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**THE SIGNIFICANCE OF SODIUM RELEASE DURING
DEVOLATILIZATION ON FUME FORMATION
IN KRAFT RECOVERY FURNACES**

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The Significance of Sodium Release During Devolatilization on Fume Formation in Kraft Recovery Furnaces

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ABSTRACT

Approximately 5-20% of sodium in black liquor was released during devolatilization of individual drops in pyrolytic atmospheres. The extent of this loss increased with increasing furnace temperature (600-900°C) and decreased with increasing relative gas velocity (0.61-1.83 m/s). This sodium loss is not caused by simple vaporization, but may result from convection of material by escaping pyrolysis gases. The contribution of sodium loss during devolatilization to overall fume formation is unknown; however, collected aerosol samples suggests that it is not the most significant source of submicron-sized fume in the recovery furnace.

INTRODUCTION

The condensation of alkali vapours, generated during kraft black liquor combustion, produce a submicron-sized inorganic aerosol which is commonly known as dust or fume. Fume particles are composed primarily of sodium carbonate (Na_2CO_3) and sodium

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sulphate (Na_2SO_4). Recovery furnace material balance calculations indicate that 10% of the sodium entering with the black liquor is ultimately captured as fume in the electrostatic precipitator [1]. Fume generation has historically been attributed to reaction and condensation of gaseous sodium species which vaporize from the high temperature and strongly-reducing environment of the char bed [2]. Cameron [3] proposed a reaction-enhanced mechanism that could explain the greater rate of fume formation observed when molten alkali salts were contacted with oxygen-containing atmospheres. Recent work has suggested that sodium release during black liquor devolatilization (i.e., char formation) may also contribute significantly to overall fume generation [4,5].

Black liquor undergoes three distinct stages of combustion when it is sprayed into the recovery furnace: drying, devolatilization, and char burning. Particle temperature rapidly increases after the water is completely evaporated from a black liquor drop. During the devolatilization stage, organic components of black liquor solids begin to decompose as particle temperature reaches 200°C [6]. Volatile gases are released as the temperature increases from 250 to 500°C ; the period of characteristic swelling occurs between 400 and 500°C [7]. In oxidizing atmospheres, the released volatiles burn in a luminous flame. Carbonaceous char, which remains at the end of devolatilization, is consumed by heterogeneous gasification reactions occurring on the char bed at the bottom of the furnace [8]. Molten inorganic compounds coalesce as smelt beads when the carbon in individual char particles is depleted.

Volkov et al. [9] were the first researchers to investigate the release of sodium during black liquor drop combustion. At the minimum exposure time of three seconds, they

reported a 20% sodium mass loss for 2-mm diameter black liquor drops burned in air at 900°C. Model predictions indicate that drying and devolatilization of similar-sized drops in air at 800°C would be complete in about three seconds [6]; therefore, it is likely that part or all of the sodium loss reported by Volkov occurred during devolatilization. While these and other experimental data indicate that sodium loss occurs during all stages of black liquor combustion [4,10], sodium release prior to char burning has only recently been considered as a possible source of fume in the recovery furnace.

Frederick and Hupa [4] proposed that sodium loss during devolatilization could be the most significant source of fume in the recovery furnace because it can account for the total amount of sodium collected in the electrostatic precipitator. In their experiments they pyrolyzed individual drops of black liquor in a muffle furnace which was purged with a mixture of N₂ and CO. Sodium loss from black liquor drops was reported as a function of exposure time over a temperature range of 700 to 1000°C. Their results indicate a rapid sodium mass loss of 14-18% prior to the end of the devolatilization stage [5]. Although this is an important finding, information to support their hypothesis - that sodium loss during devolatilization is the most important source of recovery furnace fume - is lacking. A mechanism to explain the sodium release has not been proposed. The form of the lost sodium has not been identified, nor has its impact on overall fume formation been verified.

One goal of our research was to identify the mechanism of sodium release during devolatilization. The single drop pyrolysis technique was utilized for most of the experiments because it allowed the processes occurring during the drying and devolatilization stages to be isolated from those of char burning and smelt oxidation. Results of these

experiments show that sodium loss is not the result of simple evaporation of sodium species, and may be caused by physical ejection of material. Another objective of our work was to determine the type and amount of aerosols generated during each combustion stage. An experimental system was developed that coordinated timed observation of drop combustion with a continuous record of collected aerosol. Equipment difficulties limited the extent of this work. However, limited results indicate that the majority of submicron-sized fume is formed during the char burning and inorganic reactions stages of drop combustion. The major conclusion drawn from this work is that sodium release during black liquor devolatilization is not necessarily the most significant source of fume in the recovery furnace.

EXPERIMENTAL

In single-drop sodium mass loss experiments, the relative change in black liquor sodium content was determined as a function of temperature, gas composition, and exposure time. The single drop exposure technique used in this study was based on that described by Volkov et al. [9]. Individual drops of an industrial kraft black liquor, of 2 mm average diameter, were formed on nichrome wires and inserted into a tube furnace. After 3 to 30 seconds exposure to a pyrolytic environment, the char was withdrawn into a quenching chamber purged with nitrogen gas. The variation in individual drop exposure time ($\pm 95\%$ confidence limit) was less than 5% of the mean for each determination. Timed observation of drop behaviour in the furnace was recorded on videotape. Details of the drop furnace apparatus and experimental procedure are described elsewhere [10,11].

A summary of the furnace conditions and average behaviour of the char particles selected for sodium mass loss determinations is presented in Table I. Each

experiment consisted of 4-9 determinations of sodium mass loss; a typical experiment included 2-3 replicates of three exposure times at a given set of furnace conditions. Composite samples of 4-20 fully-intact char particles were accumulated for each determination.

Sodium mass loss was also measured after pyrolyzing larger samples of the same black liquor in a heated quartz U-tube apparatus. Approximately 100 mg of liquor was applied in a 5 cm line along the bottom of twelve alumina combustion boats. Half of these samples were dried overnight at 105°C. Three boats containing dried solids and wet liquor were each pyrolyzed for 60 seconds in the U-tube apparatus, as described elsewhere [11]. The pyrolysis environment was 95% N₂ with 5% CO at 750°C. Gas flow was controlled to produce an average open-tube gas velocity of 0.61 m/s.

For both types of experiments described above, sodium mass loss was defined as the percent difference between the amount of sodium in the liquor solids and the mass of sodium in the char. Sodium mass in the char was calculated from the sodium concentration in acid-digested char samples multiplied by the digested sample volume. Sodium and solids contents of the black liquor were determined during each experiment. Inductively coupled plasma emission spectrometry (ICP) was used to measure the amount of sodium in all acid-digested liquor and char samples [12].

The technique of determining the time during combustion when inorganic aerosols were generated required coordinating drop combustion progress with continuous collection of the aerosols as they were produced. For each dynamic aerosol collection experiment, an individual drop of black liquor was formed on a nichrome wire and inserted

into the drop furnace. A fume-capturing apparatus was activated at the moment the drop entered the reaction chamber; this device moved a silver membrane across the furnace exit. Constant linear velocity of the apparatus was maintained by a dc drive with feedback speed control. After exposure to the exhaust gases from combustion, each silver membrane was divided into eight 1.3-cm sections. All sections were agitated in ultrapure water, and sodium concentration of the resulting solutions was determined by ICP. The combustion environment in the reaction chamber was 92.5% N₂ with 7.5% O₂ at 750°C; average gas velocity was maintained at 0.61 m/s. During these experiments, drop combustion progress was recorded on videotape for subsequent analysis.

RESULTS AND DISCUSSION

Sodium Loss During Devolatilization

The average amounts of sodium lost from the individual char particles as functions of exposure time and furnace conditions are plotted in Figs. 1 and 2. Error bars indicate the range of values determined for each condition. There were significant sodium losses at the shortest exposure times in all experiments; thus, the curves in Figs. 1 and 2 were drawn assuming zero sodium loss occurred at zero exposure time. The lines were not determined by statistical regression.

Similar sodium loss behaviour was observed in two laboratories using different experimental systems and black liquors. In most cases there was a sudden 5-20% sodium mass loss that occurred prior to the end of the devolatilization or swelling period; we refer to this as the initial sodium loss. Comparison of the results from pyrolysis (in 95% N₂ with 5% CO at 0.61 m/s) at 600, 750, and 900°C in Figs. 1 and 2 shows that the extent of this

initial loss increased with increasing furnace temperature. Our results from pyrolysis at 600 to 750°C exhibit the same basic trends as the 700 and 800°C data presented by Frederick and Hupa [4]. Limited data indicate that sodium loss during pyrolysis at 900°C, shown in Fig. 1, did not level off after swelling was complete but continued to increase with exposure time. Frederick et al. [5] reported similar behaviour for liquor drops pyrolyzed at 900 and 1000°C.

Two effects of gas composition are apparent in Fig. 1: the addition of CO₂ did not change the extent of sodium loss at 600°C, and the presence of O₂ enhanced initial sodium loss at 500°C. Although more scattered, the sodium losses at 600°C in 75% N₂ with 20% CO₂ and 5% CO were not statistically different than those measured during our experiments at 600°C in 95% N₂ with 5% CO. A single line was drawn through all the 600°C data to indicate similar behaviour. Note that error bars were omitted from the values of the second experiment at 600°C; this was done for clarity in the figure. Scatter in these data was of the same magnitude as in the first experiment at 600°C. Comparing results from the experiments at 500 and 600°C, shown in Fig. 1, indicates a significant effect of oxygen on sodium loss. Twenty percent of the sodium was released from the partially-swollen char during 7 seconds exposure to the 500°C oxygen-containing atmosphere. Char particles withdrawn from oxygen-free environments at 600°C after 3 seconds had swollen to approximately the same extent, but the sodium mass had decreased by only 5%.

As seen in Fig. 2, tripling the gas velocity resulted in a large decrease in sodium loss. A t-test of the mean mass losses for each experiment indicated that the decrease in sodium release (i.e., greater sodium retention) caused by increased gas velocity was significant at the 99.9% confidence limit. Reviewing the video images revealed no visible

therefore occur before all the organically-bound sodium is stabilized as Na_2CO_3 or as catalytically-active alkali sites in the char. The results in Figs. 1 and 2 indicate that this loss is a function of drop heating rate. Possible mechanisms to explain the initial sodium loss are discussed in the following section.

Li and van Heiningen [15] did measure sodium loss in an atmosphere of He with 12% CO when the final temperature of their thermogravimetric runs was 800°C ; however, the rate of this loss was less than 5% of that observed in a pure He atmosphere at the same temperature. Sodium loss at temperatures higher than 800°C can be explained by direct thermal decomposition of Na_2CO_3 [16]. Clearly this is the cause of the second phase of sodium loss occurring during pyrolysis at temperatures of 900°C and greater, shown in Fig. 1 and reported by Frederick et al. [5].

There was no apparent effect of CO_2 addition on sodium loss in our experiment at 600°C . Other work has shown that, during CO_2 gasification, Na_2CO_3 remains fixed in the char [15,16]. Among the numerous detailed mechanisms proposed to explain alkali-catalyzed char gasification, a common factor is that the alkali catalyst is cyclically reduced by reaction with carbon and subsequently oxidized by CO_2 [20]. According to this type of mechanism, elemental sodium should not be released during CO_2 gasification unless the temperature is high enough for thermal Na_2CO_3 decomposition to occur [15].

In another experiment investigating the effect of gas composition, we found greater sodium loss at 500°C in an oxygen-containing atmosphere than at 600°C in an oxygen-free atmosphere. Although no glowing combustion was observed during this experiment, it is likely that oxidation of the char increased the particle temperature more than

100°C higher than the furnace environment [21]. The significantly higher particle temperature would result in a higher heating rate and correspondingly greater sodium loss than would be expected in a non-oxidizing environment at 500°C.

Mechanism of Sodium Loss

In the U-tube experiment, liquor samples in the combustion boats exhibited similar behaviour to that observed for pyrolyzing single drops. There was a period of boiling and bursting immediately after insertion of the wet liquor samples; bursting was not observed for the oven-dried samples. After exposure for a few seconds, swelling liquor was visible above the top of the boat. The char surface rapidly contacted the flowing gas; therefore, devolatilization products should have been carried away by the gas flow as in the drop furnace. The swollen material never touched the inside surface of the quartz tube. Great care was taken to insure that no sodium was retained by the alumina boats [11].

Results of the U-tube experiment are summarized in Table II. Calculated solids contents, given in Table II, agree well with the standard determination of 72.3% solids for this liquor sample [22]; thus, samples dried in the ceramic boats reached 100% solids. There was a substantial amount of volatiles released during these experiments. In fact, the total char mass loss in Table II is somewhat higher than the values of 15-25% determined for pyrolysis of individual drops at 750°C. The results in Table II show that there was no statistically-significant difference in the sodium contents of the black liquor, dried solids, or the pyrolyzed char samples. Constant sodium content, on an initial solids basis, implies that there was *no sodium loss* during devolatilization in these experiments. For comparison, the results in Fig. 2 indicate there was a 20% ultimate sodium loss for single drop pyrolysis in

95% N₂ with 5% CO at 750°C.

In a thermogravimetric study of model organic alkali compounds, Stewart et al. [16] found that sodium and potassium benzoate samples exhibited two distinct weight loss regions at 450-550°C and 750-900°C. Considerable evidence was presented to demonstrate that no alkali losses occurred over the lower temperature range, and that substantial amounts of alkali were vaporized as a result of Na₂CO₃ reduction by carbon at the higher temperatures. These findings support the result of the U-tube experiment, which leads us to question if the sodium mass loss measured during the single drop experiments is not merely an artifact of the technique. Nevertheless, our single drop results, and those of other researchers [4,15], suggest there are alkali losses of 5-10% which occur during devolatilization at temperatures below 750°C. Two mechanisms have been proposed to explain this initial sodium loss: vaporization and convection [11,23]. Vaporization implies that there is a partial pressure of gaseous sodium species above a condensed sodium-containing surface. Convection is defined herein as physical transport of sodium-containing material by gases escaping from a devolatilizing particle. The following discussion considers each of these mechanisms in turn.

Single particle temperatures are high enough to produce a slight vapour pressure of elemental sodium during the swelling period of devolatilization (400-500°C) [6]. It is also possible that the fugitive sodium is associated with volatile organic compounds. A low molecular weight organo-sodium compound that has substantial vapour pressure and thermal stability at devolatilization temperatures could be swept from the boundary layer surrounding the black liquor particle into the bulk phase. The compound would there decompose to low molecular weight gases and elemental sodium. Subsequent reactions with

O₂, H₂O, and CO₂ would produce submicron-sized fume [3,6]. Direct comparison of the results from the U-tube experiment with the individual drop experiments is convoluted by differences in liquor sample geometry. However, the result that no sodium loss occurred, despite substantial char mass loss, suggests that sodium release during devolatilization is not a result of evaporation of organic sodium compounds. Furthermore, any mechanism depending on an unsubstantiated volatile intermediate is subject to criticism; thermally stable organo-sodium compounds must be identified before such a mechanism can be considered tenable.

Figure 3 confirms a result noted in the last section, that increasing average gas velocity greatly reduces sodium mass loss. In Fig. 3 we have compared the averaged results from our single drop experiments at 750°C (from Fig. 2) with similar values reported by Frederick and Hupa [4]. Frederick and Hupa's experiments were conducted at 800°C with no forced convection. All points in Fig. 3 represent 10 seconds pyrolysis of 5-12 mg drops in 95% N₂ with 5% CO; the 50°C temperature difference is not expected to significantly affect the sodium loss. Figures 2 and 3 clearly indicate there is greater sodium retention at higher flow rates. Tripling gas velocity did not significantly increase the heating rate at 750°C, as demonstrated by the similar drying and devolatilization times given in Table I. Therefore, the difference in sodium mass loss can not be attributed to a heating rate effect. While the reason for the velocity effect is unknown, the argument remains that if the sodium mass loss was due to direct vaporization, then the increased removal rate of the alkali species by the higher gas velocity should have resulted in greater sodium release.

The above results suggest that vaporization is not the mechanism of sodium loss during black liquor devolatilization. During the first observations of spent liquor drop

combustion, researchers noted that the drops bubbled violently during drying [24,25].

Bubble formation and erupting jets of gases were also observed in photographic images of devolatilizing black liquor solids and coal particles [7,26]. Eruptions of water vapour and pyrolysis gases from the surface film of a liquor drop could result in ejection of tiny particles of liquor and char. Convection of sodium-containing material is a possible mechanism of sodium loss during the gas evolution phase of devolatilization. Higher particle heating rates caused by higher furnace temperature would produce more rapid volatiles evolution. The correspondingly more violent devolatilization may explain the effect of heating rate on initial sodium loss apparent in Figs. 1 and 2. Tripling gas velocity certainly did not significantly *reduce* heating rate at 750°C; nevertheless, the higher flow rate apparently reduced material loss during devolatilization.

Liquor properties affecting swelling behaviour would also be expected to affect convective sodium loss. Results presented by Frederick et al. [5] indicate that there was not a substantial effect of black liquor type on sodium mass loss. The analyses of their liquors were not reported; thus, it is not certain if the chosen samples represent a wide enough range of properties to cause differences in swelling behaviour. van Heiningen et al. [27] made a series of black liquor chars for gasification experiments by pyrolyzing black liquor in N₂ at 700-800°C; a significant effect of liquor type on sodium loss can be calculated from their reported data. While the pine liquors experienced a $15 \pm 10\%$ sodium loss during pyrolysis, the birch liquors apparently did not release sodium at all [27]. Viscosity, surface tension, extractive content, extent of oxidation, and inorganic content are expected to affect the physical processes occurring during devolatilization [7]. The effect of these variables on sodium mass loss remains to be systematically investigated.

Another possible form of convection is physical transport of atomic sodium from the char surface by gas eruptions during devolatilization. Meijer et al. [18] measured catalyst loss and retention under various conditions for alkali-impregnated model coal chars. Sodium was found to be the least stable alkali species investigated; it exhibited greatest losses during both pyrolysis and gasification. If black liquor char contains similar catalytic sites, then it follows that the sodium clusters are only loosely bound to the char surface. This sodium could be carried away by erupting gases. Additional work is being conducted at another university to investigate the nature of the catalytic sites in black liquor char [28].

Sodium Release and Fume Formation

Regardless of the mechanism of sodium release during devolatilization, the impact of sodium loss on fume formation can be evaluated by collection of generated aerosol as a function of exposure time. The rate of sodium deposition on silver membranes from two dynamic aerosol collection experiments is plotted against elapsed drop combustion time in Fig. 4. For each membrane section, average deposition rate was calculated from the total mass of sodium collected during a 3 second time interval (i.e., the combustion time which elapsed during 1.3-cm travel of the collection medium). Particle entrainment and collection efficiency calculations indicate that submicron-sized fume should have been collected preferentially to larger aerosol on the silver membranes [11]. This was confirmed by SEM analysis which revealed only 0.10-0.25 μm fume on all investigated sections. It can therefore be assumed that the sodium deposition rate history shown in Fig. 4 approximately represents the rate of fume formation.

The solid vertical bar in Fig. 4 indicates the end of the devolatilization stage;

this time was taken from the videotape records of drop combustion progress. Due to mixing in the exhaust gas stream, material released from a burning drop could strike the silver membrane anywhere within the spatial range of the flue opening [11]. This 9-second uncertainty interval, caused by potential overlap of collected material, is indicated by the shaded area in Fig. 4. Accordingly, the values to the right of the shaded area represent fume formation after the end of the devolatilization stage. This important result demonstrates that a maximum in sodium release, leading to fume formation, occurred during either the char burning or inorganic reactions stage of drop combustion but not during devolatilization.

SEM photomicrographs of aerosol samples collected on stationary filters provide qualitative evidence that less submicron-sized aerosol was formed during pyrolysis at temperatures below 900°C than during combustion in air at 750°C [11]. Only at temperatures high enough for Na_2CO_3 decomposition to occur (900°C) were substantial quantities of fume collected. A comparison of photomicrographs indicates that approximately the same amount of fume was collected during the *pyrolysis of 5 drops* at 750°C as during the *combustion of a single drop* of the same liquor at 750°C. These results support the hypothesis that sodium release prior to char burning is not a significant source of fume formation. The SEM photomicrographs will be presented in a subsequent publication on inorganic aerosol formation during black liquor drop combustion.

Frederick and Hupa [4] suggested that sodium loss during devolatilization is the most significant source of fume in the recovery furnace. Their justification was that the amount of sodium released during their single-drop pyrolysis experiments was an order of magnitude higher than that measured during the other stages of combustion. Granted, this

fugitive sodium could be a source of submicron-sized fume within the recovery furnace; however, it could also be captured by airborne particles or deposit on the char bed and heat transfer surfaces. Operational experience indicates that 10% of the sodium in the fired liquor is captured as fume in the electrostatic precipitator [1], yet sodium losses measured during single liquor drop pyrolysis were commonly greater than 10%. If physical ejection of char is responsible for the initial sodium loss, it is quite possible that this material never leaves the recovery furnace boundary.

Single drop experiments provide fundamental information about the processes occurring during black liquor combustion. However, the high amount of sodium loss measured in these studies may be an artifact of the experimental technique. The form of the lost sodium from single drop experiments must be conclusively identified. It is also important to determine industrially if sodium release during devolatilization contributes significantly to aerosol generation in the furnace that may plug boiler passages or load the precipitator.

CONCLUSIONS

Approximately 5-20% of the sodium present in black liquor was released during the devolatilization period in single drop pyrolysis experiments. The extent of this loss increased with increasing furnace temperature. Exposure to an oxygen-containing atmosphere at 500°C resulted in significant particle heating and higher sodium loss than would be expected in an inert environment. Higher relative gas velocity resulted in a substantial decrease in sodium release.

After the sudden initial loss, continued sodium release was only observed

during pyrolysis at 900°C. A substantial amount of fume was collected during this experiment. Carbon monoxide suppresses Na_2CO_3 decomposition at temperatures below 800°C [15]; therefore, the additional sodium loss and fume formation at 900°C resulted from Na_2CO_3 decomposition.

Experimental results and literature information indicate that sodium loss during devolatilization is not due to simple vaporization of atomic sodium or volatile sodium compounds. The sodium loss measured during these experiments may be due to convection of alkali-containing material by eruptions of pyrolysis gases through the char surface.

Results of aerosol collection experiments indicate that the majority of sodium collected as submicron-sized fume was released during the char burning and inorganic reactions stages of black liquor drop combustion. While sodium loss during devolatilization may contribute to fume formation in the recovery furnace, these results suggest that it is not necessarily the most significant source of submicron-sized aerosol.

Experiments to determine conclusively the source and characteristics of aerosols present in the recovery furnace are needed and have not yet been conducted.

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ATTACHED TABLES AND FIGURES

- Table I. Summary of single-drop sodium mass loss experiments: furnace conditions, average drop size, and stage times.
- Table II. Results of U-tube liquor pyrolysis experiment. 100 mg sample size; pyrolysis conditions: 95% N₂ with 5% CO at 750°C and 0.61 m/s.
- Figure 1. The effect of exposure time, furnace temperature, and gas composition on sodium mass loss during pyrolysis. Av. gas velocity was 0.61 m/s in all experiments.
- Figure 2. The effect of exposure time and average gas velocity on sodium mass loss during pyrolysis. Gas composition was 95% N₂ with 5% CO in both experiments.
- Figure 3. Effect of average gas velocity on sodium loss after 10 s pyrolysis. Data at 0 m/s were from 800°C,¹⁰ filled circles are from this work at 750°C.
- Figure 4. Sodium deposition rate from dynamic collection experiments; combustion in 92.5% N₂ with 7.5% O₂ at 750°C and 0.61 m/s.

Table II. Results of U-tube liquor pyrolysis experiment. 100 mg sample size; pyrolysis conditions: 95% N₂ with 5% CO at 750°C and 0.61 m/s. All values reported as mean ± 95% confidence limit.

Sample	Na cont., % ^a	Liquor solids, %	Char mass loss, %
Liquor	16.2 ± 0.4	-	-
Solids	16.2 ± 0.2	72.0 ± 2.5	-
Pyrolyzed liquor	16.5 ± 0.6	-	29.6 ± 1.0 ^b
Pyrolyzed solids	16.4 ± 0.6	72.2 ± 1.2	32.1 ± 2.0

^a Sodium content; reported as % of initial black liquor solids.

^b Estimated from liquor sample solids content.

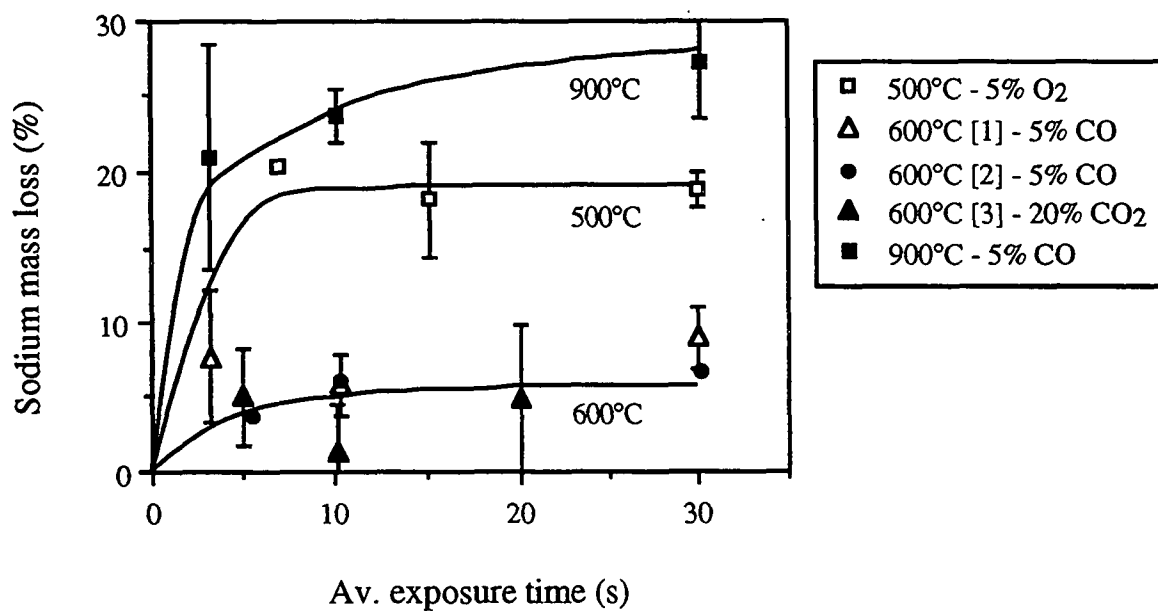


Figure 1. The effect of exposure time, furnace temperature, and gas composition on sodium mass loss during pyrolysis. Av. gas velocity was 0.61 m/s in all experiments. Lines are not based on statistical regression.

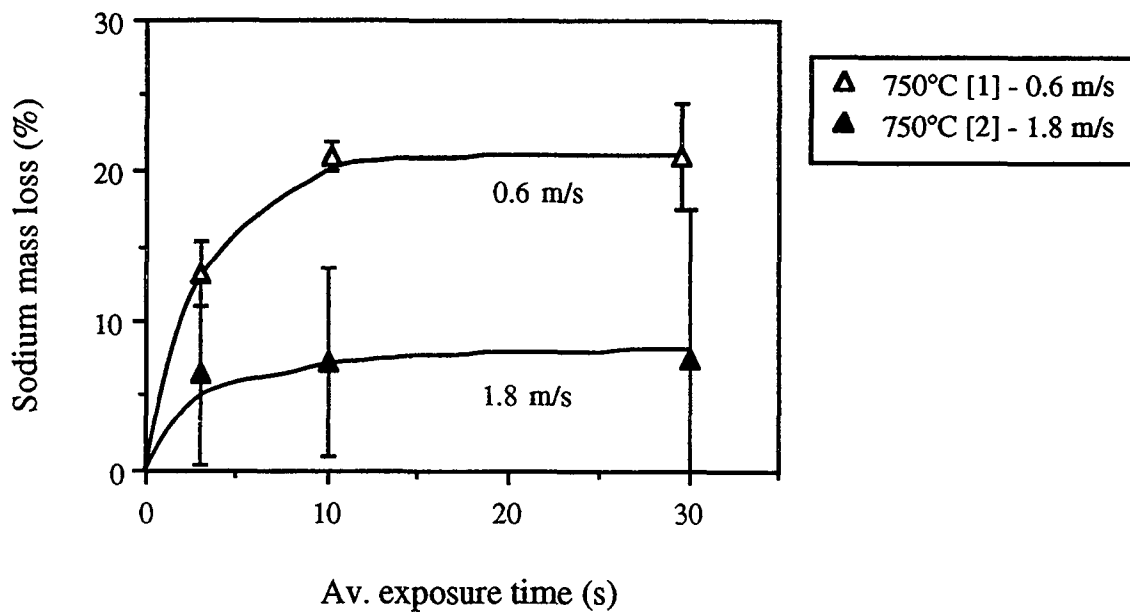


Figure 2. The effect of exposure time and average gas velocity on sodium mass loss during pyrolysis. Gas composition was 95% N_2 with 5% CO in both experiments.

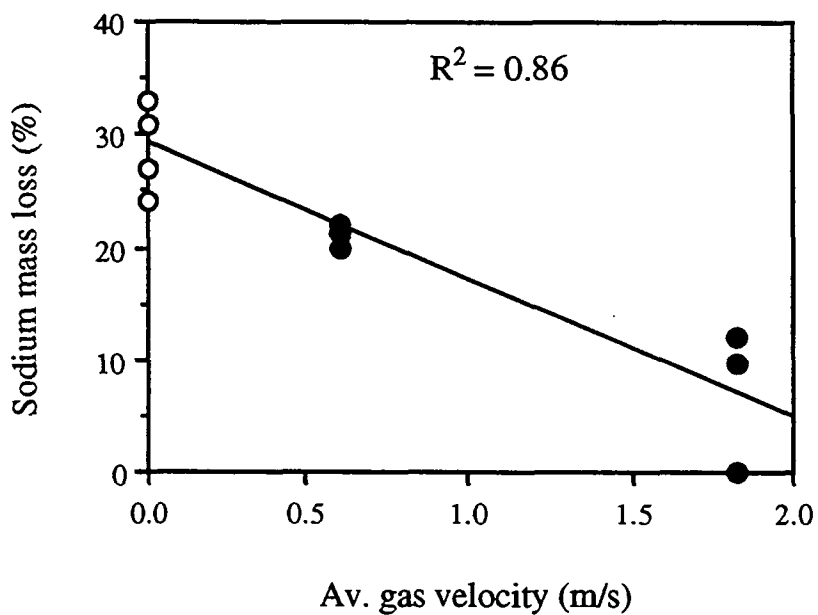


Figure 3. Effect of average gas velocity on sodium loss after 10 s pyrolysis. Data at 0 m/s were from 800°C,¹⁰ filled circles are from this work at 750°C.

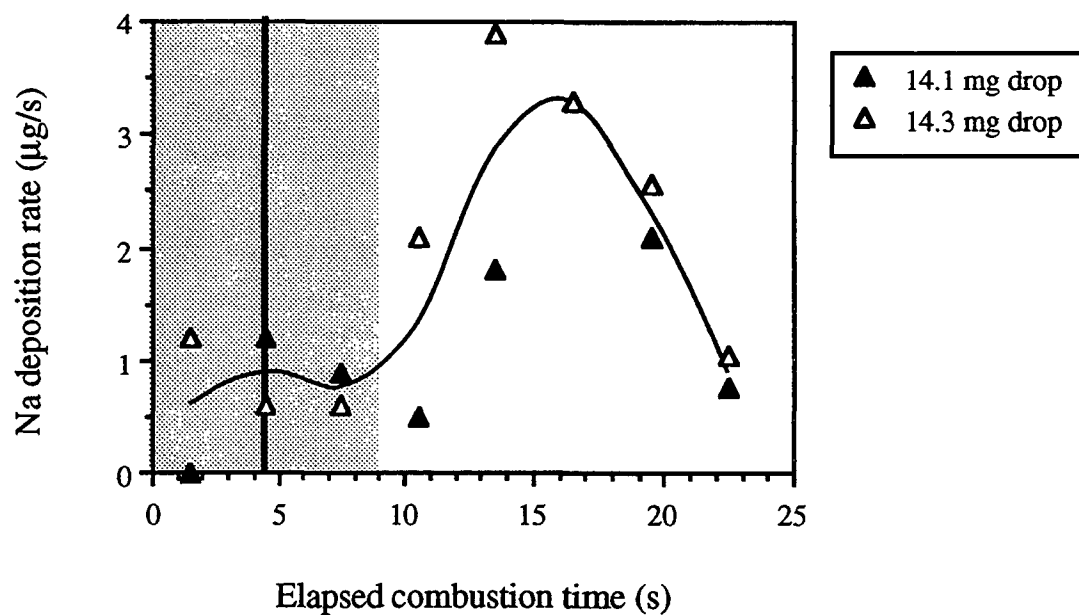


Figure 4. Sodium deposition rate from dynamic collection experiments; combustion in 92.5% N_2 with 7.5% O_2 at 750°C and 0.61 m/s. End of devolatilization stage indicated by vertical bar (see text).