Spontaneous Combustion of Paint Loaded Filters

January 14, 2002

Prepared for:
Iowa Waste Reduction Center
University of Northern Iowa
1005 Technology Parkway
Cedar Falls, Iowa 50613-6951

Prepared by:

Grunde Jomaas
Staff Engineer

Douglas Carpenter, MScFPE
Principal Engineer

Reviewed by:

Richard Roby, P.E., Ph.D.
Technical Director

Christopher Schemel
Senior Engineer

EXECUTIVE SUMMARY

Combustion Science & Engineering, Inc. (CSE) performed an analysis of the self-initiated thermal decomposition phenomenon of paint-loaded filters that has occurred on several occasions as reported by the Iowa Waste Reduction Center. By conducting a series of self-heating tests on samples of filters loaded with paint, CSE has shown that in selected circumstances the exothermic decomposition of the paint-loaded filters could lead to thermal runaway and eventually ignition of the filters. These circumstances are related to the temperature, size, and composition of materials surrounding the filters.

The exothermic decomposition of the paint releases energy. If the energy generated within the pile is greater than the energy lost from the pile, the internal temperature will increase. The non-linear nature of the chemical reactions promotes an exponential rise in the temperature, eventually reaching the ignition temperature of the paint and/or filters. At a certain critical pile size the configuration does not allow effective dissipation of the energy produced by the reaction for a given temperature. CSE's test data were used to determine the Frank-Kamenetskii parameter for self-heating and the results indicate that the packing density is the single most critical factor. Furthermore, filters loaded with paint with a higher VOC content are more prone to self-heat than filters with a lower VOC content.

To correct the self-heating problem, the geometry of the storage of the filters must be changed to allow for less temperature build-up and better heat dissipation. This can be effectively accomplished by reducing the volume of the storage containers and by reducing the packing density (number of filters per volume unit). In addition, filters should never be mixed with ordinary trash, as trash surrounding the filters will cause the same insulating effect as tightly packed filters.

INTRODUCTION

Industrial painting operations have been identified as a significant source of emissions of hydrocarbons to the atmosphere. The Clean Air Act has increased emphasis on the reduction of emissions of hydrocarbons. Hydrocarbons that generally end up in the atmosphere are called volatile organic compounds (VOCs). The 1990 Amendments to the Clean Air Act specifically target emissions of more than 100 different VOCs. The development of energy efficient and cost-effective strategies for controlling emissions of volatile organic compounds (VOCs) and hazardous air pollutants (HAPS) from painting processes are key objectives of the U.S. Environmental Protection Agency (EPA). One method of reducing emissions from industrial painting operations is through paint reformulation where the percent content of VOCs in the paint is reduced. This is accomplished by replacing the more volatile organic solvents in the paint with less volatile organic compounds.

The Iowa Waste Reduction Center (IWRC) has seen an increase in reported spontaneous combustion incidents involving paint booth waste (i.e. filters and floor sweepings). Combustion Science & Engineering, Inc. (CSE) was contracted by IWRC to perform an analysis of this phenomenon to determine what parameters associated with paint booth operations have a potential effect on spontaneous combustion. The term spontaneous combustion (or self-ignition) describes the culmination of a runaway temperature rise in a body of combustible material. All organic materials, like many of the components in paint, when exposed to the atmosphere, undergo an oxidation reaction that is exothermic (releases energy). The rate at which the oxidation process releases energy can range from insignificantly slow to very fast. A self-heating condition within a body arises when the heat generation by an exothermic process exceeds the rate which heat is lost to the surroundings. If the conditions are correct, the pile temperature can eventually reach the ignition temperature of the material.

This report details the complete analysis conducted by CSE of this spontaneous combustion problem. The change in paint formulation is one of many parameters associated with paint booth operations that have a potential to effect discarded paint filters with respect to self-heating. To determine other relevant parameters, CSE performed an analysis of a survey conducted by the IWRC of paint booth operators that detailed facility operational conditions and fire history. Parameters identified in this initial analysis were used to design a series of experiments that determined the effect of the identified parameters on the self-heating phenomenon. The experimental design was consistent with both the survey analysis and a theoretical model of the self-heating process (due originally to Frank-Kamenetskii, (1969)). This approach allowed CSE to determine the parameters effecting the phenomenon and make recommendations to reduce the potential in the future.

SURVEY ANALYSIS and EXPERIMENTAL DESIGN

Many variables may influence the occurrence of spontaneous combustion for a given system; the collection of data and analysis can become difficult. The physical and chemical variables that may influence spontaneous ignition for a given system include: paint formulation, filter material, filter usage, amount of paint used per day, filter loading, filter change interval, filter conditions, painting practices, and paint booth waste storage practices. There are a wide variety of paint formulations and paint booth filter materials. The number of parameters in this process precluded an experimental study varying all the potential variables. In addition, many of the process parameters could be highly correlated with other process variables or influenced by factors outside of the control of a laboratory setting. Therefore, the set of variables had to be reduced to a practical (defined in terms of both cost and time) number that allowed a reasonable number of tests to be performed while extracting the greatest possible amount of information.

The best approach for analyzing complex systems where some parameters may be either difficult to control or highly correlated with other variables is to design an experiment allowing a multivariate analysis using level effects of controllable parameters. A well-designed experiment based on a preliminary analysis of existing data provided by the Iowa Waste Reduction Center and process experience was formulated to reduce the required number of experimental runs needed to obtain useful information. The overall approach was to develop a model for a given system that will predict the conditions under which spontaneous ignition can occur based on experimentally derived parameters and the theory developed by Frank-Kamenetskii.

Figure 1 shows the distribution of filter materials for those facilities that have not experienced fires (labeled “no”) and for those facilities that have experienced fires (labeled “yes”) based on the results of the survey. The predominate type of filter material used in facilities that did not experience any fires were fiberglass and paper. The predominate type of filter material used in those facilities that did experience fires was paper followed by fiberglass. The paper filter represents an absorbent filter medium and the fiberglass filter represents a non-absorbent filter medium. The absorbency of the filter material may have a significant effect on the material loading conditions. This factor may have an effect on the ability of the material to self-heat to spontaneous combustion. The experimental design included both fiberglass and paper filter materials, since the survey results indicated that paper and fiberglass are the most common filter materials.

Figure 2 shows the distribution of the percent volume of VOC for those facilities that have not experienced fires and for those facilities that have experienced fires. For those facilities that have not experienced fires, the percent VOC by volume of the paint shows a largely uniform distribution between 0 to 80 percent VOC with an increase in the 40 to 50 % VOC range. The distribution of percent volume of VOC for those facilities that experienced fires were more discrete with the peaks occurring around the 10% and 70% range. There does not seem to be any EPA classification that would define the percent VOC by volume in the paint in terms of “low”, “medium”, or “high”. For the work presented here, two representative ("high VOC" and a "low VOC") paints were tested.

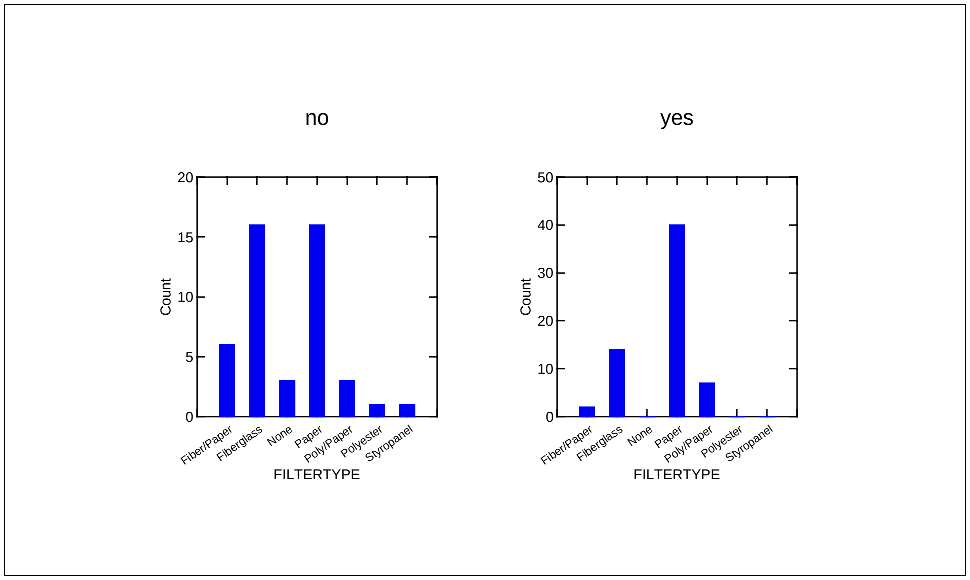

Figure 1 – Distribution of the type of filter material used for those facilities that did not experience fires (labeled "no") and for those facilities that did experience fires (labeled "yes").

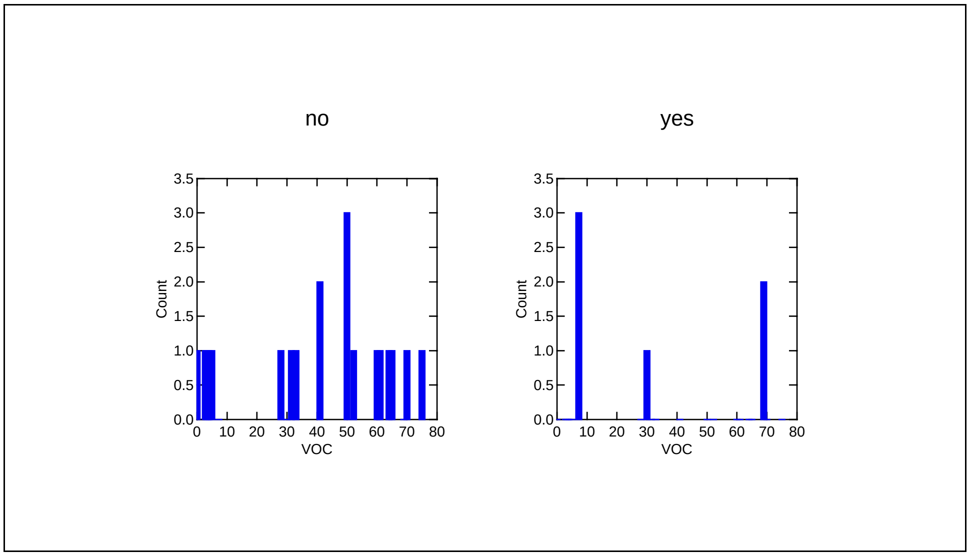

Figure 2 - Distribution of the % volume of VOC in paint for those facilities that did not experience fires (labeled "no") and for those facilities that did experience fires (labeled "yes").

Figure 3 shows the distribution of the percent volume of VOC by weight for those facilities that have not experienced fires and for those facilities that have experienced fires. A VOC content by weight in the 40 to 50 % VOC range seems to be most critical.

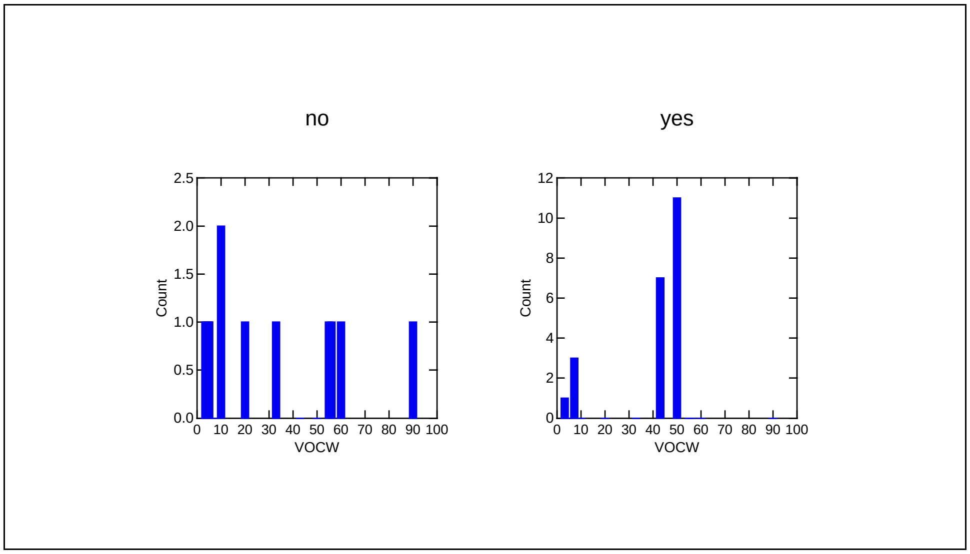

Figure 3 - Distribution of the % VOC by weight in paint for those facilities that did not experience fires (labeled "no") and for those facilities that did experience fires (labeled "yes").

Figure 4 shows the distribution of gallons of paint used per day for those facilities that did not experience fires and for those facilities that did experience fires. The distributions show that fires more often are occurring for those facilities with significantly higher paint usage per day than for the facilities that did not experience any fires. Based on the limited data, this suggests that the mass loading of the filters may be an important variable in terms of self-heating. However, the high mass loading will also increase the number of filters disposed, and this high number of filters (i.e. increased pile size) may be the cause of the fires.

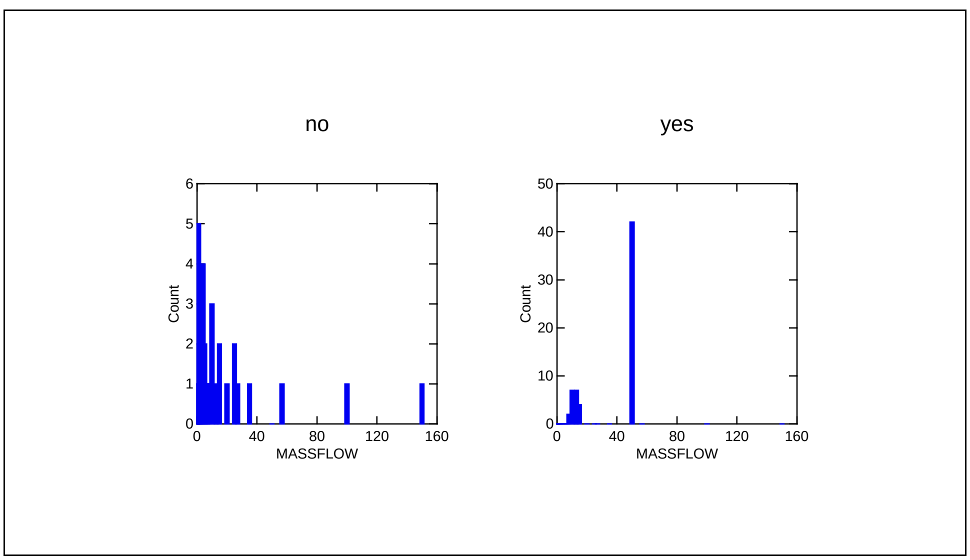

Figure 4 - Distribution of the gallons of paint used per day for those facilities that did not experience fires (labeled "no") and for those facilities that did experience fires (labeled "yes").

Figure 5 shows the distribution of the interval between filter changes. The distributions show that the change interval for those facilities that experienced fires was generally much shorter than the change intervals for those facilities that did not experience fires. Therefore, even with higher mass loading and shorter change intervals those facilities are still experiencing fires. This result suggests that the changing interval of the filters may not be frequent enough to prevent spontaneous combustion. Again, the result may also suggest that the sheer number of filters to be disposed of is the problem.

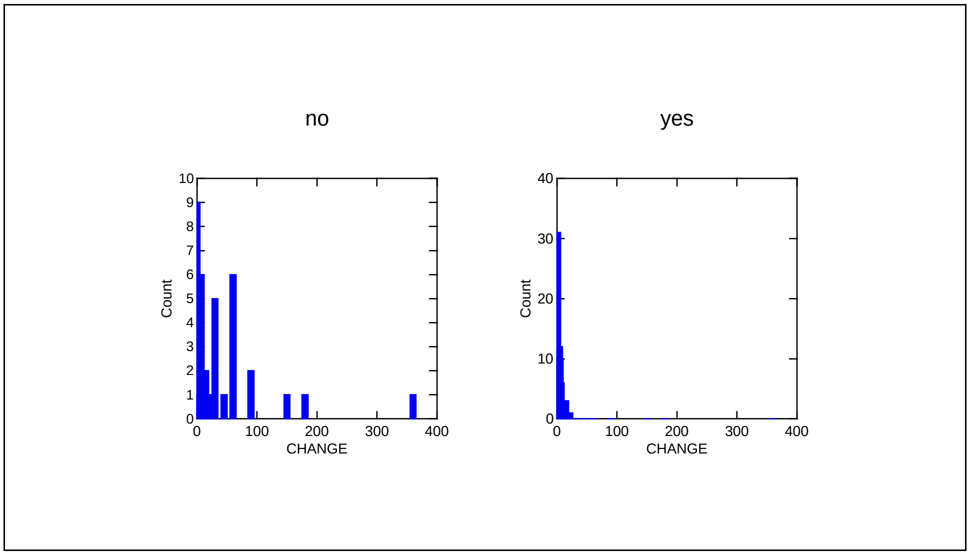

Figure 5 - Distribution of the interval between filter changes in hours for those facilities that did not experience fires (labeled "no") and for those facilities that did experience fires (labeled "yes").

Figure 6 shows the distribution of the condition of the filters (wet or dry) for those facilities that did not experience fires and for those facilities that did experience fires. The distributions show that the condition of the filter is not likely to be a significant variable in terms of whether the self-heating leads to spontaneous combustion. Therefore, the experiments were performed with dry filters, since this was the most common condition reported.

Due to the potentially large set of variables that might have an influence on self-heating of paint-loaded filters, an analysis was performed to arrive at a reduced set of variables for the experiments. A preliminary examination of the limited survey data along with an engineering analysis of the paint booth process provided a reasonable technical basis for the reduced number of variables that will be investigated further. Based on the analysis of the survey results, CSE proposed that the testing should include two (2) types of filter material (paper and fiberglass), two (2) types of paints ("high VOC" and "low VOC"), two (2) mass loading levels ("high" and "low" loading), and three (3) pile or cube sizes.

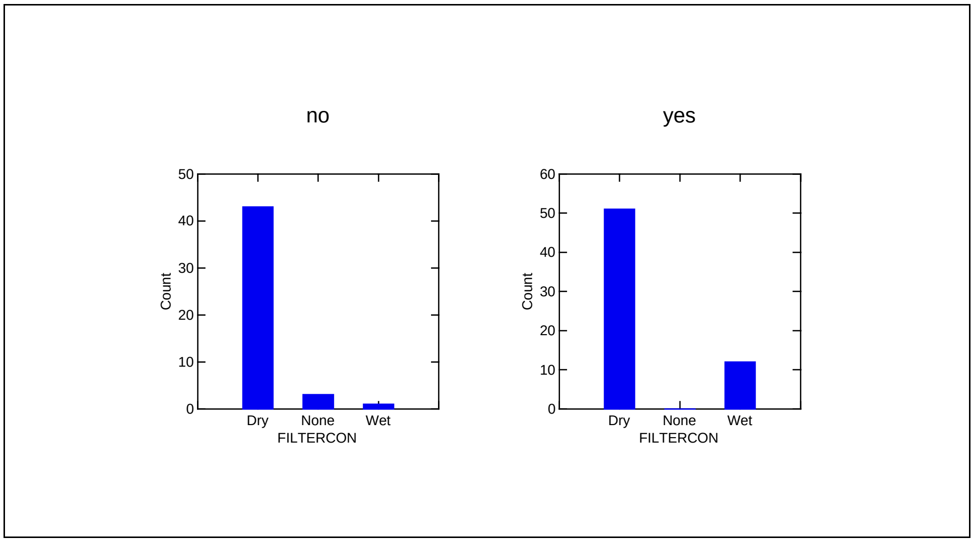

Figure 6 - Distribution of the condition of the filter (wet or dry) for those facilities that did not experience fires (labeled "no") and for those facilities that did experience fires (labeled "yes").

THEORY

Spontaneous combustion is a special case of combustion, as no external ignition source is needed to cause a fire. The paint-loaded filters satisfy all the criteria needed to undergo spontaneous combustion:

- The paint reacts exothermically with oxygen from air.
- The temperature elevation increases the reaction rate, exhibiting an exponential temperature-time relationship.
- The filters have low conductivity (good insulators). As a result, the exothermic reaction is most inclined to occur in the core (the heat losses has to be less than the heat generated by the exothermic reaction).
- The filters are porous and form a rigid char as a result of the reaction.

A model presented by Frank-Kamenetskii (Beever, 1995) is commonly used to analyze self-heating processes and to predict critical temperatures for various pile sizes.

Frank-Kamenetskii Model

The self-heating potential of a pile of material is dependant on the balance between the rate of energy-generation within the pile and the rate at which heat is lost to the surroundings. The Frank-Kamenetskii theoretical model uses a dimensionless group of terms know as the Frank-Kamenetskii parameter, δ, to characterize this balance. This parameter is fixed by the relevant physical and chemical properties of the material together with the pile size and ambient temperature. For a given material and geometry (i.e. cube, cylinder, etc.), a value of the Frank-Kamenetskii parameter, δ, can be determined from a series of experiments. Once δ is determined, the critical value, δ_c, provided in literature, can be compared with the value that is calculated based upon the experimental results. If the calculated value of δ exceeds δ_c, the pile is expected to self-heat to spontaneous combustion for any ambient temperature or pile size greater than those used to calculate δ.

An advantage of this method of testing and critical parameter estimation is that a relatively small number of samples or pile sizes need to be tested. In effect, relatively small cubes can be used to obtain information that can in turn be used to estimate critical parameters for larger geometries made from the same material (that for practical reasons such as size, hazard, and cost are unsuitable for testing).

When using experimental data to evaluate Frank-Kamenetskii parameters, sample size and ambient temperature are varied to find the critical conditions for self-heating of a given material. The critical temperature, T_R, is found by an iterative testing procedure.

The Frank-Kamenetskii parameter is defined as:

$$\delta = \frac{E}{R}\frac{\rho Q}{\lambda}\frac{r^2}{T_R^2}A\exp\left(\frac{-E}{RT_R}\right)$$

Rearranging this, we get:

$$\ln\left(\frac{\delta T_R^2}{r^2}\right) = P - \frac{E}{RT_R}$$

Where:

$$P = \ln\left(\frac{E}{R}\rho\frac{QA}{\lambda}\right)$$

E is the apparent activation energy for the exothermic reaction, and *r* is a measure of the pile size. *P* is the logarithm of a number of material properties that do not have to be determined individually for the analysis performed in this report.

A plot of $\ln\left(\frac{\delta T_R^2}{r^2}\right)$ vs. $\frac{1}{T_R}$ provides a straight line with intercept P and slope $\frac{-E}{R}$, which can be used to solve for the Frank-Kamenetskii parameter, δ. This parameter can then be compared to the critical value of the Frank-Kamenetskii parameter, δ_c to determine if self-heating that results in thermal runaway can occur. This data and model can then be used to obtain critical pile sizes at different ambient temperatures using the appropriate values of δ_c.

EXPERIMENTAL PROCEDURE

CSE conducted self-heating tests consistent with obtaining data for use in the Frank-Kamenetskii mathematical model for predicting the conditions for spontaneous combustion. The goals of these tests were two-fold. First, CSE wanted to recreate the failure with respect to thermal degradation experienced by the paint filters. The second goal was to determine what parameters were responsible for this failure. The tests necessary to achieve these goals are described below.

The parameters used in the testing were:

- Either fiberglass or paper filters were used.
- VOC was varied in two levels, high and low.
- Loading levels were varied by the amount of paint sprayed, full and half load.

A small paint booth with an exhaust fan, necessary to draw the paint through the filter, was used for loading the filters. Both types of filters were installed in a similar manner. The filter (two filters for paper) was secured to a metal mesh using a small wire grid. This metal mesh on the backside of the filter made it easier to position the filter in the paint booth. The paint gun was placed approximately three feet upstream of the filter in the center of the cross section. Rotation of the gun made it possible to maintain a reasonably even spray over the surface of the filter. Since this process was manually controlled, filters were initially cut into sections and weighed to check that the load was uniform across an individual filter. In addition, whole filters were also weighted regularly after being loaded with paint. In both cases, small differences were found and deemed to be insignificant in the context of this work.

CSE purchased low VOC paint from Diamond Vogel Paints. The manufacturer of the paint measured the VOC-content of the low VOC paint to be 3.9 lb/Gal. The high VOC paint, identified by the Iowa Waste Reduction Center as representative of the paint used by those facilities experiencing fires, could not be obtained. As a result, CSE created the high VOC paint through the appropriate addition of Xylene to the low VOC paint, based on information contained in the specific MSDS sheets for the high and low VOC paints. This is consistent with the practices of both the paint manufacturer and the end-users. The paint manufacturer stated that the difference in the paints were primarily the VOC content. In addition, CSE engineers had been provided with information that the operators may be adding thinner to the low VOC paint to make it easier to work with and to obtain a better surface finish, which is consistent with the higher VOC paints. Therefore, creating high VOC paint in this manner seemed most appropriate**.**

Based on the information contained in the MSDS sheets, CSE engineers diluted the low VOC paint with Xylene (54% VOC by Volume) to obtain a higher VOC paint (68% VOC by Volume) consistent with the MSDS sheet. The paint and thinner were mixed in 2.5 liters batches, however, the volume varied slightly between batches.

CSE originally proposed using the manufacturer's recommended pressure drop for filter change as a measure for the paint loading process. To achieve similar loading to what actually occurs in an industrial setting, the filters were sprayed as opposed to being dipped in the paint. However, during the accelerated loading of the filters, it was found that the pressure drop for filter change out could not be achieved, even when the filters were loaded so heavily that no additional paint could be absorbed. In real life situations, these filters are replaced by visual inspection or based on some time increment. Therefore, based on the amount of paint used to maximize the pressure drop, the spraying of five (5) liters of paint mixture on the filters was deemed to be a fully loaded condition. The half loading condition was achieved by application of half of the paint used for the fully loaded condition.

The filters were allowed to cure for one day after being loaded with 2.5 liters of paint. Spray rates varied, however it took approximately 10 minutes per liter of paint mixture with Xylene (i.e. high VOC) and about 20 minutes per liter of undiluted paint (i.e. low VOC). Figure 7 is a schematic of the paint-loading apparatus. To maximize the efficiency of the loading of the filters, the apparatus was modified from the proposed design.

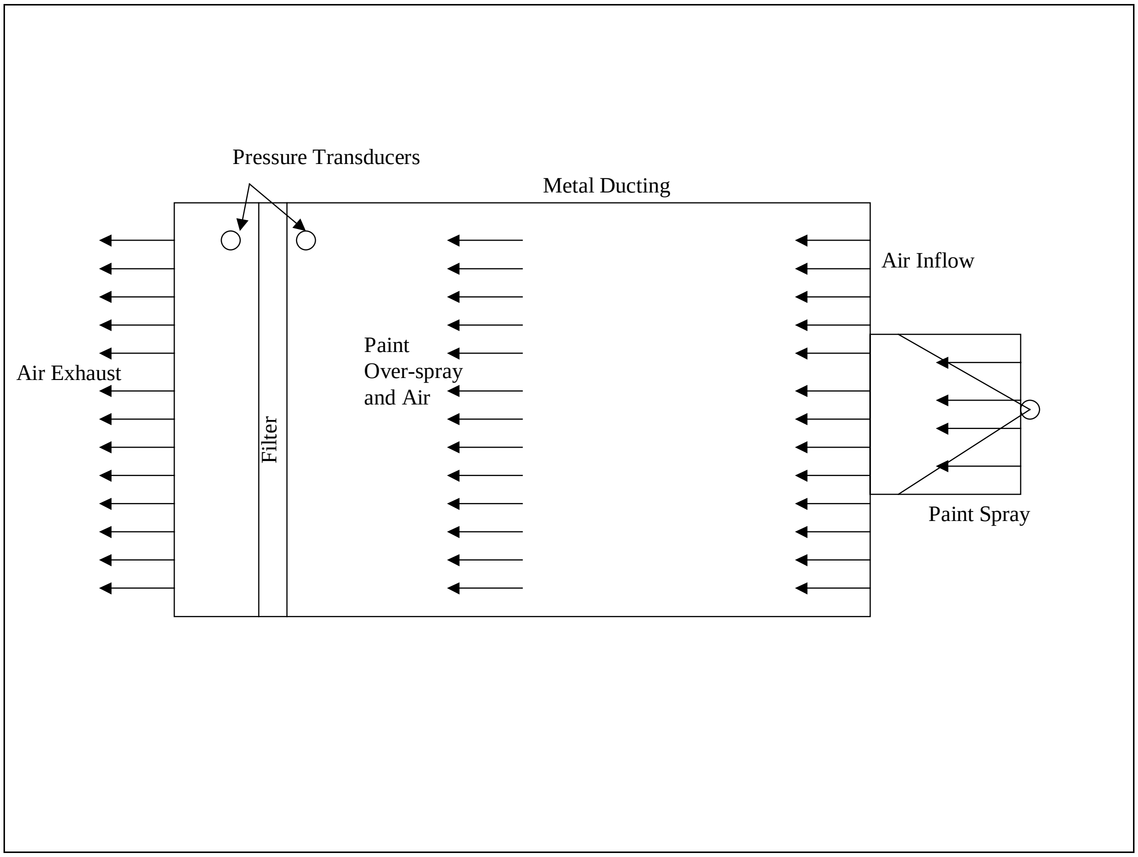

Figure 7 – General schematic of filter loading apparatus.

CSE originally proposed to do the testing in 2, 4, and 6-inch cube sizes, but the 2-inch cubes did not self-heat under safe operation of the convective oven. As a result, the paint-loaded filters were cut up and placed in 4, 5, and 6-inch cubes made out of wire mesh. The assembly was weighed and then mounted in the middle of the convective oven as shown in Figure 8. Thermocouples were located on six different parts of the sample (center, front, left, right, bottom, top), and one thermocouple recorded the ambient temperature in the oven.

Figure 8 - Photograph of sample in temperature-controlled oven.

The oven was quickly heated to the desired temperature, and a data acquisition program recorded the temperature, providing continuous updates of the temperature development at all thermocouple locations. During a test, the temperature of the loaded filters may continue to rise and can result in thermal runaway (spontaneous ignition) or the sample can stop heating up and reach a thermal equilibrium and/or cool back down to the ambient temperature (no ignition). If the ambient temperature condition resulted in spontaneous ignition, the oven temperature was reduced for the next test. If the ambient oven temperature did not result in spontaneous ignition, the oven temperature was increased for the next test. This iterative process was sustained until the critical temperature was determined within ± 2.5°C.

After each test, the samples were weighed to record mass loss; however, since the paint tended to drip, this data was inconsistent and, therefore, not used for calculations. In addition, pictures were taken to record discoloration, thermal decomposition, and for visualization in general.

TEST RESULTS

Although critical self-heating is the main concern, any form of thermal decomposition and/or self-heating is unwanted. Samples that were exposed to sub-critical oven temperatures still decomposed exothermically to some extent, as can be observed by comparing Figure 9 (before test) and Figure 10 (after test, sub-critical). A plot of the center temperature versus time for a sub-critical sample, shown in Figure 11, provides quantitative support for the significance of the sub-critical self-heating. Temperatures as high as 400°C were observed in sub-critical samples.

Figure 9 - Paint loaded filters in wire mesh before test.

Figure 10 - Paint loaded filter after test (sub-critical).

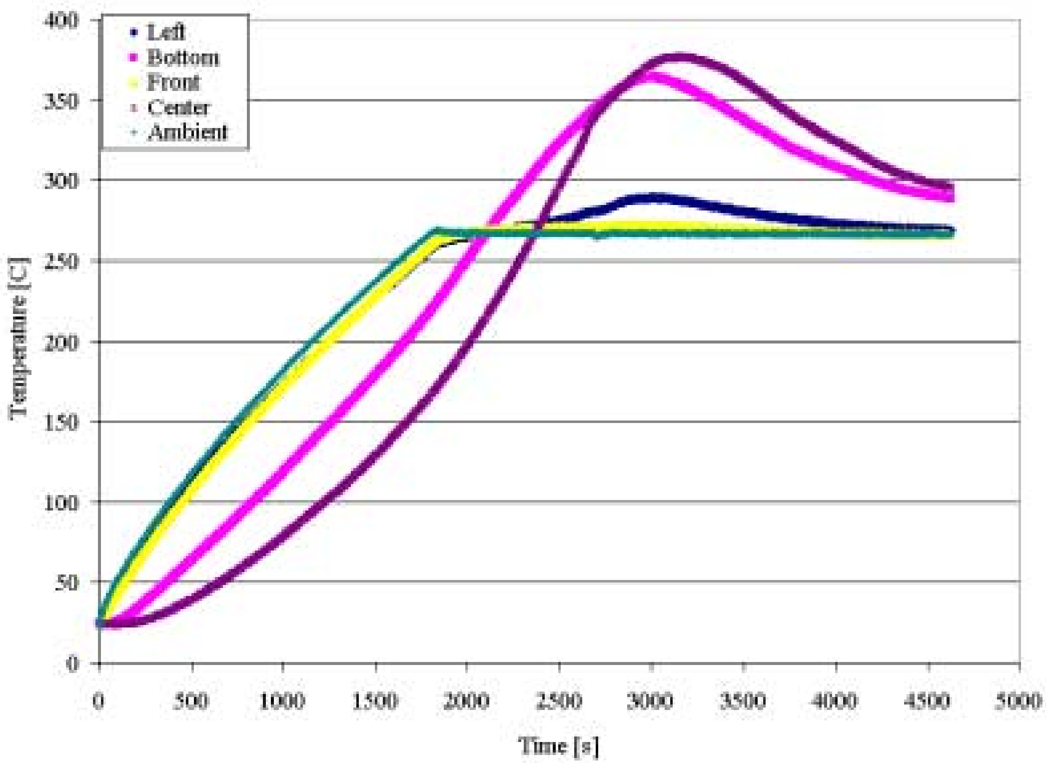

Figure 11 - Temperature versus time for sub-critical sample.

A number of samples, which were categorized as sub-critical, were exposed to increased air entrainment upon removal from the oven by physically moving the wire mesh cage with the test samples through the air, thus increasing the airflow through the sample. This increased air supply led to flaming ignition on several occasions. This was also observed with samples that experienced thermal runaway. Figure 12 shows a sample that experienced thermal runaway, but did not transition to flaming combustion while in the convective oven. However, when the airflow to the combustion zone was significantly increased, flaming combustion occurred, as seen in Figure 13. These observations suggest a strong oxygen-limited reaction is taking place.

Figure 12 - Sample that self-ignited.

Figure 13 - Increased air velocity to the center induced flaming ignition.

Figure 14 shows the temperature versus time plot from a test that was stopped because the temperature in the center had started to decline, indicating sub-critical reaction (although very close to a critical condition). As can be observed from the sudden temperature rise toward the end, the sample ignited when CSE engineers opened the door on the convective oven. The reason for this temperature increase was that the sample did not have access to enough air until the door was opened. Once the additional air was supplied, the temperature and the amount of fuel present was enough to cause ignition. Notice that all the other thermocouple readings decrease due to the cooling from the cold air entering the oven.

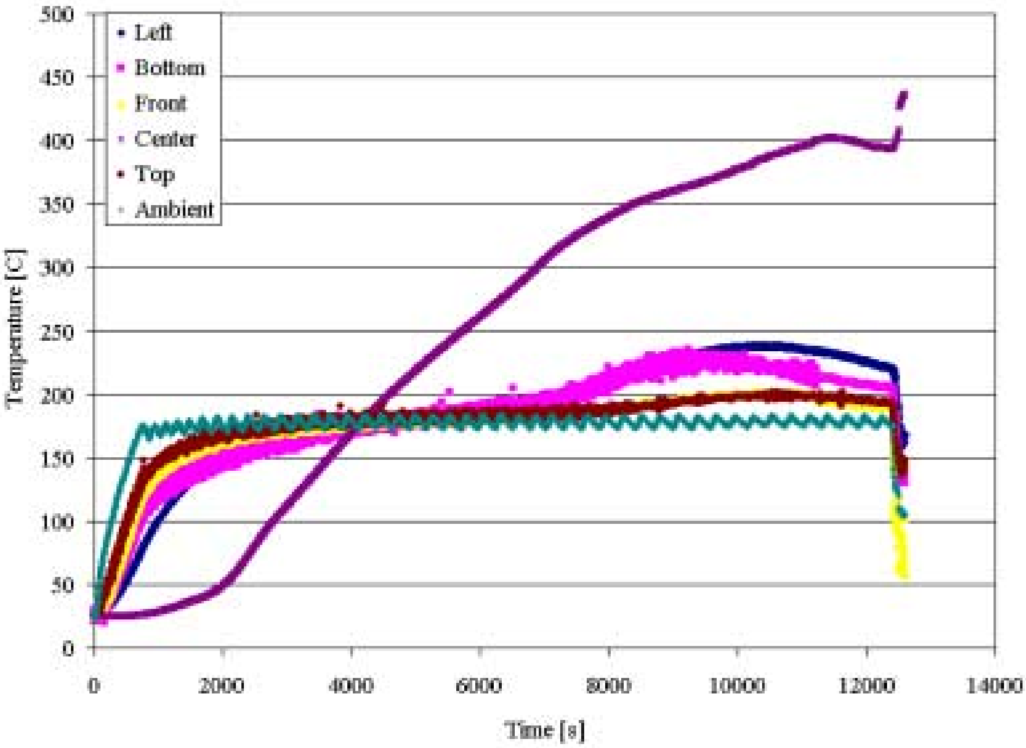

Figure 14 - Ignition of sub-critical sample with added air supply.

In addition to the oxygen-limited condition surrounding the pile of filters, there can be a reduction in the flow of air into the pile produced by the fiberglass filters themselves. Due to the compressibility of the fiberglass filters, the oxygen supply to the core and the packing density of the paint-loaded filters are related, since an increase in packing density decreases the porosity of the filters. Thus, packing density is an additional parameter that must be considered. The packing density is examined in the modeling section. The results of the testing of both the fiberglass and paper filters under different conditions are discussed in the following sections.

Fiberglass Filters

CSE engineers performed a large number of tests of paint loaded fiberglass filters to determine the effect of the parameters such as paint loading density and the VOC content in the paint.

Paint Loading Density

Table 1 shows that decreasing the loading density of the paint filters decreases the critical temperature for spontaneous ignition for all the pile sizes tested. This finding is consistent with the survey results presented in Figure 5 that shows that more fires are occurring in situations with shorter filter change-out intervals (i.e. less paint on filters).

Table 1 - Tabulation of Experimental Results.

Cube Size (Length of side) [in]	Critical Temperature [°C]			
	Fiberglass Filters*		Fiberglass Filters*	
	Full Load (High VOC**)	Half Load (High VOC**)	High VOC** Full Load	Low VOC Full Load
4	262	244	262	291
5	248	226	248	246***
6	233	212	233	248

*These numbers are from tests with 2 sheets per inch of length of the cube.
**High VOC paint was low VOC paint with thinner (Xylene) added to create the appropriate VOC content.
***Uncertainty about the packing density

One possible reason for the decrease in critical temperature with decreased loading density may be that the paint acts as a heat sink. In other words, the paint that is in excess of what is needed for exothermic decomposition will have to be heated enough to drip away or evaporate before the self-heating can become critical. Since the heat capacities of liquids commonly are high, a substantial amount of energy is needed to heat the excess paint. Furthermore, in filters with a full load of paint, the paint restricts the airflow, and the exothermic reaction may be slower due to the lack of oxygen. Finally, it is important to mention that this may be a phenomenon that is a function of the high temperature in the oven tests, and thus, may not be experienced at lower temperatures. The high temperature in the oven tests may result in pyrolization of the paint, which may create rich volatile conditions that could not occur at lower temperatures. The rich conditions may reduce the reaction rate through oxygen reduction within the pile

In the proposal, CSE suggested that the absorbency of the filters could be important for the self-heating problem, in the sense that filters of an absorbent material would self-heat more readily because such filters could contain more paint. Test results show that this is not the case, since filters with a half load of paint are more prone to critical self-heating than filters with a full load as will be discussed in the section on the effect of packing density.

The survey data did not show any significant difference between wet and dry filters, and the experiments performed by CSE engineers were consistent with this finding. Fresh filters and filters that had dried for more than two weeks provided similar results.

VOC Content of Paint

Table 1 also shows that increasing the VOC content of the paint decreases the critical temperature required for spontaneous ignition to occur for all the pile sizes tested. For example, the filters with the high VOC paint caused thermal runaway at an oven temperature 20°C lower than an ambient temperature that failed to cause thermal runaway for filters with low VOC. This is shown in Figure 15.

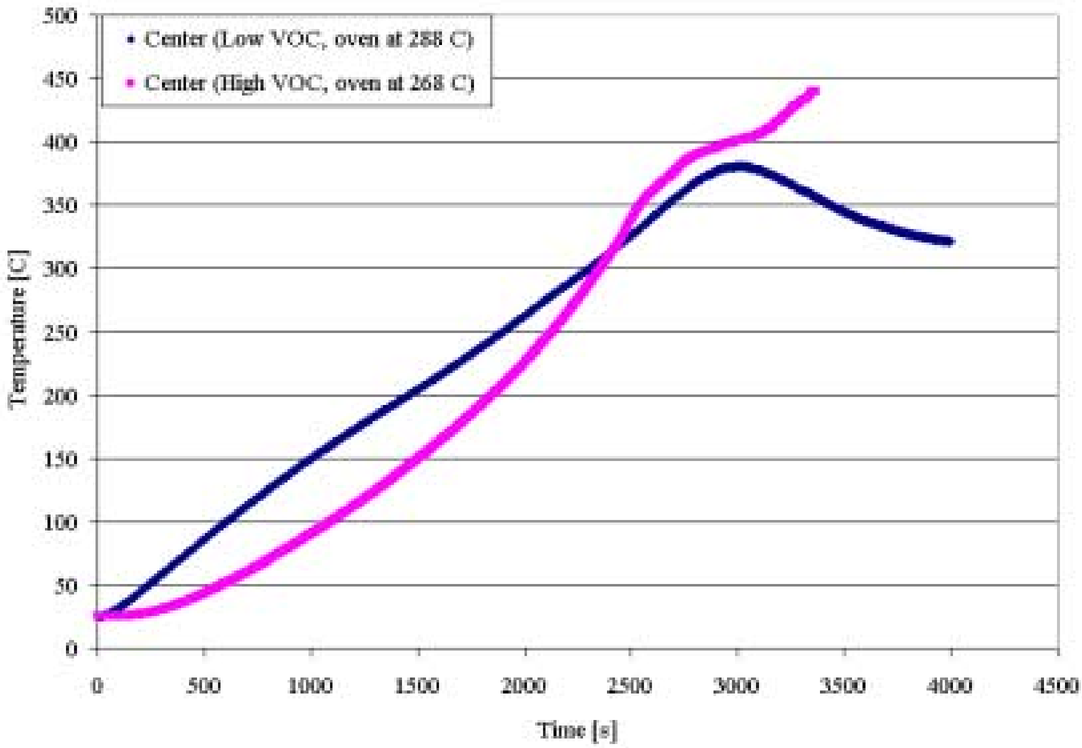

Figure 15 - Significance of VOC content in the paint applied to the filters (4 inch, full load).

Paper Filters

The paint-loaded paper filters were also found to undergo exothermic decomposition. However, it became problematic in determining the critical temperatures required for self-heating for this material. Figure 16 shows a plot of temperature versus time for a 6-inch cube filled with paper filters loaded with the low VOC paint. While the center temperature exceeded the oven temperature and is representative of typical data for self-heating materials, surface ignition of the paper filters was observed in some of the tests. Therefore, the contribution of the paper to the self-heating process should be examined.

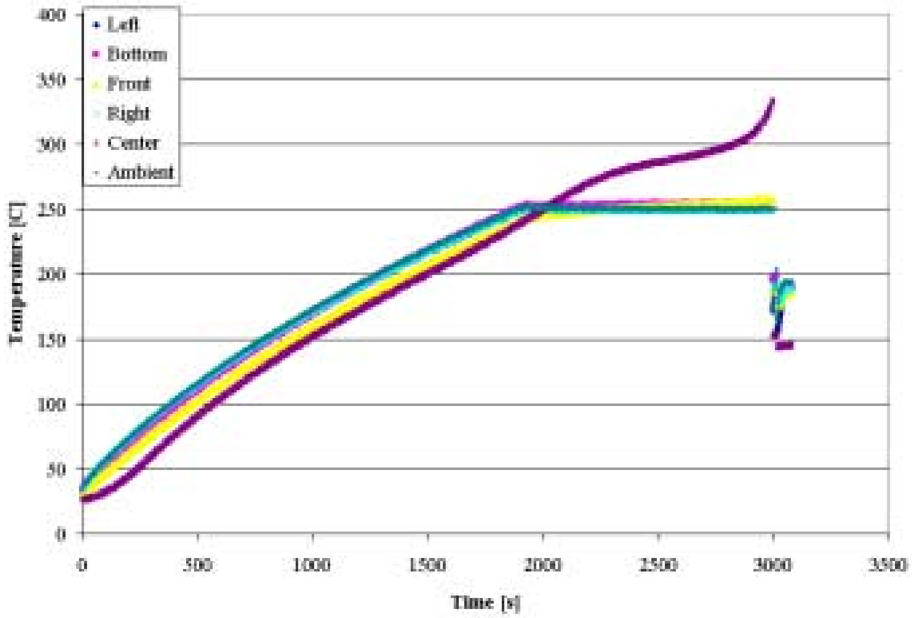

Figure 16 - Temperature versus time for 6-inch cube, paper filters with low VOC paint.

CSE engineers performed a test with paper filters without paint to test this hypothesis that the paper filters were self-heating. Figure 17 is a plot of temperature versus time for the test with paper filters only.

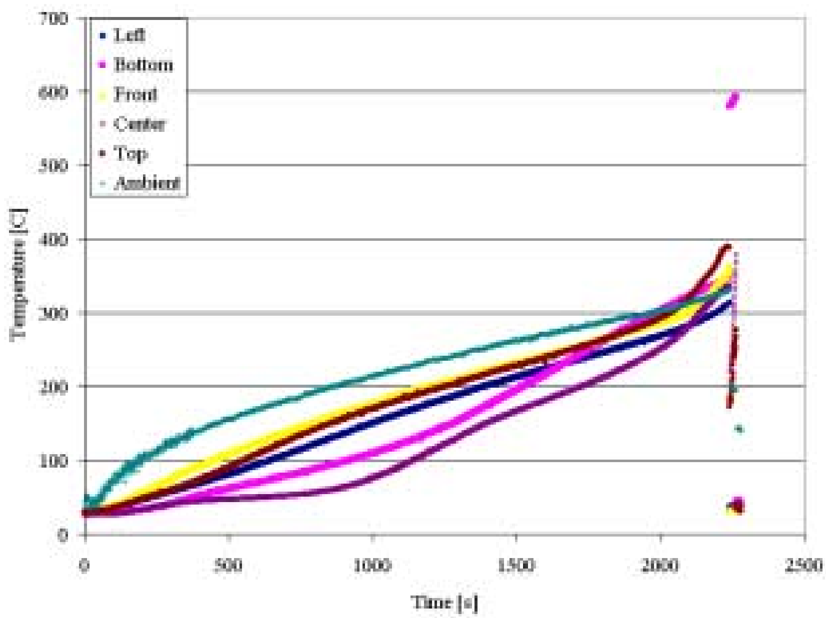

Figure 17 - Temperature versus time for 5-inch cube of paper filters without paint.

It can be seen that once the temperature reached a little more than 300°C, flaming ignition occurred. The discontinuity in the data for the bottom thermocouple at the very end of the plot indicates that flaming ignition occurred at this point, since the temperature increased several hundred degrees Celsius in just a few seconds. The other thermocouple readings decreased because the CO_2 suppression system, located at the top of the oven, activated.

The critical temperature at which flaming ignition was initiated corresponds to the critical temperature where the paint-loaded filter experienced thermal runaway, and confirms that the thermal runaway was not a direct consequence of the exothermic decomposition of the paint-loaded filters. Therefore, the paper filters ignited before it was possible to determine the critical temperatures for the oxidizing paint.

One solution would be to test much larger cube sizes which, according to self-heating theory, would lower the required ambient temperatures to achieve critical self-heating. However, this was outside the scope of this project and would require a much larger oven than is currently available to CSE.

RESULTS AND DISCUSSION

Based on the test data, a model was constructed to obtain critical pile sizes at different oven temperatures. The critical value for the Frank-Kamenetskii parameter for cube geometries has been shown to be $\delta_c = 2.52$ (Beever, 1995). For this analysis, the data from the fiberglass filters was used. The Frank-Kamenetskii parameter was calculated for a range of piles sizes and oven temperatures. The results are discussed in the following section.

Packing Density

An important variable in determining the self-heating properties of the fiberglass filters is the density of the filter material within the pile. Due to the compressibility of the fiberglass filters, the packing density of the filters in the wire mesh cage can be varied. The packing density has both an effect on the supply of air into the core of the pile as well as affecting the heat losses to the surroundings due to an increase in the insulation effect of the pile.

If the filters are packed tightly, the heat losses from the exothermic reaction in the core decrease. As a result, it would be expected that the critical temperature for thermal runaway for a given cube size would decrease with tighter packing of filters. However, tighter packing also decreases the air available for the exothermic process in the core, and may prevent the expected thermal runaway for the given configuration. At the other extreme, low packing density is expected to increase the heat losses, and increase the critical temperature. Still, the increased air entrainment, as discussed in the previous section, at such a configuration may induce a thermal runaway that results in flaming ignition.

CSE engineers performed additional experiments to quantify the effect of the packing density parameter. Figure 18 shows a plot of temperature versus time for two different packing densities. The configuration that was packed tighter experienced thermal runaway, whereas, the less compressed packing behaved sub-critically under otherwise similar conditions (oven temperature of 250°C, full load, high VOC). Figures 19 and 20 show how increased packing density decreases the critical size for a given temperature.

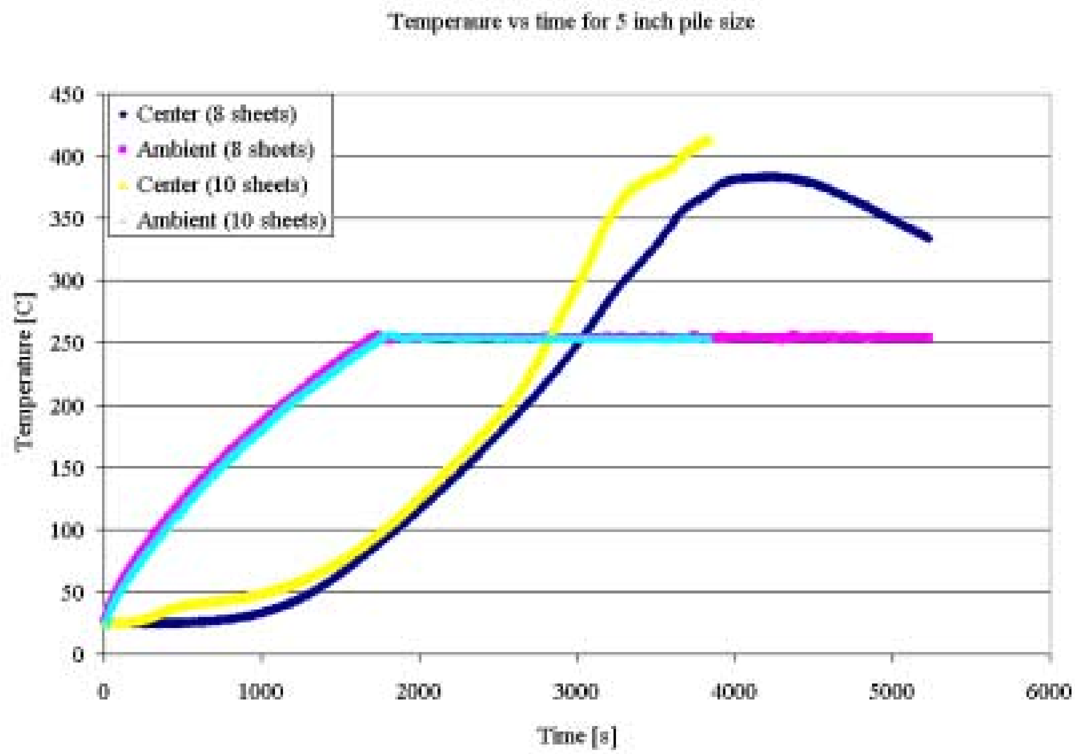

Figure 18 - Significance of packing density of filters (high VOC, full load).

Table 2 contains test data that supports the finding that the packing density is the single most critical factor of the self-heating problem. The change in loading conditions from full load to half load decreased the critical temperatures approximately 20°C for the cube sizes tested. By increasing the packing density, the critical temperatures decreased approximately 75°C for the cube sizes tested. This clearly indicates that the packing density is a more significant variable than the filter loading density. Further, it is important to understand that the filters did not reach their maximum possible compression and could have been packed even tighter. Since the trend in Figures 19 and 20 are expected to be valid for an increased packing density, the critical temperatures are expected to continue to decrease with increased packing densities.

Table 2 – Tabular Data on the Effect of Packing and Loading Density on the Critical Temperature.

Cube Size (Length of side) [in]	Critical Temperature [°C]			
	Fiberglass Filters*, High VOC**		Fiberglass Filters, High VOC**	
	Full Load	Half Load	Half Load 2 sheets/inch	Half Load 5 sheets/inch
4	262	244	244	170
5	248	226	226	150

*These numbers are from tests with 2 sheets per inch of side length of the cube.
**High VOC paint was low VOC paint with thinner (Xylene) added to create the appropriate VOC content.

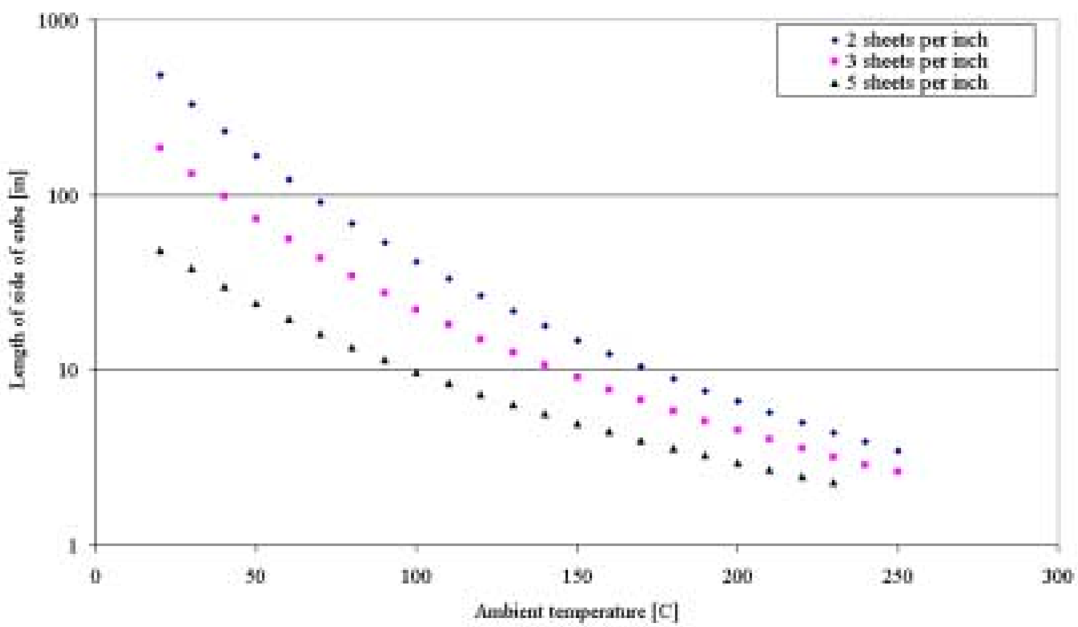

Figure 19 - Effect of packing density on critical temperature-size correlation (Logarithmic scale) (high VOC, half load).

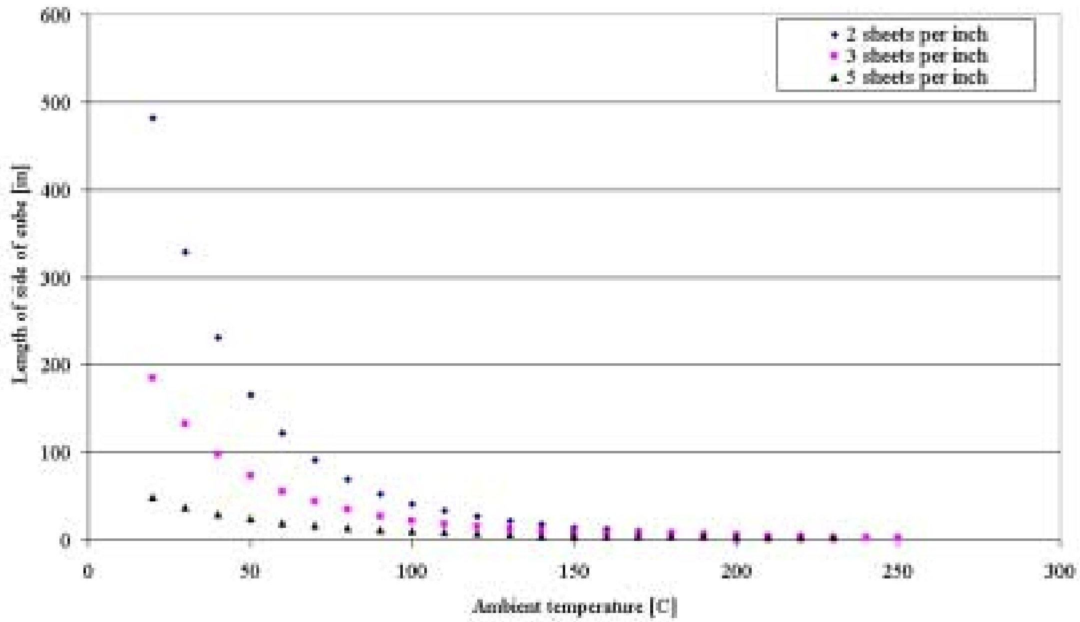

Figure 20 - Effect of packing density on critical temperature-size correlation (Normal scale) (high VOC, half load).

Paint filters are often disposed of in steel containers (i.e. dumpsters) with a volume ranging from 6 to 40 cubic yards. These volumes equate to a side length of 65 inches to 123 inches (assuming a cube). Figures 18, 19, and 20 indicate that as long as filters are not compressed into the containers, and provided the ambient temperature is below 50°C (122°F) (a temperature that is likely to occur in a trash container on a hot summer day), fires due to self-heating are not likely to occur. Once the filters are being compressed beyond the compression provided by their own weight, the containers are more likely to have fires, even at normal ambient temperatures (around 25°C (77°F)).

As previously discussed, increasing the packing density decreases amount of airflow through the pile and increases the insulation effect of the pile (i.e. less heat losses). Based on additional testing the results show that increasing the filter loading decreases the critical temperature of a given cube size. This suggests that sufficient air can penetrate through the filters, thus supporting the oxidation of the larger quantity of paint. While the porosity of the filters can change significantly, the porosity of the compressed fiberglass filters is much larger than for other systems of materials that self-heat (e.g. wood). In addition, as the fiberglass filters are compressed they nominally approach the same thickness as the paper filters, which based on survey results (Figure 1) are the filter type that experiences the most fires. Therefore, the increased insulating effect of the pile is considered the more dominate variable as the compressibility of the fiberglass filters is increased.

Figure 21 further supports the finding that packing density is a more important parameter than paint loading. Samples packed with 3 sheets per inch of cube side length, were only half loaded with high VOC paint. Samples packed with 2 sheets per inch of cube side length, were fully loaded with high VOC paint. Thus, the samples with 2 sheets per inch of cube side length contained more paint on a mass basis. Still, the samples packed with 2 sheets per inch had a higher critical temperature for each of the tested cube sizes. Figure 21 shows how significant this difference is when extrapolated to ambient temperatures.

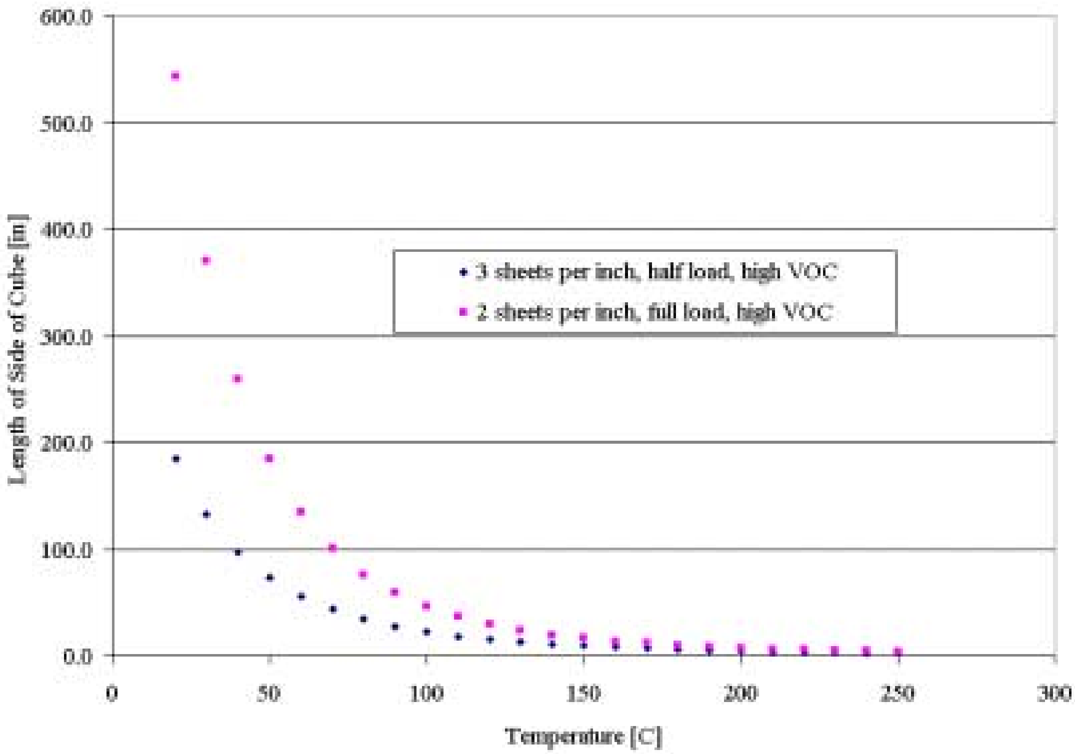

Figure 22 - Effects of packing density and effect of loading.

CONCLUSIONS

Based on the test results and additional analysis, the following conclusions are as follows:

- The experiments performed by CSE engineers confirm that an exothermic reaction takes place when the paint reacts with air. The paint-loaded filters were found to undergo exothermic decomposition that can result in self-heating leading to ignition under certain conditions.

- Increasing the percent VOC content of the paint (i.e. adding Xylene or another type of paint thinner to low VOC paint) decreased the critical temperature for spontaneous ignition for all pile sizes tested (i.e. all other parameters being equal, low VOC paints are less likely to lead to a fire through self-heating).

- Decreasing the loading density of paint filters decreased the critical temperature for spontaneous ignition for all pile sizes tested (i.e. all other parameters being equal, filters with low paint-load are more likely to lead to a fire through self-heating).

- Testing showed that heating of the paper filters alone (i.e. not loaded with paint) caused ignition. Therefore, a critical pile size for paper filters is not included since the low ignition temperature for the paper filters prevented CSE engineers from establishing the critical temperatures needed to perform calculations based on the theory presented by Frank and Kamenetskii. However, the limited results provided by the tests indicate that the paper filters should be expected to perform no better than fiberglass filters. The main support for this assumption is the fact that the exothermic reaction would only need to bring the temperature up to around 300°C to ignite the paper filters, a temperature that is significantly lower than the one required for ignition of the fiberglass filters. Figure 1 further supports the assumption that the paper filters are a more critical problem than fiberglass. This data indicates that about 75% of the facilities using paper filters had experienced fires, whereas only 50% of the facilities using fiberglass filters had experienced fires.

- Initially, variables such as VOC content in the paint and loading density were expected to be the most significant, by both CSE and the Iowa Waste Reduction Center. However, CSE has found that the main concern is the heat loss from the filters to the surroundings. In other words, the insulation around the reaction zone has to be minimized to prevent fires. Reducing the packing density can solve this problem, since the more tightly the filters are packed, the better insulation is provided to the center portion of the waste, where the exothermic decomposition can develop with very small heat losses. The analysis of the experimental data shows how dramatic the effect of increased packing density is for the predicted critical temperature-size correlation. The findings of the survey are consistent with the findings that the packing density is the single most critical factor for the temperature range of interest (20-50°C (68-122°F)). Survey data shows that facilities with a high consumption rate of paint have most fires. Although consistent with test results, a high consumption rate is expected to increase the use of filters, and may result in tighter packing of filters in the drum/container used for waste disposal. Survey data also indicates that only facilities that have a high turnover on filters experienced fires. Again, this is consistent with the test results since it seems logical that higher turnover of filters would lead to higher packing density.

- The criticality of the packing density can also explain why fires have been reported in dumpsters where perhaps the filters are not the only waste. One trash bag of paint-loaded filters (nominally 2 to 3 feet in diameter) contains enough paint for spontaneous ignition. Ignition will occur as long as the insulation and compression around it is sufficient. In a dumpster, all the trash surrounding the filters acts as insulation. As a result, pile size is not that of the filters alone. Rather, all the trash surrounding the filters makes up the pile size. As a result, a 6 cubic yard container with a bag of paint-loaded filters in the center will account for a pile size where the length of the side is approximately 65 inches (approximating the container as a cube). The Frank-Kamenetskii predictions presented in Figure 20 suggests that such a container will be large enough for self-heating to occur on a hot summer day. Therefore, it is important not to store the filters in places that will have ambient temperatures that are higher than normal (25°C (77°F)). It is important to notice that this prediction may have significant error bands, especially because of the large extrapolation from 4, 5, and 6-inch cubes to a pile size of 65 inches. As a result, a factor of safety should be incorporated when using the results of any modeling.

- In general, the compressibility and insulating effect of the filters is highly dependent on the conditions of disposal. The findings of this work suggest that these conditions are the dominant controlling factor. This may explain the lack of any clear trends in the survey data that would provide the reason(s) for the increase in reported fires.

RECOMMENDATIONS

Based on the testing and analysis, the following recommendations are made:

1) Do <u>not</u> dispose paint-loaded filters in a commercial dumpster where the filters can be compressed and insulated by other rubbish. This is especially true of disposal systems that compress the trash.

2) Do <u>not</u> dispose of the waste in trash bags that are picked up by traditional garbage trucks that routinely compress the trash to obtain more space.

3) Do <u>not</u> compress the filters beyond the compression provided by their own weight when disposing in large containers such as dumpsters (6 to 40 cubic yards).

4) Use smaller metal trash containers such as 55-gallon drums to dispose of the filters and do not compress the filters significantly.

5) Keep the storage containers at normal ambient temperatures (lower than 25°C (77°F)), since high ambient temperatures will increase the probability of a fire dramatically.

REFERENCES

Beever, P. F., (1995). "Self-Heating and Spontaneous Combustion", 2nd edition, *SFPE Handbook of Fire Protection Engineering*, Society of Fire Protection Engineers (SFPE), Section 2, Chapter 12, pp. 2-180.

Drysdale, D., *An Introduction to Fire Dynamics*, 2nd edition, Wiley, 1998.

Frank-Kamenetskii, D. A., (1969). *Diffusion and Heat Transfer in Chemical Kinetics*, Plenum, New York.

Friedman, R., *Principles of Fire Protection Chemistry*, NFPA, 2nd Edition, 1989.