any such analysis, the sample was degassed at 250°C in a vacuum to about 10<sup>-3</sup> torr. The Nitrogen isotherms were analyzed by the BET equation to determine the surface area of the char. BJH adsorption cumulative pore size of the sample was also determined.

**Adsorption.** Most of NO<sub>x</sub> in flue gas from combustion is in the form of NO. Also, NO<sub>2</sub> is readily adsorbed on the activated carbon. Consequently, efforts were directed to determine conditions for maximal removal efficiency of NO. Experiments were conducted to evaluate the effects of carbon preparation conditions, adsorption temperatures, flue gas flow rate, and the concentrations of oxygen, water vapor, and NO on the adsorption efficiency of NO. The experimental system simulated flue gas with variable concentrations of N<sub>2</sub>, carbon dioxide, oxygen, NO, and H<sub>2</sub>O. The gas flow rate varied from 250-1500 ml/min. The sample was heated at a 40°C/min gradient from room temperature to the heat-treatment temperature desired.

NO and NO<sub>2</sub> concentrations were analyzed by a chemiluminescent NO-NO<sub>2</sub>-NO<sub>x</sub> analyzer (ThermoElectron Co., Model 14A). The amount of NO<sub>x</sub> adsorbed by the activated carbon was determined from the difference in NO<sub>x</sub> concentration of the inlet and outlet gases. It was assumed that the missing NO<sub>x</sub> was adsorbed by the activated carbon. Some reactions were repeated at least twice to examine reproducibility.

**Reduction and Regeneration.** Reduction of NO and regeneration of the activated carbon were accomplished by heating the NO loaded char in the absence of oxygen. In order to evaluate the behavior of the process over time, a purge gas flow of nitrogen was applied during experiments, whose outlet was directed to a gas analyzer. The sample was then heated from room temperature to 600°C at a 40°C/min gradient. The gas flow rate for de-sorption and regeneration was 1.0 L nitrogen per minute.

**Space Maximum Allowable Concentration.** The space maximum allowable concentration (SMAC) of NO in a human occupied cabin is 4.8 ppm, and thus reduced NO concentrations to the level of SMAC can serve as an indicator for meeting the requirement. Experiments were conducted at room temperature using rice hulls activated carbon (RH-2-700-1-750). The principle variables manipulated were inlet of oxygen concentration and the ratio of weight to flow rate, W/F, (W: weight of the activated carbon in g. and F: flow rate of flue gas in L/min) in order to determine the conditions to keep outlet NO concentrations below SMAC. Inlet gas concentrations were controlled by varying gas flow rates. Oxygen concentration ranged from 5% to 20% and W/F ranged from 15 to 45 g.min/L.

## Results and Discussion

### Preparation and Characterization of Activated Carbon

**Burnoff.** In order to determine optimal carbonization temperatures, rice hull samples were heated between 300°C and 900°C for two hours in pyrolysis and between 350°C and 950°C for one hour in activation, the temperature of activation being 50°C higher than that of pyrolysis. Afterwards, percent burnoff was measured. Higher carbonization temperatures caused larger portions of the samples to burn off and turn to ash, leading to greater amounts of material to be lost, as shown in Fig.2. About 75.6% of the rice hull sample burned off when temperatures were kept at 900°C in pyrolysis and 950°C in activation, while just 61.8% burnoff was recorded at 700°C in pyrolysis and 750°C in activation. To prevent significant burnoff and ash generation, it is recommended that reactions not be run at temperatures exceeding 750°C.

**Surface Area and Cumulative Pore Area.** The activated carbons were characterized by the measurement of their average pore size and surface area. There are three types of pores which developed in the solid: micropores (<2nm), mesopores (2-50nm), and macropores (>50nm). The average pore size has an effect on the total surface area that is available for adsorption. The BET surface area and BJH average pore size of activated carbon prepared from rice hulls (RH) under different conditions were measured. Temperature and hold time used for activation was varied. As the temperatures varied from 350°C to 800°C and the activation time from 0.5 hr to 5 hrs, the BET and BJH of

activated carbon from rice hulls ranged from 76.5 m<sup>2</sup>/g to 172.9 m<sup>2</sup>/g and from 25.1 to 67.1 A, respectively. In general, the BET increases with the increase of temperature until about 700°C. Further increases of temperature results in decreases of BET surface area. The BET of rice hulls activated carbon was 76.5 m<sup>2</sup>/g, 167.1 m<sup>2</sup>/g, 172.9 m<sup>2</sup>/g, and 147.9 m<sup>2</sup>/g with an activation temperature of 350°C, 600°C, 700°C, and 800°C, respectively. The time used for activation did not affect the BET surface area substantially under the conditions (0.5 hr – 2 hrs) employed. The BJH average pore size initially increases with the increase in time, but decreases with prolonged activation. Prolonged activation results in an increase in burnoff. The BJH average pore size of rice hulls char activated at 600°C was 25.1 A, 67.1 A, and 45.1 A with an activation time of 0.5 hr, 1.0 hr, and 2 hr, respectively.

It is imperative that the larger the BET surface area and the larger the BJH cumulative pore areas, the higher the adsorption efficiencies must be. Typical BJH adsorption cumulative pore areas for different samples are shown in Fig.3. From the graph, it can be inferred that activated carbon made from rice hulls has a large BJH adsorption cumulative pore area, close to that of coconut shell (commercial products), but significantly larger than two other biomass (wheat straw and peanut shells) samples shown. Because of the superior surface area and average pore size measured for rice hulls activated carbon than those of wheat straw and peanut shells, this study concentrates on rice hulls carbon.

**Determining Optimal Temperature and Time for Carbon Preparation.** Optimal pyrolysis and activation temperatures and times for carbon preparation were determined based on the amount of NO<sub>x</sub> that can be adsorbed by the activated carbon. The adsorption capacities of rice hull activated carbons generated by different pyrolysis and activation temperatures are shown in Fig.4. A simulated flue gas containing 250 ppm NO, 5% O<sub>2</sub>, 10% CO<sub>2</sub>, with N<sub>2</sub> as the balance was passed through the tubular reactor containing 2 g of activated carbons at a flow rate of 250 ml/min (W/F=8g.min/L) at 25°C. It is evident from the plots that the NO removal efficiency increases in the order of RH-2-300-1-350, RH-2-400-2-450, RH-2-500-1-550, RH-2-600-1-650, RH-2-700-1-750, and RH-2-800-1-850. Activated carbon derived from the highest tested pyrolysis and activation temperatures exhibited the best adsorption efficiency. The better adsorption efficiency is attributed to higher microporosity obtained at higher carbonization temperatures. But samples carbonized above 700°C have a higher burnoff rate than those carbonized at lower temperatures. In order to obtain a better production yield of activated carbon, 700°C and 750°C for pyrolysis and activation, respectively are chosen as optimum for the preparation of rice hull activated carbon.

The NO adsorption efficiencies of samples carbonized by differing pyrolysis and activation times are shown in Figure 5. It is evident from the plots that activated carbons carbonized by prolonged pyrolysis and activation times have better adsorption efficiencies than those carbonized by shorter times due to higher pore count and BET surface area. It can be seen from these figures that the micropore count and the surface area of activated carbon increases with longer preparation time, thus explaining why the

samples with the longest pyrolysis and activation times have the best adsorption efficiencies. However, prolong activation results in more burnoff and the production of ash. A balance must be reached when setting reaction parameters; one that will generate the largest surface area without a significant burnoff. We found that the optimal pyrolysis and activation times are two and one hour, respectively.

### **Parametric Study of the Removal Efficiency of NO**

**Temperature Effects on Adsorption.** The removal efficiency of NO by carbon was studied at various temperatures: 10°C, 100°C, 300°C, 400°C, and 500°C. A gas mixture containing 250 ppm NO in N<sub>2</sub> was passed through a column of carbon with a W/F of 15.4 g-min/L. Fig.6 shows that NO removal efficiency decreases with increased temperatures, when kept below 100°C. However, further increases in temperature beyond 100°C reversed the course, causing an increase in NO removal efficiency. This phenomenon is attributed to the reduction of NO by activated carbon, which results in the formation of nitrogen gas.

The results from this set of experiments indicate that at the condition of W/F employed, NO can be completely reduced to N<sub>2</sub> at temperatures equal to or above 500°C, while only some of the inlet NO is reduced to N<sub>2</sub> at temperature below 500°C. The fraction of NO converted to N<sub>2</sub> increases with the increase of reaction temperatures.

**Oxygen Effects on Adsorption.** Six experiments using 0%, 0.5%, 1%, 3%, 5%, and 10% O<sub>2</sub> were performed at room temperature. Fig.7 shows that when 10% oxygen is present, all of NO in the flue gas was removed for more than one and half hours, and that 98.7% of NO was removed even after 2hrs by using a W/F of 15.4 g-min/L. As can be seen from Fig 6, NO removal efficiency decreases along with decreases in O<sub>2</sub> concentration in the flue gas. Only about 10% of inlet NO was removed after 2 hrs in the absence of oxygen. It is obvious that the presence of oxygen is critical for the NO adsorption by carbon to be effective. This phenomenon is attributed to the catalytic oxidation of NO by O<sub>2</sub> on the carbon surface to form NO<sub>2</sub>, which is more readily adsorbed by the activated carbon.

**Moisture Effects on Adsorption.** It is expected that the high temperature flue gas will be cooled down before passing to the carbon bed to avoid the combustion of carbon due to the presence of flue gas oxygen. This cooling down results in the condensation of water vapor. Flue gas can contain up to 3.0 % v/v H<sub>2</sub>O even after cooling down to room temperature, thus it is important to study the effect of water vapor on the removal efficiency of NO by carbon. Fig. 8 shows that moisture causes a significant decrease in NO removal efficiency by carbon. The more water vapor present in the flue gas, the lower the NO removal efficiency exhibited. This is due to the fact that water vapor competes effectively with NO for the adsorption sites on carbon particles. The detrimental effect of water vapor on NO adsorption can be overcome by the removal of water vapor either by drying agents or by cooling flue gas to low temperatures prior to adsorption.

**Flow Rate Effect on Adsorption.** The effect of flue gas flow rate on the NO removal efficiency of a given amount of carbon was studied. A simulated flue gas with a composition of 250 ppm NO, 5% O<sub>2</sub>, 2% H<sub>2</sub>O, 10% CO<sub>2</sub> with N<sub>2</sub> as the balance was passed through a column of 15.3 g. carbon at 25°C. Fig.9 illustrates adsorption profiles of NO by rice hull activated carbon at five different flow rates. The NO removal efficiency after 2 hrs was 84%, 68%, 48%, 42%, and 36% with a flow rate of 250 ml/min, 500 ml/min, 750 ml/min, 1000 ml/min, and 1500 ml/min, respectively. As would be expected, smaller flow rates favor the NO removal efficiency as the adsorption time is longer compared to that of larger flow rates.

### **Reduction of NO by Activated Carbon**

The adsorbed NO can be desorbed from activated carbon if temperature of the carbon bed is raised. Further increases of temperature results in the reduction of NO by activated carbon to produce N<sub>2</sub>. Simultaneously, the activated carbon is regenerated as a result of the reduction of NO to N<sub>2</sub>.

Experiments on the reduction of the adsorbed NO by the activated carbon were performed by heating the NO saturated carbon under anaerobic conditions. In order to evaluate the behavior of the process over time, a purge gas flow of 1.0 L/min N<sub>2</sub> was passed through the carbon bed and subsequently directed to the NO<sub>x</sub> analyzer. Desorption was conducted with a temperature ramp rate of 40°C/min from room temperature to 600°C. As the temperature of the carbon bed was increased, NO was desorbed from the surface of the activated carbon. Further increase of the temperature results in the reduction of NO by the activated carbon to N<sub>2</sub>. The fraction of the adsorbed NO that is reduced to N<sub>2</sub> can be calculated by subtracting the NO coming out of the carbon bed from the total amount of NO adsorbed. The fraction of the adsorbed NO that is reduced depends on the temperature and the flow rate of N<sub>2</sub> gas.

Fig.10 shows the fraction of the desorbed NO integrated over the temperatures as the temperatures of the carbon bed was raised. As can be seen, the fraction of the total NO desorbed as NO reaches the maximum at 550°C and that this fraction was less than 100% of the total NO adsorbed, the difference of which being attributed to the reaction of NO with the activated carbon to form N<sub>2</sub>. The fraction of the adsorbed NO desorbed as NO is 48.2% in the case when NO adsorption was done without the presence of H<sub>2</sub>O vapor, and 64.5% in the case when NO adsorption was performed with 2% H<sub>2</sub>O. This result indicates that NO reduction by activated carbon is inhibited by the presence of water vapor. Water vapor can compete with NO for the reaction with activated carbon. From the desorption curve as a function of temperature, the NO desorption mainly took place at temperature below 300°C, while the NO reduction by carbon occurred at temperature above 300°C, the higher the temperature the more effective the reduction is. Since the ramp rate was 40°C per min., it would take 7.5 minutes to raise from 300°C to 600°C, the temperature range when most of the NO reduction takes place. During the 7.5 min. time interval, about 50% of the adsorbed NO was reduced to N<sub>2</sub>. Consequently, it can be

concluded that the complete reduction of NO to N<sub>2</sub> at 550°C can be done within 15 minutes in a closed system.

Another set of experiments were performed to study the reduction of NO by activated carbon as a function of temperature and W/F, the ratio of the amount of carbon to flow rate of N<sub>2</sub>. In this study, temperatures were varied between 300 and 550°C and W/F between 10 and 40 g.min/L. Fig. 11 shows that with a feed gas containing 250 ppm NO with the balance N<sub>2</sub>, the fraction of NO reduced by activated carbon increases with the increase of temperature at a given W/F, and the fraction also increases with the increase of W/F at a given temperature. All of NO was reduced to N<sub>2</sub> at 550°C with a W/F above 20 g.min/L, and at 500°C with a W/F 40 g.min/L. It would require a W/F larger than 40 g.min/L to convert all of NO to N<sub>2</sub> at temperature below 500C.

The NO reduction efficiency also depends on the concentration of NO in the system. Fig 12 shows NO reduction at 500°C for two inlet NO concentrations, 250 ppm and 1000 ppm. As can be seen, higher inlet NO concentrations cause less fraction of NO to be reduced. Only 55% of inlet NO was reduced at 500°C with an inlet NO concentration of 1000ppm and a W/F of 40g.min.L-1.

### **Space Maximum Allowable Concentration (SMAC) of NO**

Experiments were conducted at room temperature using rice hull activated carbon (RH-2-700-1-750) to determine at what conditions it would prolong efficient adsorption of NO and that outlet concentrations would be less than SMAC (4.8 ppm). The principle variables manipulated were inlet oxygen concentration, ranging from 5% to 20%, and weight to flow rate ratio (W/F), ranging from 15 to 45 g.min/L (W/F). The time that the carbon bed can hold before the NOx concentration exiting the bed exceeds the SMAC, will be called SMAC time.

Fig.13 shows SMAC time at different oxygen concentrations. The SMAC time increases along with increases in O<sub>2</sub> concentrations. The SMAC time was longer than 6 hours with oxygen concentration of 10% and W/F of 45 g.min/L, while about 10 hours were obtained with an 15% oxygen and W/F of 45 g.min/L. As previously mentioned, oxygen presence enhances NO adsorption, thus allowing the SMAC time to be longer. Increasing W/F, especially above 20g.min/L, also increases the SMAC time.

Experiments were conducted to determine the effects of the regeneration on activated carbon in terms of NO removal efficiency, as assessed by the carbon's SMAC time. Fig.14 shows the SMAC time after different numbers of regeneration cycles. The results indicate that regeneration improves the removal efficiency of NO. This phenomenon is attributed to the increase of surface area and micropores of the activated carbon. However, it was observed that additional carbon burns off occurs during regeneration, which causes the overall amount of activated carbon to decrease after each regeneration cycle.

The loss of mass was determined to be about 0.16% of activated carbon per cycle of regeneration. The SMAC time was 163 minutes and 372 minutes for the first and the 8th

cycle run, respectively. The larger the activated carbon adsorption efficiency, the longer the SMAC time will be.

## **Conclusion**

Commercial activated carbon, made mostly from materials such as coconut shells and coal, has been studied for the adsorption and/or reduction of NO<sub>x</sub> and SO<sub>2</sub> (Kaneko et. al., 1988; Lu and Do, 1991; Tsuji et.al., 1991; Illan-Gomez et.al., 1993; Yougen and Cha, 1996). In this study, we have demonstrated that rice hulls, an inedible by-product of crop that may be grown in space vehicles, can be converted to the activated carbon for the adsorption and reduction of NO in an effective manner. No expendable material, such as binders, is needed for making an effective activated carbon. After the saturation of the adsorbed NO<sub>x</sub>, the activated carbon can be regenerated for reuse. The regeneration can be simply done by heating the carbon bed under anaerobic conditions to about 550°C, when the adsorbed NO<sub>x</sub> is reduced to N<sub>2</sub>. The regenerated activated carbon exhibits improved NO adsorption efficiency.

The optimal carbonization temperature of rice hulls was found to be around 700°C when the burnoff was 62 %. The BET surface area of the activated carbon was determined to be 172 m<sup>2</sup>/g. Higher carbonization temperatures caused larger portions of the rice hulls to burn off and turn to ash. The presence of oxygen in flue gas is necessary for an effective adsorption of NO by the activated carbon. On the contrary, water vapor inhibits the adsorption efficiency of NO. Consequently, water vapor in flue gas should be removed either by condensation at low temperatures or by drying agents before adsorption to ensure high NO adsorption efficiency. All of NO in the flue gas was removed for more than one and a half hours when 10% oxygen was present and using a ratio of the carbon weight to the flue gas flow rate (W/F) of 15.4 g-min/L. For NO saturated activated carbon, the loss of carbon mass was determined to be about 0.16% of the activated carbon per cycle of regeneration.

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## Figure Captions

Figure 1. Schematic diagram of the experimental set-up used for the preparation of the activated carbon, adsorption, and reduction of NO.

Figure 2. Rice hull burnoff as a function of Pyrolysis and Activation Temperatures (Activation temperature was 50°C higher than pyrolysis).

Figure 3. BJH cumulative pore area of activated carbons prepared from coconut shell, peanut shell, wheat straw, and rice hull.

Figure 4. The effect of pyrolysis and activation temperatures on the adsorption of NO; Flue gas composition was 250 ppm NO, 5% O<sub>2</sub>, 10% CO<sub>2</sub>, and the balance N<sub>2</sub>; W/F=8g.min./L.

Figure 5. The effect of pyrolysis and activation time on the adsorption of NO; Flue gas composition was 250 ppm NO, 5% O<sub>2</sub>, 10% CO<sub>2</sub>, and the balance N<sub>2</sub>; W/F=8g.min./L.

Figure 6. The effect of temperature on NO adsorption by the activated carbon, RH-2-700-1-750; Flue gas composition was 250 ppm NO and the balance N<sub>2</sub>; W/F=15.4g.min./L.

Figure 7. The effect of oxygen on NO adsorption by the activated carbon, RH-2-700-1-750; Flue gas composition was 250 ppm NO, 10% CO<sub>2</sub>, and the balance N<sub>2</sub>; W/F=15.4g.min./L.

Figure 8. The effect of water vapor on NO adsorption by the activated carbon, RH-2-700-1-750; Flue gas composition was 250 ppm NO, 10% CO<sub>2</sub>, 5% O<sub>2</sub>, and the balance N<sub>2</sub>; 25°C, W/F=15.4g.min./L.

Figure 9. The effect of flow rate on NO adsorption by the activated carbon, RH-2-700-1-750 (15.3g); Flue gas composition was 250 ppm NO, 10% CO<sub>2</sub>, 5% O<sub>2</sub>, 2% H<sub>2</sub>O, and the balance N<sub>2</sub>; 25°C

Figure 10. Fraction of NO desorbed when integrated over temperatures as the temperature of the carbon bed was raised at 40°C/min. N<sub>2</sub> was used as carrier gas at 1 L./min. Before the desorption, NO adsorption by the activated carbon had been performed under two different conditions: without and with 2% water vapor.

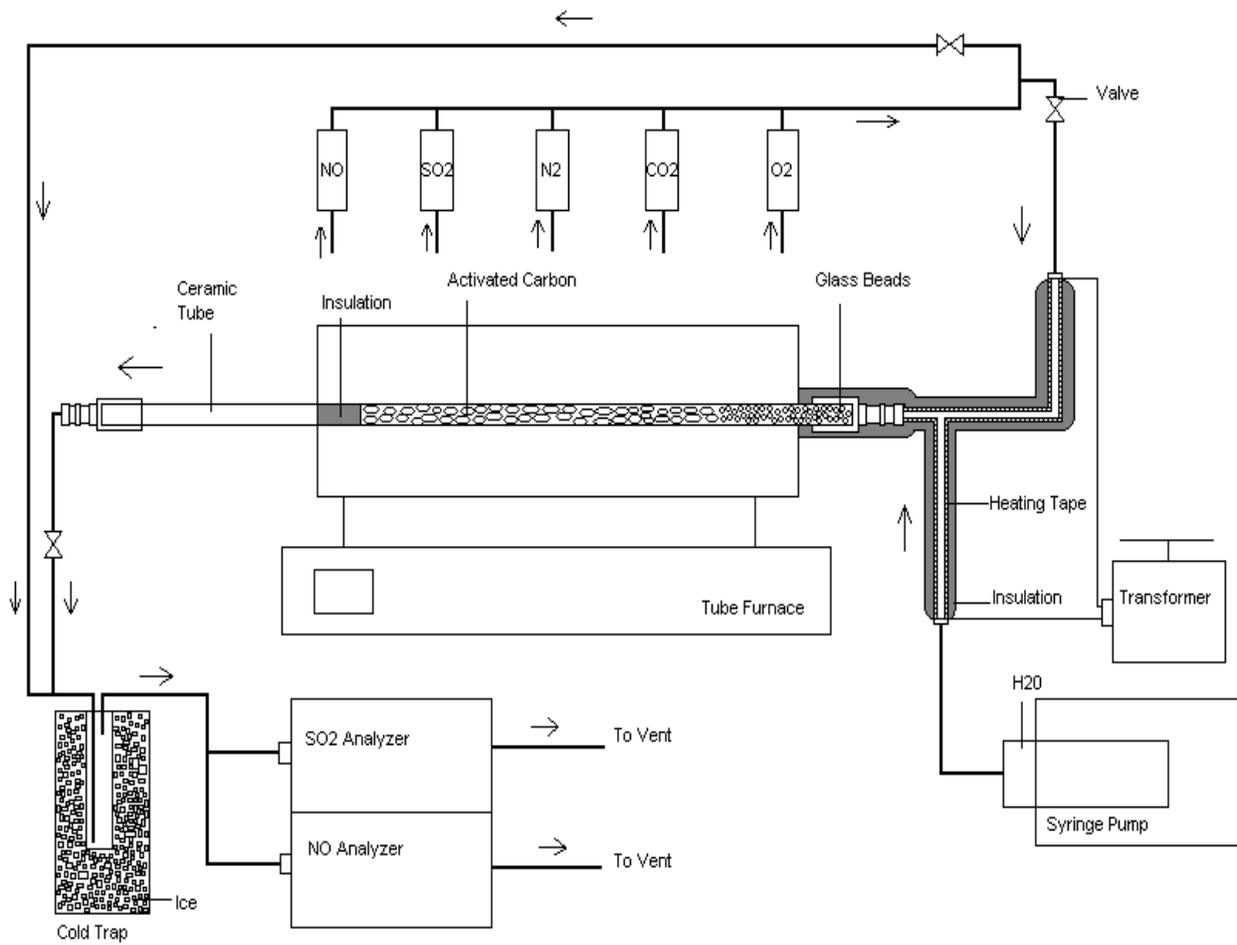
Figure 11. The effect of temperature on NO reduction by the activated carbon at various ratios of carbon weight to flue gas flow rate (W/F in g.min/L)

Figure 12. The effect of NO concentration on NO reduction efficiency by the activated carbon at various ratios of carbon weight to flue gas flow rate (W/F in g.min/L).

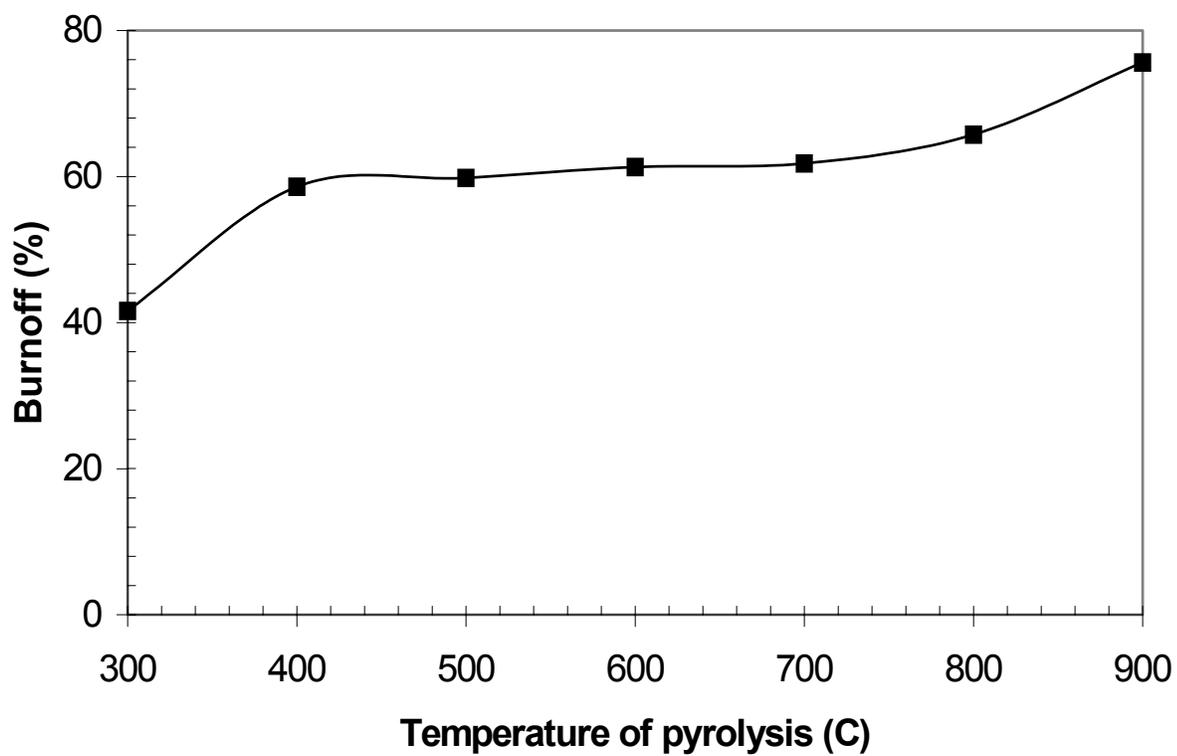
Figure 13. The effect of oxygen on SMAC time using the activated carbon, RH-2-700-1-750; Flue gas composition was 250 ppm NO, 10% CO<sub>2</sub>, and the balance N<sub>2</sub>; 25°C.

Figure 14. The number of regeneration on the SMAC time using the activated carbon, RH-2-700-1-750; adsorption conditions: 250 ppm NO, 10% O<sub>2</sub>, 10% CO<sub>2</sub>, and the balance N<sub>2</sub> at 25°C with W/F: 30g.min./L; regeneration conditions: 100% N<sub>2</sub> at 600°C for 15 min.

Figure 1

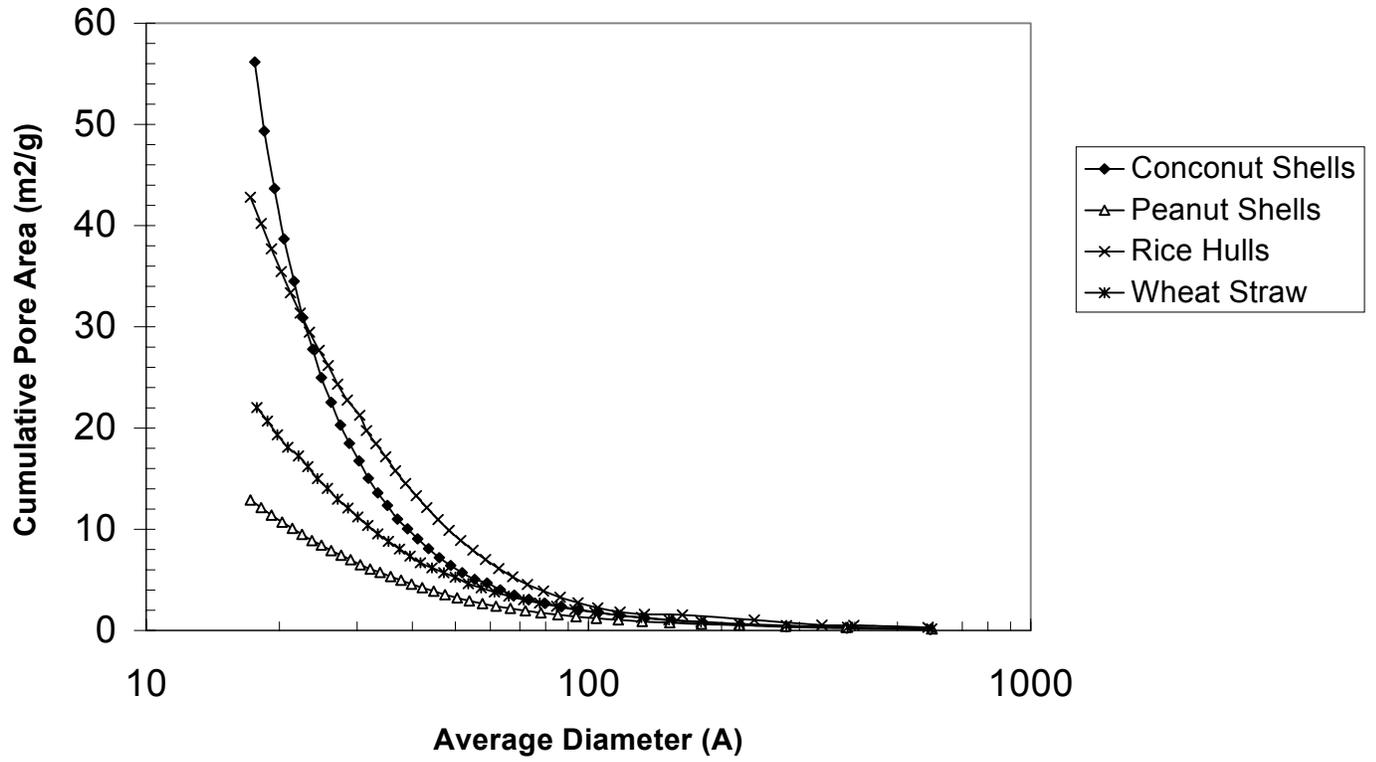


# Figure 2

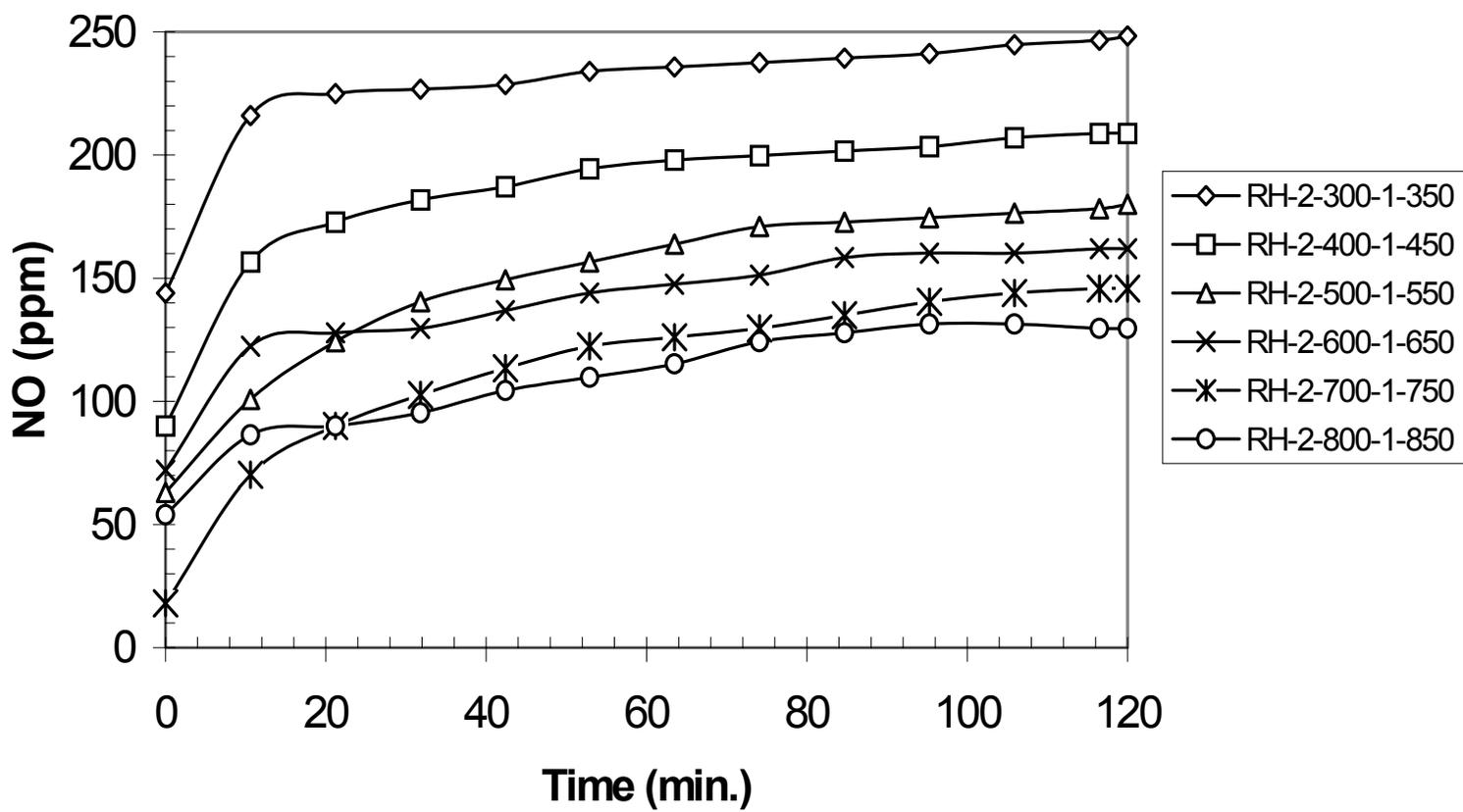


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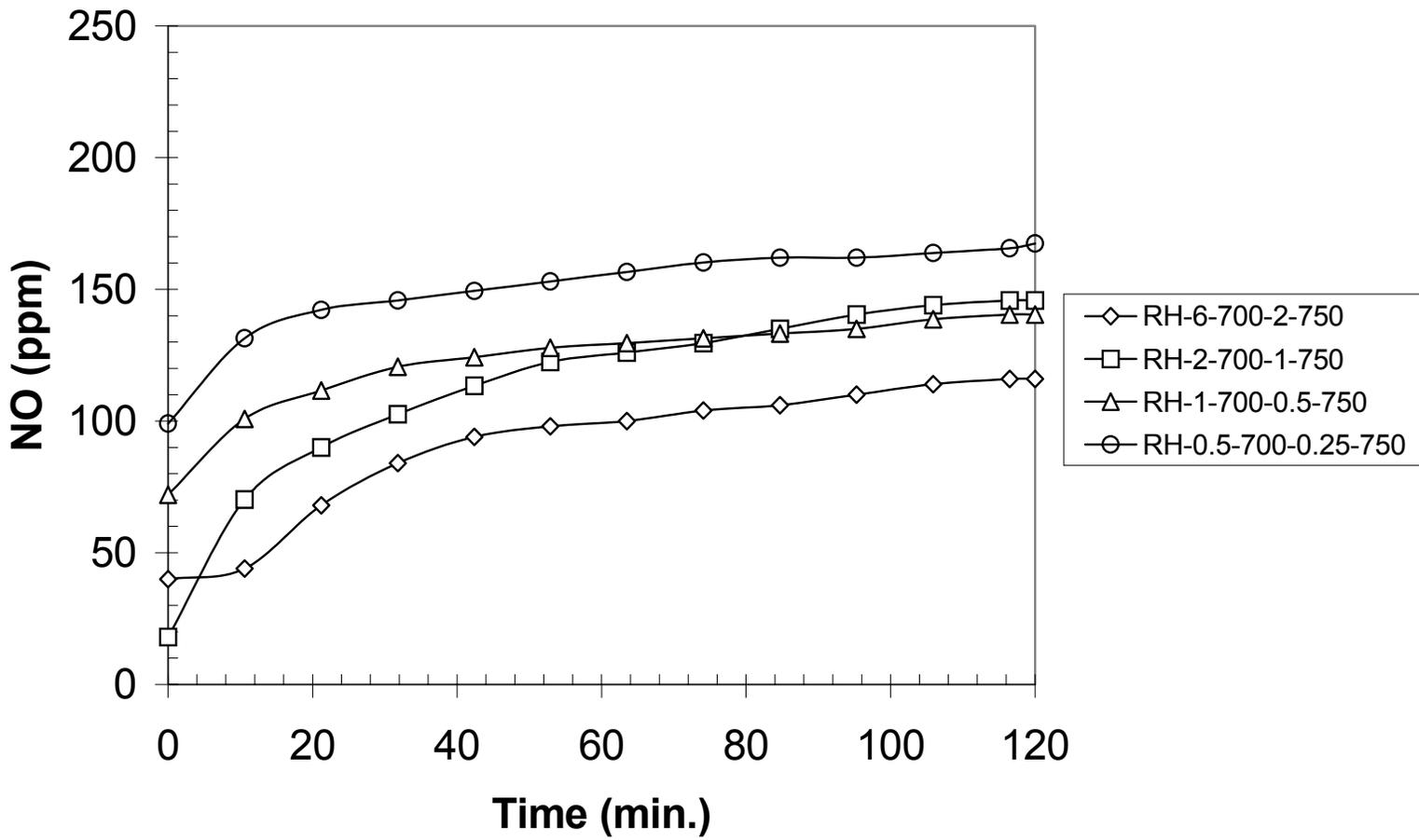
**Figure 3**



### Figure 4



**Figure 5**



**Figure 6**

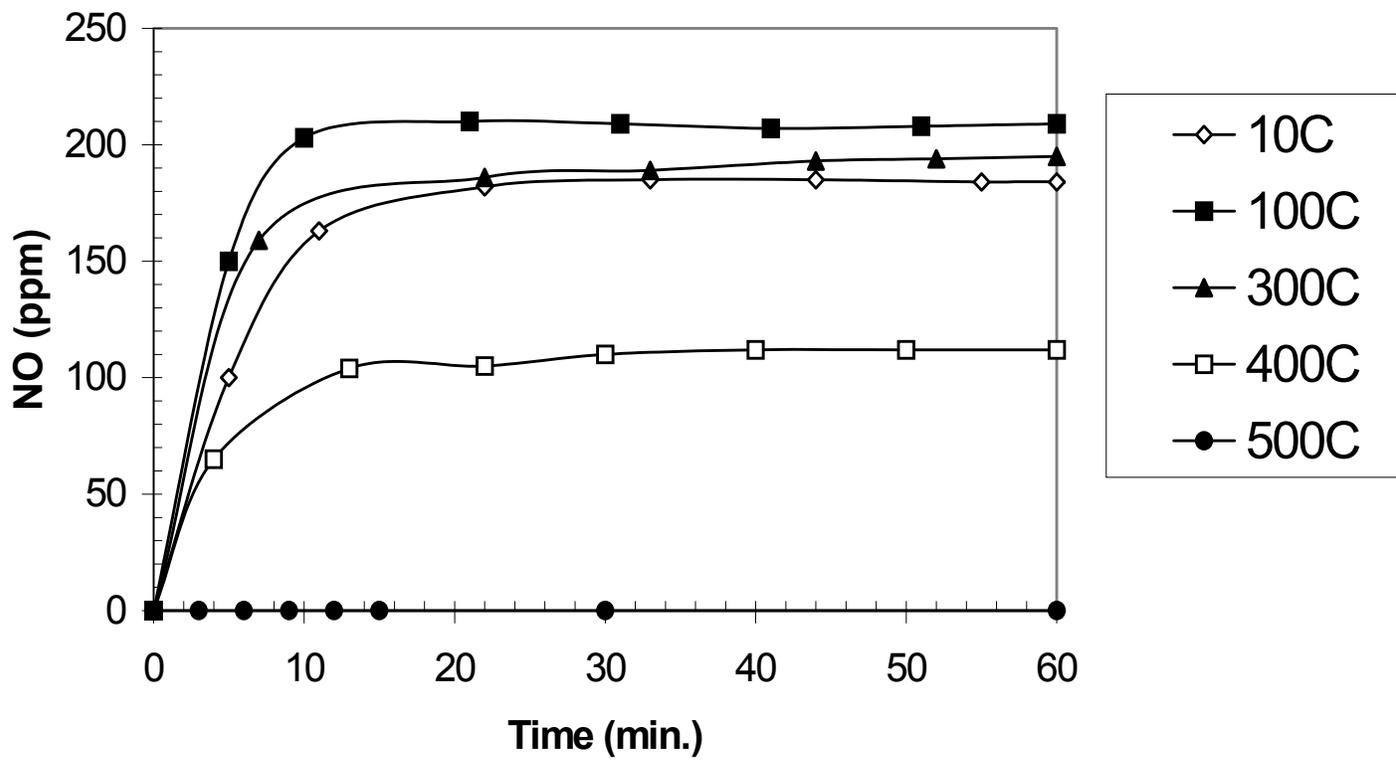


Figure 7

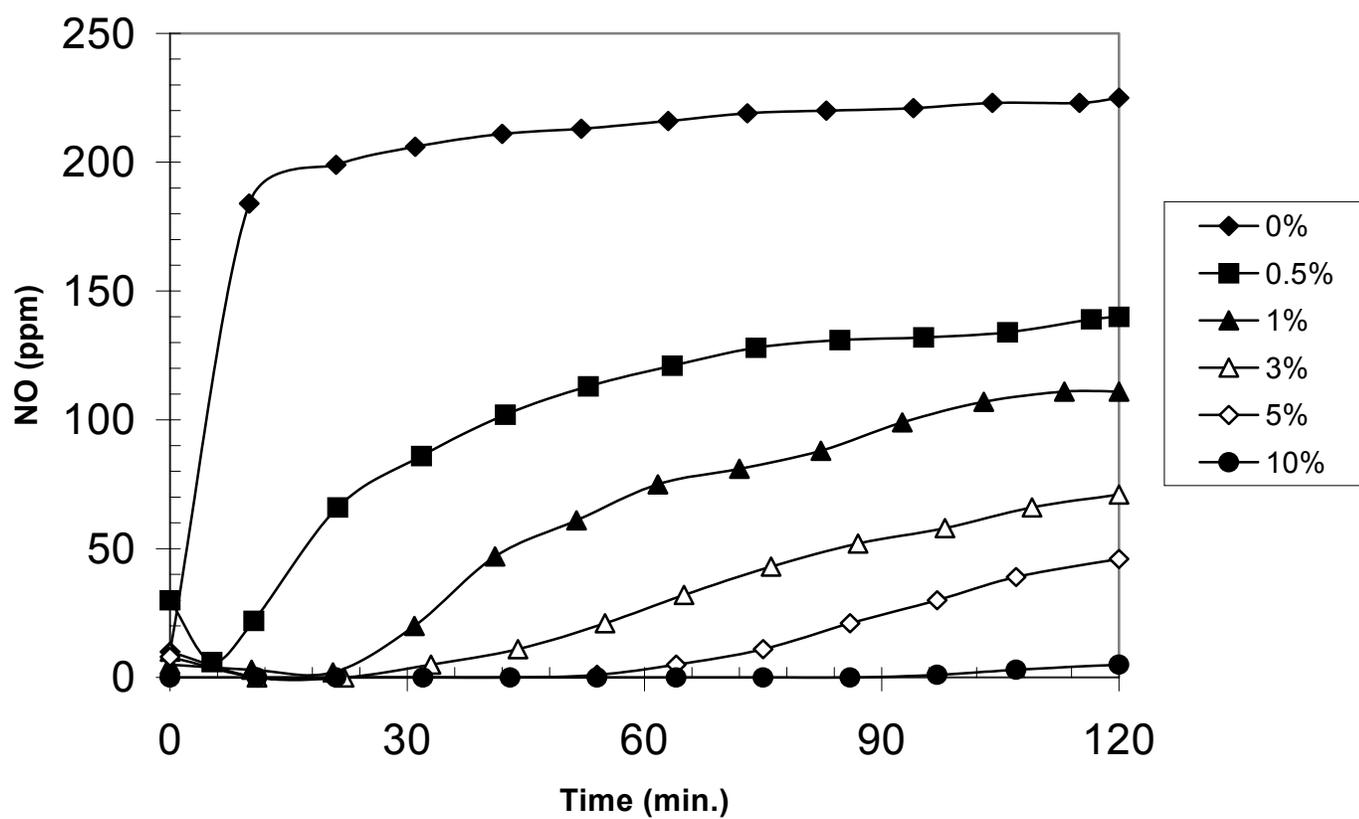


Figure 8

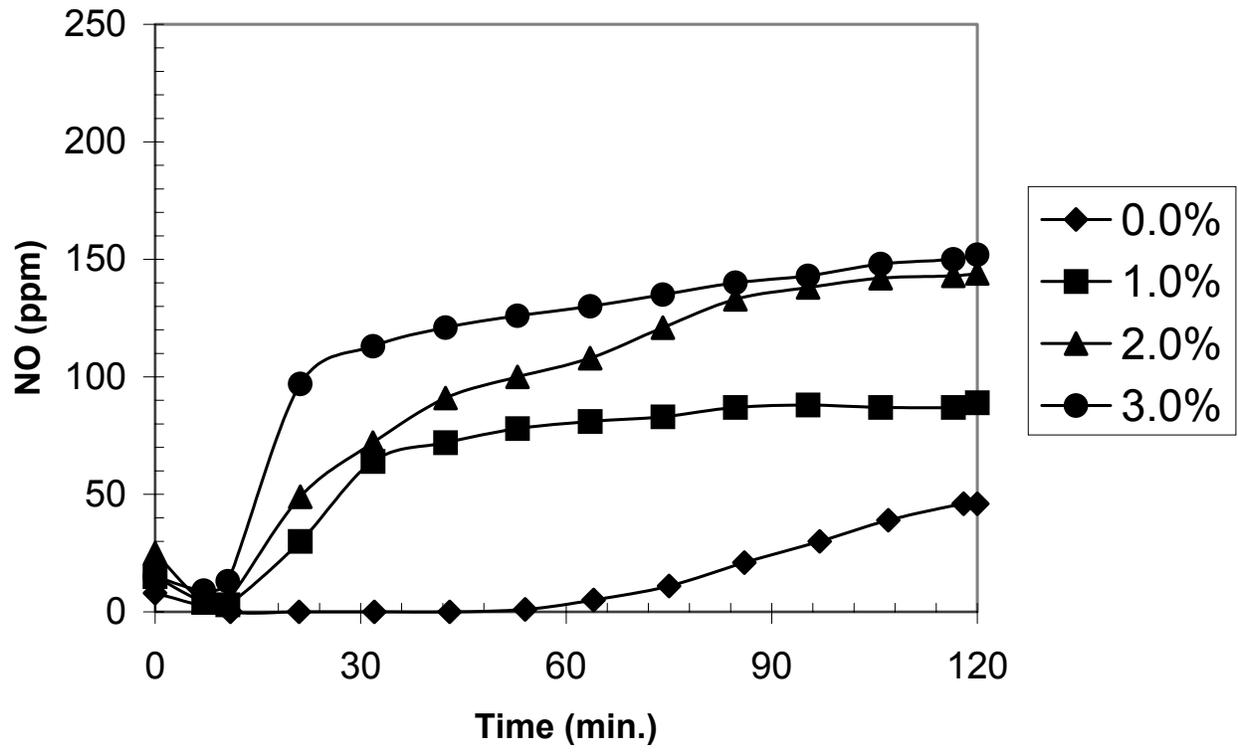
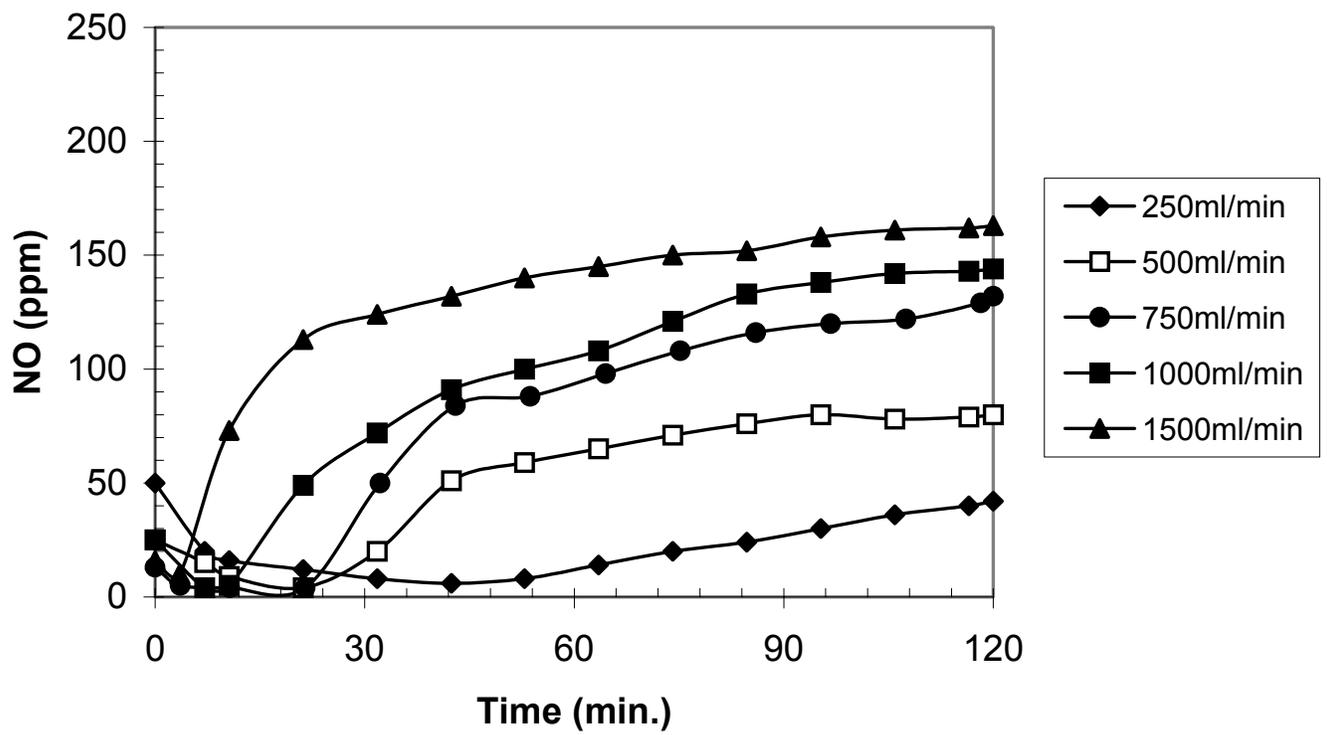


Figure 9



**Figure 10**

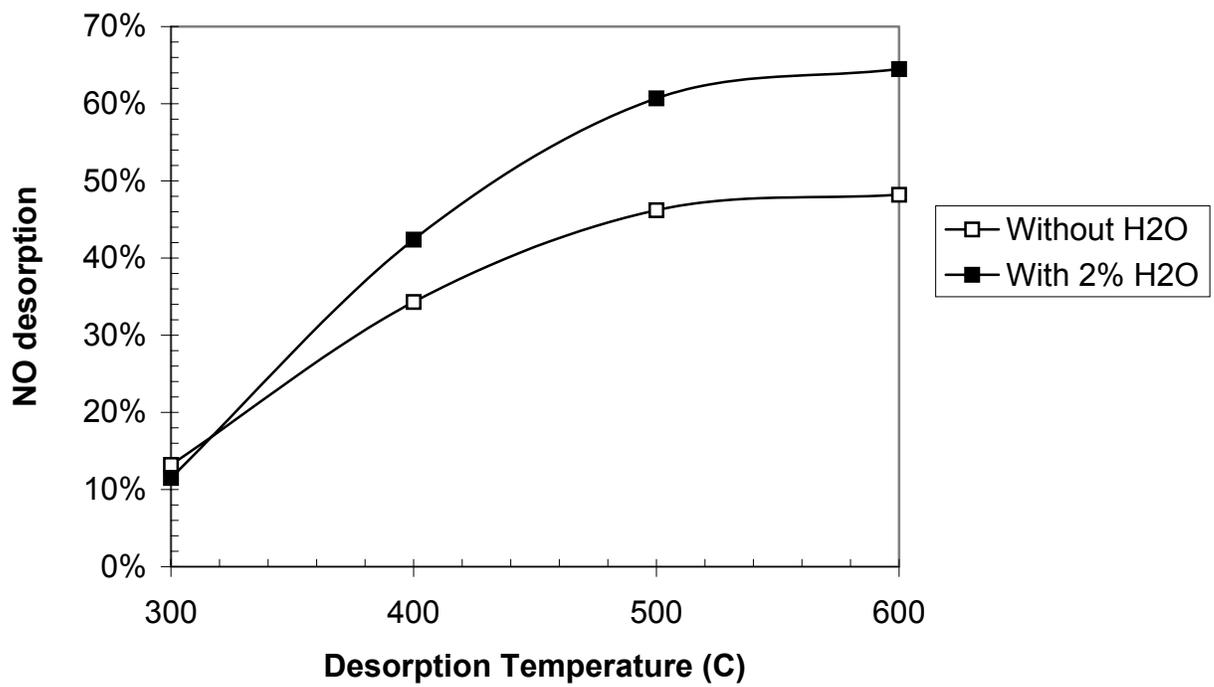


Figure 11

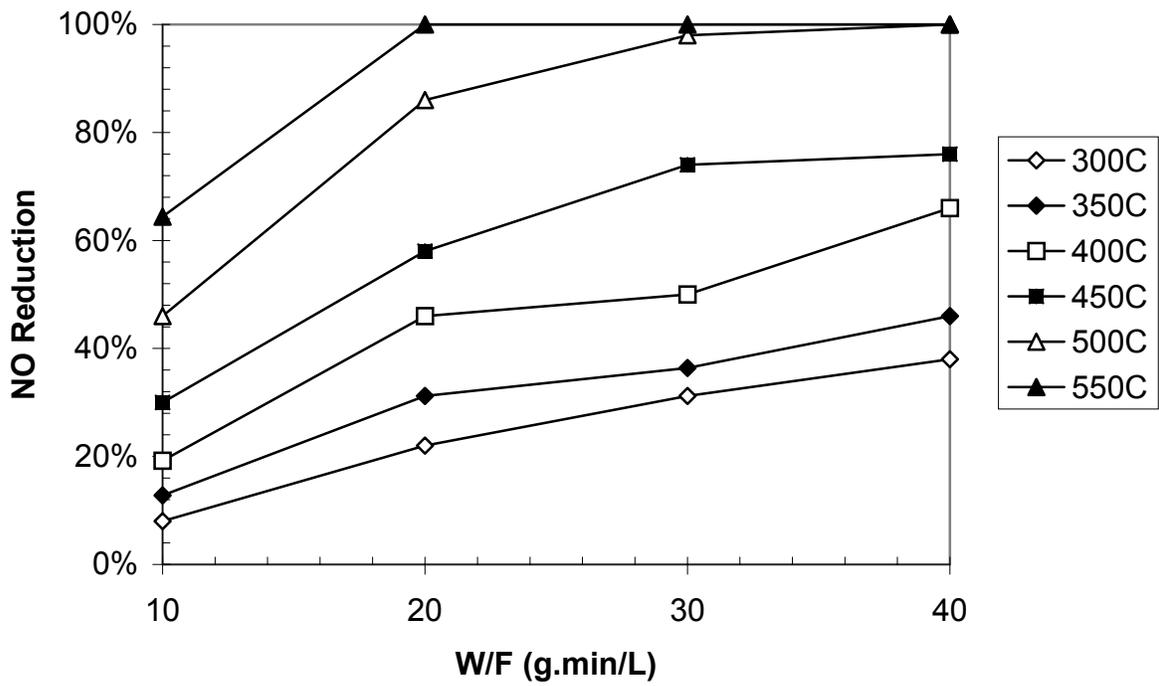


Figure 12

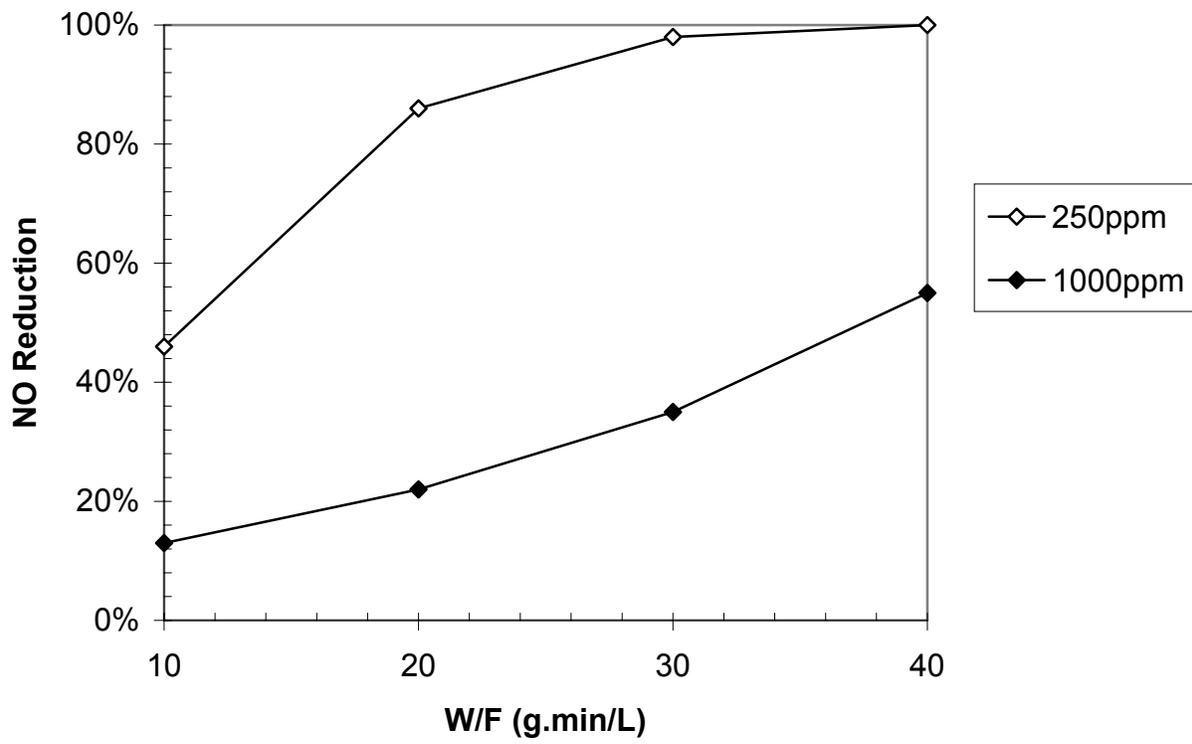
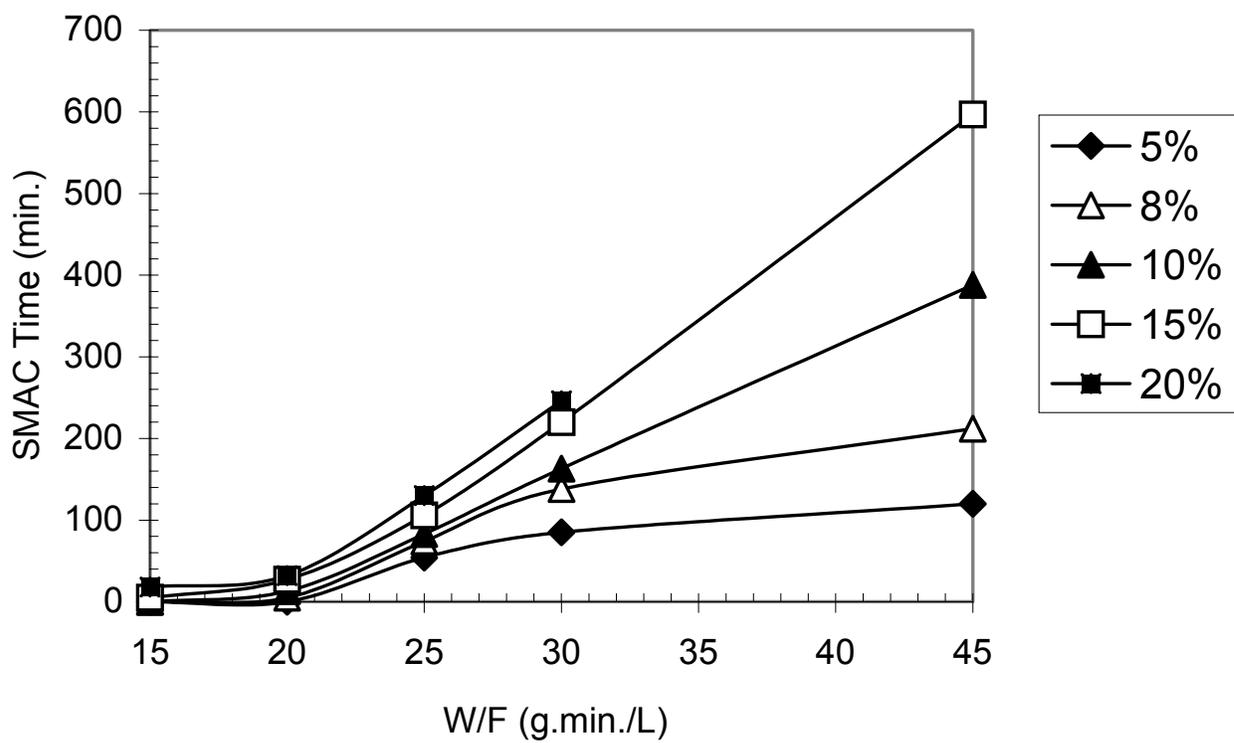


Figure 13



**Figure 14**

