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ABSTRACT

We report the development of a novel experimental technique that combines video microscopy and thermogravimetric analysis to optimize the detection of coal and char particle ignitions. This technique is particularly effective for detecting ignitions occurring in coal or char samples containing multiple particles, where other commonly used techniques fail. The new approach also allows for visualization of ignition mechanism. Devolatilized char particles appear to ignite heterogeneously, while coal particles may ignite homogeneously, heterogeneously or through a combination of both mechanisms.

INTRODUCTION

The first studies of coal ignition were undertaken to prevent mine explosions like the one investigated by Faraday and Lyell in 1844 (Faraday and Lyell, 1845). Since then, many experimental and theoretical studies have focused on the ignition characteristics of coal particles in an effort to optimize the operation of coal-fired power plants and industrial-scale utility boilers (Essenhigh, et al., 1989). The detection of coal particle ignitions, however, remains a very challenging task. Although increasingly sophisticated experimental techniques have been employed to study this complex process, there are still many unanswered questions concerning the effect of important operating parameters on coal particle ignition and combustion.

Coal particle ignitions follow either a homogeneous or a heterogeneous mechanism. The first step of the homogeneous mechanism involves rapid release of volatiles upon heating of the coal particles. As the volatiles escape, they ignite and burn in the gaseous phase surrounding the particle. After this stage, heterogeneous combustion reactions continue to take place on the surface and in the interior of the particles until all the carbon is consumed. On the other hand, heterogeneous ignitions occur when heat generation rates due to combustion reactions are much higher than the heat removal rates. As a result, the particles rapidly reach temperatures that can be several hundred degrees above the ambient temperature (Semenov, 1928) and they ignite often with bright light emissions.

Because of the importance of particle interactions in industrial coal combustion, most laboratory reactors employ designs which approximate these interactions. One common type of laboratory combustion reactor is the drop tube or entrained flow reactor, where multiple coal particles are pulsed or continuously flown through a tubular furnace. In this case, little information about the behavior of individual particles can be obtained. The same argument can be made for coal

combustion studies in a fluidized bed. A common approach to ignition detection in these types of experiments is to measure the light emissions, with photomultipliers (Gupta, et al., 1990, Wall, et al., 1988). Although this approach is useful for studying the role of particle interactions, it cannot distinguish individual particle ignitions nor can it determine whether the light emissions observed at a given time point come from one or more particles.

To accurately study ignition phenomena, many researchers have conducted single or isolated particle experiments. Here, a common approach to ignition detection and characterization is the use of two-color near infrared pyrometry (Levendis, et al., 1989) to measure particle temperatures. Using this technique, Levendis et al (Levendis, et al., 1989) observed that the ignition of char particles originated from localized "hot spots" on the particle surface before spreading across the entire particle. Gomez and coworkers studied ignitions by combining luminosity measurements with simultaneous analysis of the carbon monoxide and carbon dioxide produced when a single coal particle ignites and burns (Gomez and Vastola, 1985). Since total luminosity measurements cannot distinguish between volatile matter ignition (homogeneous mechanism) and surface reaction (heterogeneous mechanism), the product gas was analyzed to determine the mechanism of ignition. To directly detect the combustion of volatiles in the region surrounding a coal particle, Huang and coworkers combined luminosity measurements with measurements of temperature profiles around coal particles (Huang, et al., 1988). This approach can provide useful information about the ignition mechanism by differentiating between volatile burning around the particle and reactions occurring at the surface or in the particle interior (Zhang and Wall, 1994).

In contrast to total luminosity measurements, video microscopy is effective in tracking the fate of individual coal particles during pyrolysis and combustion experiments. Video microscopy techniques detect ignitions by directly observing light emissions from individual particles and are also useful for investigating ignition mechanisms. Yang and Tsai (Yang and Tsai, 1990) utilized video techniques to visualize the ignition of coal particles with diameters ranging from 6 to 15 mm. They concluded that particles ignited by both mechanisms and noted the appearance of luminous flames in the area surrounding the particle as well as on the particle surface. For experiments where ignitions result in easily observable emissions of light, video microscopy can be very effective for detection and mechanism identification. When used alone, however, we will show that even this technique may be inadequate for detecting ignitions where light emissions are faint.

Tognotti and his coworkers (Tognotti, et al., 1985) utilized thermogravimetric measurements to detect the ignition of coal particles. Their technique involved comparison of weight loss vs. temperature curves obtained by combusting coal in inert and reactive atmospheres. The ignition temperature was then determined as the temperature at which these two curves deviated (Chen, et al., 1985, Wall, et al., 1991). Thus, the thermogravimetric technique provided information about the onset of combustion rather than ignition, only identifying ignition in cases where it was the first combustion event (Zhang and Wall, 1994). Our studies have shown, however, that in many cases we may have significant extents of heterogeneous reactions before the particles ignite. This thermogravimetric ignition detection is

also not effective for multiple particle experiments since it does not provide information about which or how many particles have ignited.

Other recent studies have utilized the electrodynamic balance to study the combustion behavior of levitated char particles (Cozzani, et al., 1995, Wong, et al., 1995). In these experiments a single char particle is suspended in an electric field and heated by laser irradiation. Pyrometry measurements provide particle temperatures and video imaging provides images of the reacting particle. This type of study has proven itself very useful in studying heterogeneous reactions. The loss of particle charge when it ignites or reaches high temperatures, however, may cause the particle to drop out of view in the apparatus, complicating the observation of ignition phenomena.

From this discussion, it is apparent that experimental approaches to studying coal and char particle ignitions fall into one of two categories:

- (1) Particle ensemble experiments which allow particle interactions, but provide little or no detail about individual particle ignitions.
- (2) Single particle experiments which do not allow particle interactions, but provide great detail about individual particles.

The need is thus apparent for an experimental approach that is effective in detecting and characterizing individual ignitions occurring during particle ensemble experiments. This study presents results showing that this objective can be achieved by combining thermogravimetric analysis and digital video microscopy. Such a combined approach can provide detailed information on individual particle ignitions while still allowing us to study particle interactions. The advantages and limitations of the new methodology are discussed by presenting and analyzing results from combustion experiments with ensembles of coal and char particles ranging in size from 250 to 840 μm .

EXPERIMENTAL METHODS

Digital Video Microscopy

Ignition experiments were conducted in a thermogravimetric reactor with in-situ video microscopy imaging (TGA/VMI) that was described in detail in an earlier communication (Matzakos and Zygourakis, 1993). Briefly, the TGA/VMI reactor is a modified thermogravimetric analyzer (Perkin-Elmer, TGS-2) having a micro balance with a sensitivity of 0.1 μg . Coal or char samples placed in the balance pan are viewed with a high-magnification, extra-long working distance microscope (JENA, Model 121), equipped with a video camera (Javelin, Chromachip II). A computer-activated video timer inserts on the video signal the time elapsed since the beginning of an experiment. This allows us to relate visual observations to changes in sample reactivity or reactor temperature.

This apparatus was used to record on video tape the pyrolysis and combustion of multi-particle coal or char samples. The reacting samples were illuminated with a fiber optic light source (Dolan-Jenner, Fiber Lite) which allows for intensity adjustment. To improve the sensitivity of our video detection method, the illumination source was usually turned off and, in this case, ignitions appeared as flashes of light in a dark background. This approach allowed us to detect "faint" ignitions that would not be visible if the illumination source were on.

The video tapes of combustion experiments were analyzed off-line. For each experiment, a sequence of digital images was acquired at fixed time intervals using a frame grabber (Data Translation, QuickCapture). The digital images had a resolution of 640x480 8-bit pixels (256 intensity levels). These sequences of images were digitally processed to obtain time-resolved intensity traces for specified regions of interest (ROI) corresponding to particle locations or the entire pan.

The following procedure was followed to determine the appropriate ROI's for experiments conducted without external illumination. Before switching off the illumination source, a reference image was acquired to determine the precise location of each particle in the pan. Using information from the reference image, we defined regions of interest such that each ROI included only one particle. Every image in a combustion sequence was then processed to (a) isolate the ROI for each particle and (b) measure the maximum light intensity observed in it. The trace of this intensity allowed us to determine if a particle ignited and to measure the beginning and duration of each particle ignition. Char particles rarely moved during combustion experiments. If particle movement occurred, however, we simply monitored intensity across the entire pan. All steps of the image analysis procedure developed to obtain light intensity traces were performed using *NIH Image*, a public-domain image processing software package (available by anonymous ftp from zippy.nimh.nih.gov).

Figure 1 shows a digitized image from a combustion experiment with an ensemble of four particles. The time elapsed since the beginning of this experiment is shown in the upper right hand corner of Figure 1. Using the reference image, the four ROI's shown by the white circles were determined so that each ROI contained one particle. At the time this image was acquired, no light emissions can be seen in ROI's C and D. ROI's A and B, however, contain particles which react in an ignited state with bright (ROI B) or faint (ROI A) light emissions.

Combustion and Pyrolysis Experiments

The experiments discussed here were carried out with Illinois #6 coal obtained from the Argonne Premium Coal Sample Program (Vorres, 1990). Three coal particle sizes were used: 50-60 mesh (250-300 μm), 28-32 mesh (500-600 μm), and 20-24 mesh (710-840 μm). For each run, we placed several coal particles in the sample pan of the TGA/VMI reactor: 10-20 particles of the 50-60 mesh size, 4-5 particles of the 28-32 mesh size, and 2-3 particles of the 20-24 mesh size.

For sequential pyrolysis-combustion experiments, char samples were first prepared by heating the coal particles in pure nitrogen to various final heat

treatment temperatures (HTT) at heating rates ranging from 0.1 to 20 °C/sec. After holding the temperature at the HTT for a soak time of either 0 or 3 minutes, the char sample was quickly quenched to 200 °C. Without removing the char sample, the appropriate mixture of O₂ and N₂ was then introduced to the TGA/VMI reactor and the char particles were heated to the final combustion temperature at a rate of 20 °C/sec. For coal combustion runs, the TGA/VMI was loaded with coal particles and the sample was heated at rates varying between 0.1 and 20 °C/sec to the final combustion temperature in the presence of O₂.

The sample weight and reactor temperature were continuously monitored using a data acquisition and control computer (Apple Computer, Macintosh Quadra 900). Data were collected at sampling rates as high as 20 Hz and recorded in a file. Sample weight was sampled at high rates since the duration of some ignitions was shorter than 0.25 seconds. Sample reactivity was determined by calculating the reaction rate per unit mass of initial solid (R_o) according to the equation:

$$R_o(t) = \frac{dx}{dt} = -\frac{1}{m_o} \frac{dm(t)}{dt} \quad (1)$$

where x is the conversion of the solid, m_o is the initial mass of the solid in ash-free basis, and $m(t)$ is the mass (ash free) of char remaining unreacted at time t .

RESULTS AND DISCUSSION

Homogeneous and Heterogeneous Ignitions

The video imaging capabilities of our TGA/VMI reactor were essential in identifying the ignition mechanism of coal and char particles. Figure 2 shows a typical sequence of digital images obtained during combustion of two 28-32 mesh Illinois #6 coal particles. The particle in the upper part of the image appears to ignite heterogeneously at first with a flame originating from a "hot-spot" on its surface (frames 2A and 2B). This particle is then engulfed by a flame that appears to extend slightly beyond the original particle boundary in a few places (frame 2C), indicating the presence of a small volatile combustion front close to the particle surface. The next frame (frame 2D obtained 0.3 s after 2A) shows that volatiles emitted from the bottom particle have clearly ignited with a large luminous flame emanating from the particle surface. This flame seems to ignite volatiles released by the other particle and a second flame emanating from the top particle now joins the original flame (frame 1E). Both particles continue to glow in the last frame (frame 1F obtained 0.5 s after 2A) indicating that heterogeneous reactions continue to take place on the particle surfaces (and the particle interiors) after the volatile flames have been extinguished.

Our observations agree with literature results reporting that coal particles ignite with a combination of homogeneous and heterogeneous mechanisms, depending

on the flow velocities of reactant gases (Huang, et al., 1988, Yang and Tsai, 1990). We must note, however, that the image sequence of Figure 2 also shows interactions among neighboring particles with one particle triggering the homogeneous ignition of another one. Such interactions must be important in actual combustors, but will remain undetected in experiments that use a single coal particle. Our studies have revealed that occurrence of this homogeneous mechanism is aided by high oxygen concentrations, high combustion temperatures, and, most notably, the presence of multiple particles during a combustion run. The presence of multiple particles is perhaps the most crucial of these factors because it increases the chances of having highly combustible volatiles in the gas surrounding an igniting particle.

Although Figure 2 clearly indicates a homogeneous ignition mechanism, we have also observed ignitions in which only the surface of the coal particles becomes illuminated and the bright ignition regions never exceed the particle boundaries. This transition to a predominantly heterogeneous ignition mechanism occurs when we lower the oxygen concentration in the gas flowing through the TGA/VMI reactor.

On the other hand, char particles appear to always ignite heterogeneously, with bright ignition regions that never exceed the boundary of the particle. Ignitions of the type shown in Figure 2 have never been observed with char particles. This observation is consistent with the accepted mechanism of heterogeneous ignitions since chars produced with our experimental protocols contain insignificant amounts of volatiles. Figure 3 shows a typical ignition sequence for char particles. The char used for this run was prepared from 28-32 mesh Illinois #6 coal particles pyrolyzed at 5 °C/s to a final heat treatment temperature of 700 °C. In frame 3B, the left particle has ignited and its entire surface is glowing. Ignition of the other particle starts from a "hot-spot" localized in the leftmost part of the particle (frame 3B) and propagates over the entire particle surface (frames 3C and 3D). The glowing zone, however, never exceeds the particle boundary. By frame 2D (obtained 1.9 s after frame 3A), the ignition of the left particle appears quenched. But, large holes (seen as dark spots) appear on the surface of the right particle indicating the opening to the exterior of large internal cavities (macropores) that have formed during pyrolysis (Zygourakis, 1993).

Detection of Char Particle Ignitions

As stated previously, our approach to ignition detection involves the combination of thermogravimetric measurements and video microscopy. To discuss the effectiveness of this approach for ignition detection, we will consider first two different types of heterogeneous char particle ignitions.

Ignitions characterized by high particle temperatures are accompanied by bright emissions of light. When this occurs, the ignition is easily observed on video tape regardless of the intensity of the light source which illuminates the reacting char sample. We will refer to such ignitions as **type I** ignitions. When, on the other hand, the particle temperature is not significantly elevated during a heterogeneous

ignition, the intensity of light emission from the particle is low. Such ignitions may be difficult to detect with video microscopy, particularly when the external illumination of the sample is on. Ignitions associated with faint light emissions will be referred to as **type II** ignitions.

With type I ignitions, video microscopy is always effective in detecting the ignition of individual particles. We have also found that ignitions are accompanied by peaks in the reactivity curve caused by the sharp rise and drop of solid temperature as the particles ignite, react and are extinguished. Figure 4a shows the reactivity plot obtained for a type I ignition when only one of the particles in the char sample ignites. This peak in reactivity corresponds to ignition of one 1 of the 5 particles present in the reactor as shown by the accompanying light intensity trace (Figure 4b).

When multiple particles ignite, however, we may not be able to distinguish the different ignition phenomena using only reactivity data. Figure 5a presents the reactivity plot for an experiment for which video microscopy shows that 4 out of the 5 char particles in the sample ignited. Despite the fact that 4 ignitions occurred, only 3 peaks are observed in reactivity. The light intensity trace of Figure 5b shows that the third peak is a result of 2 separate particle ignitions. When ignitions are separated by short time intervals, the associated reactivity peaks overlap and video microscopy becomes the only means of determining which particles ignited and when these ignitions took place.

The video microscopy method has its limitations, however, and may not be sufficient to detect all particle ignitions of type II that are associated with faint light emissions. Typical ignition experiments are carried out with the external illumination source turned off to enhance the sensitivity of our video microscopy system for detecting ignitions. Even in the absence of external illumination, however, some type II ignitions may not be visible. In such cases, spikes in reactivity patterns obtained through weight measurements can help us detect ignitions.

To illustrate the sensitivity of the weight measurements, Figure 6 presents the reactivity patterns from 2 experiments conducted at a combustion temperature of 550 °C and without external illumination. No ignitions were observed during the first experiment. During the second experiment, however, one of the 11 particles present in the sample exhibited a type II ignition that was barely visible on video tape and would have undoubtedly been invisible if the external illumination were turned on. The image analysis procedure used to obtain an intensity trace for this particle was not able to distinguish the light emission from the image background. However, Figure 6 shows a sharp peak in reactivity that clearly distinguishes this reactivity pattern for the pattern obtained from the non-ignited sample. Reactivity data are thus necessary to effectively detect particle ignitions of type II. While isolated type II ignitions can be detected using reactivity data, the detection of multiple type II ignitions is much more difficult. This is because reactivity patterns alone may not allow us to tell how many and which particles have ignited, if the ignitions are separated by short time intervals.

Figure 7 presents another possible problem with ignition detection. The light intensity trace given in Figure 7b represents the maximum observed light intensity for the entire sample pan. Comparison with the reactivity plot shows that the first

spike in reactivity is the result of one particle ignition. The second peak in reactivity, however, is more difficult to explain. This peak may be due to one or several type II ignitions, however because ignitions were not detected their existence can only be proposed. In fact, this peak may be a result of the opening of the internal pore structure of the particle through heterogeneous reaction (Sundback, et al., 1984). The pore structure of devolatilized coal is characterized by a bimodal size distribution with small micropores and large macropores (Zygourakis, 1993). As the reaction proceeds, the opening of previously inaccessible porosity can lead to a sharp increase in the surface area available to reactants and, thus, to a sudden jump in particle reactivity.

Finally, our setup enabled us to observe that some char particles ignited multiple times in the same combustion sequence. These secondary ignitions commonly occur at high oxygen concentrations. Secondary ignitions produce a separate reactivity peak provided that they are sufficiently separated from the primary ignitions. An example of the detection of secondary ignitions with our setup is presented in Figures 8a and 8b. In this experiment, 5 particles were placed in the reactor pan. The first peak in reactivity shown in Figure 8a, corresponds to the ignition of 4 of the 5 particles in the reactor within a span of about 3 seconds. Six seconds after the first group of ignitions, 3 of the previously ignited 4 particles ignited again and the new group of ignitions produced a second distinct peak. The light intensity traces of Figure 8b demonstrate the ability of video microscopy to distinguish between the primary and secondary ignitions. In this case, the secondary ignitions were delayed enough to produce a separate reactivity peak. In many cases, however, the secondary ignitions occur very soon after the primary ignitions and video microscopy is the only means of detection.

Up to this point, we have focused on the effectiveness of ignition detection at a combustion temperature of 550 °C. When the combustion temperature is raised, ignitions become more frequent and overlapping of individual ignitions is more likely. Figure 9a presents a typical reactivity curve for a combustion run conducted at 750 °C. The accompanying light intensity trace (figure 9b) shows that all 5 particles in the sample ignited. The shape of the reactivity curves is much smoother than those at 550 °C, it does not exhibit the same sharp ignition peaks. When reactivity is plotted versus conversion as in figure 3.9, the curves at 750 °C bear more of a resemblance to those obtained at 450 °C, a temperature at which ignitions do not occur.

The reason the reactivity curves at 750 °C look more similar to 450 °C curves than 550 °C is not because particle ignitions do not occur. Particle ignitions are, in fact, much more common at 750 °C. When multiple particles in the sample ignite however, individual ignition peaks blend together, as discussed earlier.

Because of this behavior, ignition detection at higher combustion temperatures will rely more heavily on observation of ignitions with video microscopy than on reactivity data. Furthermore, the detection of faint particle ignitions (type II) will be much more difficult since reactivity data is not as available to complement video microscopy.

Detection of Coal Particle Ignitions

Many of the issues we discussed above also apply to the detection of coal particle ignitions. Studies on the combustion of coal particles, however, have revealed that at heating rates equal to or above 10 °C/sec the devolatilization rates are large enough to produce peaks in R_o quite similar to ignition peaks. Figure 10 shows the reactivities measured for a series of coal combustion experiments conducted at heating rates between 0.1 and 20 °C/sec. The two highest heating rates each reveal two reactivity peaks, one at a low conversion and another at a higher conversion. Without the aid of video microscopy, this might be interpreted as two distinct ignitions. However, comparison of the reactivity plots versus time and the video tapes clearly shows that the first reactivity peaks which are observed at lower conversions correspond to the devolatilization of the coal particle. Devolatilization is visible due to the plastic behavior of the Illinois #6 coal. High heating rates result in increased devolatilization rates and produced the primary peaks observed in Figure 9. Similar peaks are observed when pyrolyzing coal particles in pure N₂ (see Figure 11).

Video tapes from these coal combustion experiments revealed that the second peaks observed for 10 and 20 °C/sec heating rates (see Figure 10) were overlapping peaks from multiple particle ignitions. Again, video microscopy is necessary in this case to provide information about individual particle ignitions. No ignitions were observed at a heating rate of 0.1 °C/sec. This is confirmed by the flat reactivity curve.

The video tape for the 1 °C/sec experiment revealed that several very faint ignitions occurred on one of the four particles. The faint emission of light by these ignitions is in agreement with the relatively low reactivity of this sample. Since these experiments were conducted without external illumination, it was possible to detect the faint ignitions. If image analysis had not detected any ignitions for this experiment, reactivity data could still provide evidence of the occurrence of ignitions, though not enough to determine that the same particle ignited more than once.

The devolatilization peaks of Figures 10 and 11 occur regardless of whether the particles ignite or not, provided that the heating rate is 10 °C/sec or higher. We should note, however, that the temperatures at which these first peaks occur (about 600 °C for 10 and 20 °C/sec heating rates when combusted at 700 °C) do suggest that heterogeneous reactions may contribute to the weight loss associated with this peak.

CONCLUSIONS

The TGA/VMI reactor allows us to observe and record the structural transformations of individual coal and char particles during pyrolysis and combustion. Post-processing of the video tapes enabled us to characterize important ignition phenomena including the mechanism of particle ignitions. Devolatilized

char particles were observed to ignite heterogeneously, while coal particles ignited heterogeneously, homogeneously, or through a combination of both mechanisms.

The combination of video microscopy, digital image analysis and thermogravimetry is a very efficient method to detect ignitions under a wide variety of conditions that may lead to light emissions ranging from very bright to faint. While allowing us to study the interactions among the many particles of a coal or char sample, the technique presented in this study provides time-resolved light intensity traces that can be compared to the sample reactivity pattern.

Combining the video tape analysis with simultaneous weight loss data provides comprehensive ignition detection. The TGA/VMI reactor provides detailed information on individual particle ignitions while still allowing particle interactions, thus combining the qualities of single and multiple particle experiments.

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Figure 1 (198) Frame from a digitized experiment showing 4 regions of interest (ROI) which are centered around char particles and are being monitored to determine maximum light intensity.

Figure 2 (48)Sequence of digital images from a coal combustion experiment. For this run, 28-32 mesh Illinois #6 particles were heated at 5 °C/sec to a final combustion temperature of 750 °C. The oxygen concentration was 50%. Elapsed time in seconds of respective frames A-F: 0.0, 0.1, 0.2, 0.3, 0.4, 0.5.

Figure 3 (54) Sequence of digital images from a char combustion experiment. The chars were prepared from 28-32 mesh Illinois #6 particles heated under pure nitrogen at 5 °C/sec to a HTT of 700 °C. Combustion was carried out at an ambient temperature of 700 °C under flowing gas containing 50% O₂. Elapsed time in seconds of respective frames A-F: 0.0, 1.0, 1.1, 1.9, 2.2, 2.5.

Figure 4 (236) Reactivity pattern [A] and accompanying light intensity trace [B] obtained for a char combustion run during which 1 out of the 5 char particles ignited. Conditions: 28-32 mesh Illinois #6, pyrolysis heating rate: 10 °C/sec, HTT: 700 °C, combustion Temp.: 550 °C, 33% O₂.

Figure 5 (230) Reactivity pattern [A] and accompanying light intensity trace [B] obtained for a char combustion run during which 4 out of the 5 char particles ignited. Conditions: 28-32 mesh Illinois #6 particles, pyrolysis heating rate: 1.0 °C/sec, HTT: 700 °C, combustion Temp.: 550 °C, 33% O₂.

Figure 6 (69,115) Reactivity patterns for 2 char combustion runs. During one, a faint ignition was observed for 1 out of the 11 particles in the sample. Conditions for both: 50-60 mesh Illinois #6 particles, pyrolysis heating rate: 10 °C/sec, HTT: 700 °C, combustion temp.: 550 °C, 21% O₂.

Figure 7 (97)Reactivity pattern [A] and accompanying light intensity trace [B] showing secondary peak which may not be due to ignition. Conditions: 28-32 mesh Illinois #6 particles, pyrolysis heating rate: 10 °C/sec, HTT: 625 °C, combustion temp.: 550 °C, 33% O₂.

Figure 8 (197) Reactivity pattern [A] and accompanying light intensity trace [B] showing primary and secondary peaks, illustrating the detection of secondary ignitions. Conditions: 28-32 mesh Illinois #6 particles, pyrolysis heating rate: 10 °C/sec, HTT: 700 °C, combustion temp.: 700 °C, 50% O₂.

Figure 9 (293) Reactivity pattern [A] and accompanying light intensity trace [B] for char combustion run in which all five sample particles ignite. Conditions: 28-32 mesh Illinois #6 particles, pyrolysis heating rate: 500 °C/sec, HTT: 700 °C, combustion temp.: 750 °C, 33% O₂.

Figure 10 Series of coal combustion experiments showing the presence of a devolatilization peak as well as a blended ignition peak for higher heating rates. Conditions: 28-32 mesh Illinois #6 particles, combustion temp.: 700 °C, 21% O₂.

Figure 11 Series of coal pyrolysis experiments illustrating the peak in devolatilization rate occurring in pure N₂. Conditions: 28-32 mesh Illinois #6 particles, HTT: 700 °C.