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January 19, 2017

Mr. Ray Ault
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Dear Mr. Ault:

Please find enclosed a hard copy of Progress Report 8 that pertains to our collaborative research project on "Quantification of Energy Transfer from Wildland/urban Interface Fires".

Sincerely,

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PERFORMANCE EVALUATION OF

WILDLAND FIRE CHEMICALS USING

A CUSTOM-BUILT THERMAL CANISTER

PROGRESS REPORT 8

27 February 2017

PREPARED FOR FPINNOVATIONS

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EXECUTIVE SUMMARY

This project focuses on the performance evaluation of wildland forest fire chemicals using a custom-built thermal calorimeter, known as the "Thermal Canister." A laboratory test methodology was developed using a one-dimensional heat conduction model based on the uniform heating of a rectangular-shaped body. Data gathered from the thermocouples attached to the front and back surfaces of the canister walls was used as input to the heat conduction model to estimate the heat release rate from the combustion of vegetative fuels at three-second intervals.

Feather moss was used as the vegetative fuel due to its ability to absorb and retain water and water-based fire chemical products efficiently. Six different fuel treatments were used to evaluate the repeatability of the Thermal Canister assembly as well as evaluate the relative performance of the fire chemicals. The different fuel treatments selected were: untreated fuel (no water/chemicals), water at coverage level 4, Foam Product at coverage level 4, and Gel Products A, B, and C, at coverage level 4.

The low standard deviations on the average heat release rates obtained from the experimental burns suggested that the test methodology was able to produce repeatable results. It was found that use of all fire chemicals resulted in lower heat release rates from the burning vegetative fuels than when water was used, implying that they were more effective at suppressing the combustion of the vegetative fuel. Data also showed that the three gel products performed better than the Foam Product. Use of Gel Products B and C resulted in significantly lower heat release rates than all other treatments, suggesting that the two gels were more efficient at suppressing the combustion of the vegetative fuel.

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NOMENCLATURE

A surface area (m^2)

C_p specific heat capacity ($Jkg^{-1}K^{-1}$)

D diameter (m)

L length (m)

P pressure (N/m^2)

Re Reynolds's number, $\text{Re} = \frac{ul}{\nu}$

q' heat transfer rate (W)

T temperature (°C)

t time (s)

V velocity (ms^{-1})

W thickness of wall (m)

x position (m)

Greek symbols

α thermal diffusivity (m^2s^{-1})

ε emissivity

ρ density (kgm^{-3})

σ Stefan-Boltzmann constant (W/m^2K^4), 5.67×10^{-8} W/m^2-K^4

∞ ambient

Subscripts

c cross-section

e exhaust

i initial

s surface

t total

1.0 SYNOPSIS

The purpose of this project was to evaluate the performance of wildland fire chemicals. A custom-built thermal calorimeter, known as the "Thermal Canister" was developed by using a one-dimensional heat conduction model based on uniform heating of a rectangular-shaped body. An electric-powered radiant heater was used as the heat source in the experiments. The Thermal Canister was equipped with thermocouples on the front and back surfaces of the canister walls. Temperature data from these thermocouples was used as input to the heat conduction model to estimate the heat release rate from the combustion process of the vegetative fuel.

Six different fuel treatments were used to validate the repeatability of the Thermal Canister as well as evaluate the relative performance of the fire chemicals. Experimental burns for each treatment type were repeated three times for statistical consistency. The maximum standard deviation of the average heat release rates obtained from the experimental burns was less than 11% for all fuel treatments except for the Foam Product. This low standard deviation suggests that the test methodology was repeatable.

The evaluation of the relative performance of the fire chemicals was conducted using the average heat release rate of water-treated fuel as the control. The percentage improvement in performance was calculated at five time points: 300, 450, 600, 750, and 900 seconds. It was found that all chemical treatments produced lower average heat release rates than water, implying that they were more effective at suppressing combustion. Data also indicated that Gel Products B and C resulted in significantly lower heat release rates, performing between 60 - 70% better than the water-treated fuel for 4 out of the 5 time points.

2.0 MATHEMATICAL MODEL

A heat conduction model was developed by Anderson [1] to determine the temperature distribution in the Thermal Canister. The model was based on a one-dimensional, finite length-scale problem developed on the assumption of uniform heating of a rectangular-shaped body. It was assumed that the heat transfer across the exposed walls of the canister was relatively uniform, and the high thermal diffusivity of aluminum facilitated the reduction of any thermal fluctuations. The one-dimensional governing equation for the temperature distribution in the canister plate was given by

$$\frac{\partial^2 T}{\partial x^2} = \frac{1}{\alpha}\frac{\partial T}{\partial t}, \tag{1}$$

where T is the temperature, x is the spatial co-ordinate, α is the thermal diffusivity of the material, and t is time.

The boundary and initial conditions, shown in Fig, 1, were given by:

$$T(0,t) = T_1(t), \tag{2}$$

$$T(W,t) = T_2(t), \tag{3}$$

$$T(x,0) = T_{\mathrm{i}}, \tag{4}$$

where W is the thickness of the canister wall, and T_{i} is the ambient temperature. The method of superposition and separation of variables was used to solve the governing equation. The total heat release rate in the Thermal Canister based on this model was given as

$$q'(t) = \rho C_p A_c \sqrt{\frac{2(P_t - P_s)}{\rho}} \Delta T_e - \sum_{i=1}^{10} \frac{A_s}{\varepsilon} \left\{ \left(\frac{k}{W} \Delta T_w + \sigma\varepsilon [T_2(W,t)^4 + T_1(0,t)^4 - 2T_\infty{}^4] \right) \right\}_i , \quad (5)$$

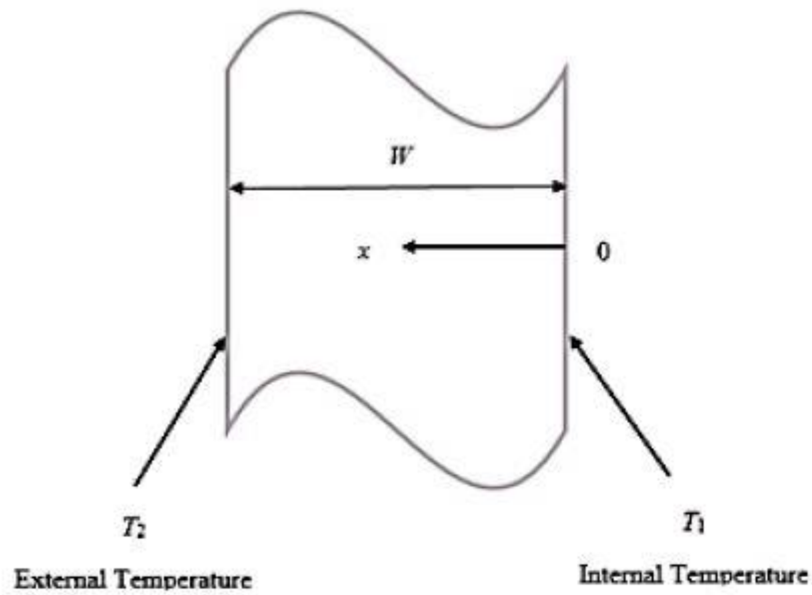

Figure 1: Representation of the thermal canister wall showing the boundary conditions [1]

2.1 Design Modifications

The theoretical model developed by Anderson suggested the use of a Pitot tube to measure the pressure of the flue gas. Preliminary experimental tests resulted in no readings obtained from the Pitot tube instrument. Pitot tubes are ineffective in measuring low fluid velocities [2], and therefore, an alternate method of estimating the heat loss from flue gases was required. Bernoulli's Principle was applied to replace the pressure term in Eq. 5 with a velocity term. Eq. 5 was modified to reflect this change as follows:

$$q'_{Total}(t) = \rho C_p A_c V \Delta T_e - \sum_{i=1}^{10} \frac{A_s}{\varepsilon} \left\{ \left(\frac{k}{W} \Delta T_w + \sigma\varepsilon [T_2(W,t)^4 + T_1(0,t)^4 - 2T_\infty{}^4] \right) \right\}_i , \quad (6)$$

where V is the velocity of the flue gas emitted from the exhaust pipe. An anemometer was used to measure this velocity.

A second modification to Anderson's original design was to increase the length of the exhaust pipe. A 0.85 m sheet metal pipe was used to replace the existing 0.012 m pipe. This modification was done in order to minimize entrance effects and ensure fully-developed flow along most of the length of the pipe. The hydrodynamic entry length of the pipe is estimated by using the following formula:

$$\frac{L_{h,laminar}}{D} \cong 0.06\,\text{Re}, \ [3] \tag{7}$$

where L_h is the length of the circular pipe, D is the diameter of the circular pipe, and Re is the Reynold's Number. Where the hydrodynamic length is much smaller than the length of the pipe, entrance effects are negligible and the flow tends to be fully-developed. It should be noted that the properties of the flue gas were assumed to be that of air to calculate the Reynold's number and the total heat release rate that is discussed later in this report.

2.0 THERMAL CANISTER FABRICATION

The Thermal Canister was fabricated from 6061 aluminum plate. The canister was comprised of four vertical walls and a horizontal lid. The dimensions of each vertical wall and the horizontal lid were 0.508 m x 0.279 m x 0.01905 m and 0.295 m x 0.295 m x 0.020 m respectively. Socket head cap screws were used to facilitate easy assembly of the Thermal Canister as well as disassembly for the purpose of mounting of fuel. An exhaust pipe of diameter 0.076 m and length 0.85 m was attached to the canister lid to enable transport of the flue gases from the

Thermal Canister (Fig. 2a). The internal faces of the canister walls and lid were painted with a high-temperature black spray paint (Krylon 1618 BBQ and Stove Paint, The Sherwin-Williams Company, Cleveland, OH, USA) to enhance absorption of radiation energy. Holes of 1.98 mm diameter were drilled in the walls and lid of the Thermal Canister, as shown in Fig. 3. The placement of the holes was similar to that of the Thermal Cube Heat Flux Sensor developed Anderson and McDonald [4]. These holes served as housing for thermocouples which were used to obtain transient temperature data at the front and back surfaces of the walls and lid.

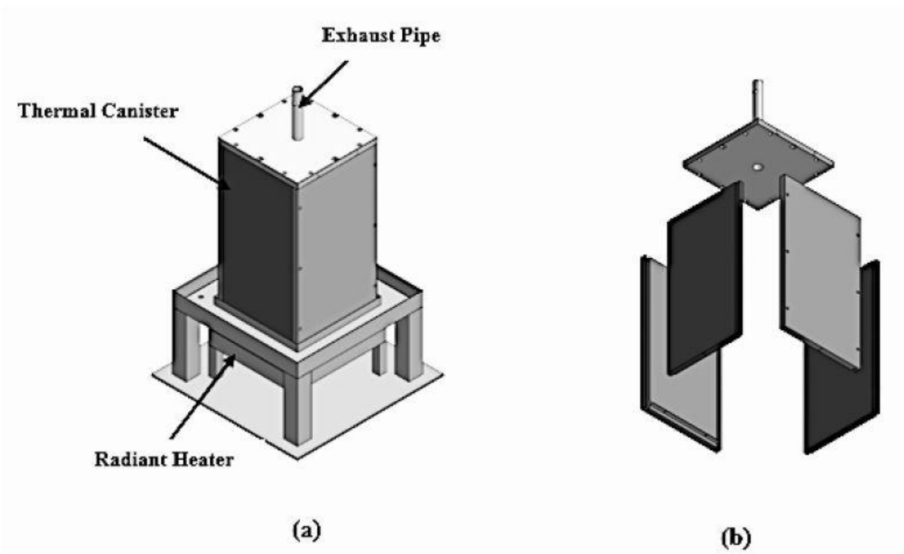

Figure 2: a) Thermal Canister Assembled, b) Exploded view of Thermal Canister [1]

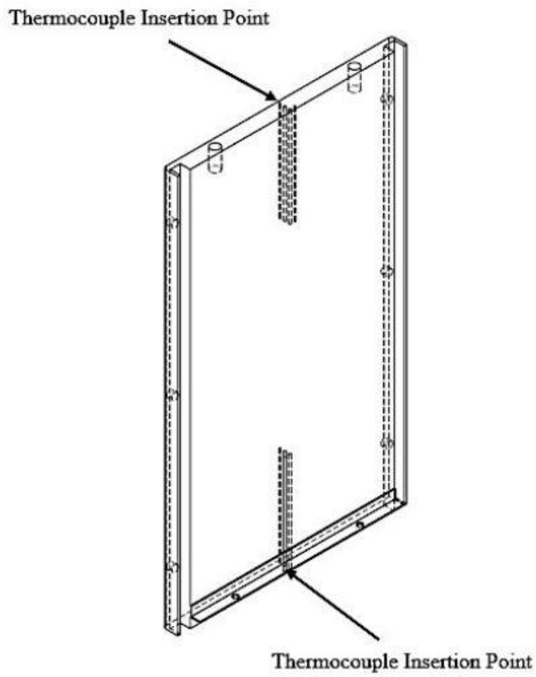

Figure 3: Representation of Thermal Canister Walls [1]

3.0 EXPERIMENTAL ASSEMBLY

The Thermal Canister was vertically mounted on a steel stand (as shown in Fig. 1a) with the open end facing the ground. The stand served as a platform for the canister to rest, and provided clearance below the canister to accommodate the heat source. The heat source used in this experiment was an electric-powered radiant panel (Omegalux QH-121260, Omega Engineering Inc, Laval, Quebec, Canada) that projected a uniform heat flux to the inside of the Thermal Canister. This radiant panel was placed on a secondary stand to minimize the distance between the face of the radiant panel and the open end of the Thermal Canister. Minimizing this distance increased the heat flux projected vertically upward towards the interior of the Thermal Canister while simultaneously reducing heat loses in the non-perpendicular directions. A small gap was maintained between the radiant panel and the opening of the Thermal Canister to enable air flow. The radiant panel was programmed to reach and maintain a temperature of 500° C.

J-Type 30 gauge thermocouples (Omega Engineering Inc., Laval, Quebec, Canada) were used to measure the temperature of the walls, lid, and exhaust flue gases of the Thermal Canister. A total of 30 thermocouples were fitted in the holes that were drilled in the walls and lid of the canister. The thermocouples were differentially wired to minimize the propagation of error [4]. An additional thermocouple was inserted at the inlet of the exhaust pipe to measure the temperature of the flue gases. Two data loggers were used to collect data from these thermocouples. The 30 thermocouples fitted in the walls and lid of the Thermal Canister were connected to a multi-channel data acquisition unit (34970A Data Acquisition/Data Logger Switch Unit, Keysight Technologies Inc., Santa Rosa, California, USA), and the exhaust pipe thermocouple was connected to a stand-alone data logger (DaqProTM 5300, Fourier Systems Inc., Mokena, IL, USA).

An anemometer (2G-2948 EDRA Anemometer, Airflow Developments Ltd., Richmond Hill, Ontario, Canada) was placed above the exhaust pipe outlet to measure the velocity of the flue gases. The entire assembly was placed next to a ventilation hood. The ventilation in the hood was switched off to enable natural convection of air during the experimental burns.

4.0 EXPERIMENTAL PROCEDURE

Red stemmed feather moss was selected as the fuel to be used in the experimental burns. Feather moss was chosen as the preferred fuel due to its ability to absorb and retain water efficiently and other water based chemical products (foams, gels, etc.). The moss was placed in a forced convection oven at 110°C for four hours. This drying process removed moisture, thus preventing any variability due to the moisture content in the fuel. The fuel masses were measured after three hours and after four hours to ensure that the moisture content was less than 5% before ending the drying process. A steel woven wire mesh (0.0075" wire diameter) of dimensions 25 cm x 25 cm was used as a surface to hold the fuel during the experiments. Forty-five (45) grams of feather moss was measured and placed on the steel mesh. The treatment of the fuel was applied prior to placement of the fuel in the Thermal Canister assembly.

4.1 Preparation of the Fire Chemicals

The performance of six different types of treatments was evaluated using the Thermal Canister assembly. The names of the products used as treatments have been intentionally excluded for proprietary reasons. The different treatments were: zero coverage level (no water/fire chemicals applied), water, Foam Product, and three Gel (water enhancer) Products: A, B, and C, all at coverage level 4. Chemical concentrates for the foam and gel products were provided by FPInnovations. The mixing ratios used (presented in Table 1) for the preparation of the foam and gel products were selected as per manufacturers' recommendations. Dry chemical concentrates were mixed by weight and wet chemical concentrates were mixed by volume.

Chemical Product	Mixing Ratio
Foam Product	0.65%
Gel Product A	0.65%
Gel Product B	0.65%
Gel Product C	3%

Table 1: Fire chemical product mixing ratios

The foam and gel products were thoroughly mixed using a high performance blender (Ninja, Euro-Pro Operating LLC, Ville St. Laurent, Québec, Canada). A Marsh funnel (Fann Instrument Company, Houston Texas, USA) was used to determine the time required for a fixed volume of the foam and gel products to flow through the funnel. The time was indicative of the viscosity of the product. One thousand, five hundred (1500) mL of foam and gel products was used in the Marsh Funnel test, with each test repeated three times. The results from the Marsh funnel test are presented in Table 2.

Chemical Product	Time, (s)
Foam Product	24 ± 1
Gel Product A	24 ± 1
Gel Product B	63 ± 2
Gel Product C	22 ± 1

Table 2: Fire chemical product flow time through a Marsh funnel

4.2 Experimental Burns

The Thermal Canister lid was removed to allow for the placement of the fuel bed by way of the top of the assembly. This ensured that the physical placement of the radiant panel at the open end of the Thermal Canister was not disturbed. The lid was replaced after the successful placement of the fuel, and fastened to the walls of the canister using socket head cap screws. The two data loggers were programmed to record temperatures and differential voltages at three-second intervals. The data recording process was initiated when the radiant panel was switched on. The experiment was repeated three times for each type of fuel treatment to validate the repeatability of experiments under the same parametric conditions (mixing ratio, mass of fuel, incident heat flux, etc.). Data obtained from the experiments was extracted and processed using Eq. 6 to calculate the heat release rate.

5.0 RESULTS AND DISCUSSION

5.1 Evaluation of Repeatability

Experimental burns for each treatment type was repeated three times to evaluate the ability of the Thermal Canister to collect data reliably under the constant parametric conditions of coverage level, moisture content of fuel, initial and ambient temperatures, incident heat flux, etc. The standard deviation of every data point corresponding to the same time stamp from the three data sets was computed. The maximum standard deviation value was represented as a percentage of the respective average heat release rate value.

5.1.1 Zero Coverage Level

Figure 4 shows the heat release rates from three experimental burns with a feather moss fuel bed and zero coverage level.

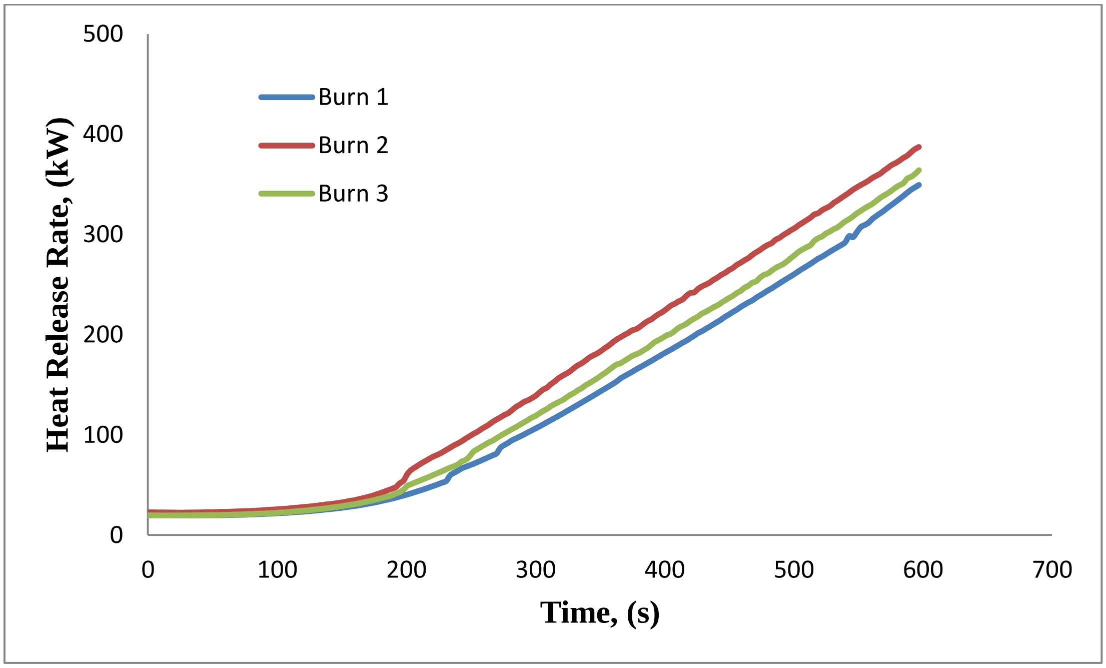

Figure 4: Heat release rate of three experimental burns with a feather moss fuel bed and zero coverage level.

The maximum standard deviation among the three sets of data was found to be 24 kW at 537 seconds where the average heat release rate was 312 kW. This represents a maximum percentage deviation of 7.7% during the burn cycles.

5.1.2 Water at Coverage Level 4

Figure 5 shows the heat release rates from three experimental burns with a feather moss fuel bed treated with water at coverage level 4.

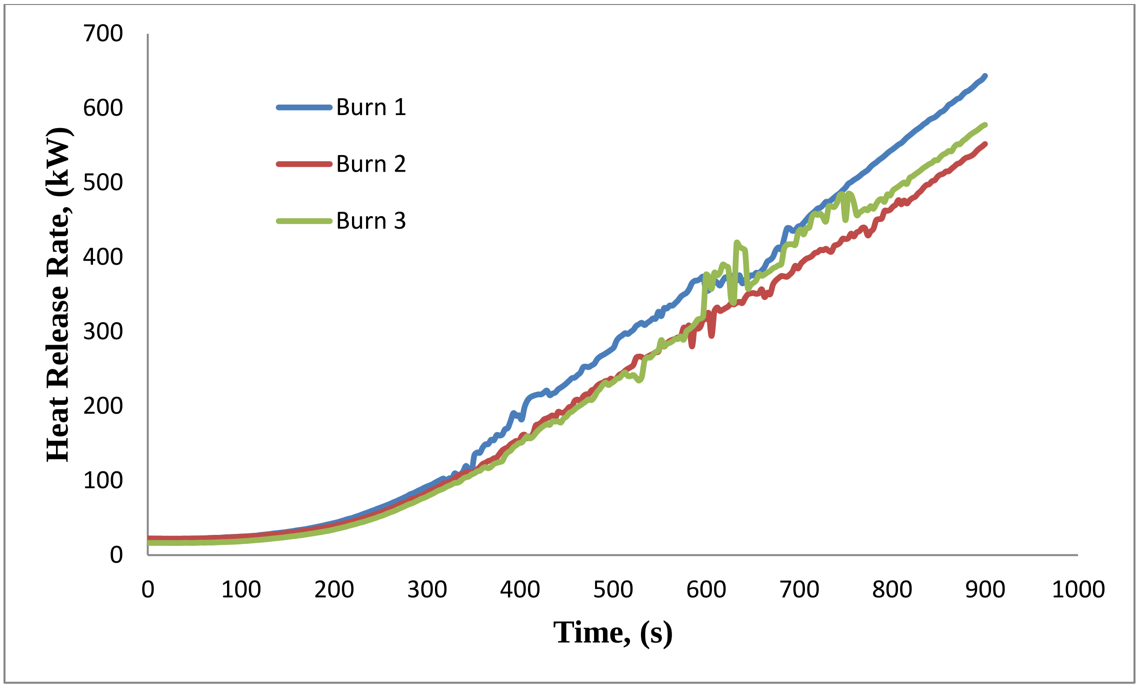

Figure 5: Heat release rate of three experimental burns with a feather moss fuel bed treated with water at coverage level 4.

The maximum standard deviation among the three sets of data was found to be 47 kW at 900 seconds where the average heat release rate was 590 kW. This represents a maximum percentage deviation of 8.0% during the burn cycles.

It was observed that the heat release rates for all experimental burns involving treated vegetative fuels produced non-smooth curves. This suggests that the presence of the treatment products influenced the combustion of the vegetative fuels, resulting in an irregular combustion process. The suppression of combustion caused by the different treatments resulted in combustion occurring in different parts of the fuel bed at different times during the experimental burns. The interaction of the treatment products with the random orientation of the fuel bed also contributed to the irregular combustion process. Therefore, sudden fluctuations were observed in the heat release rate data that was plotted.

5.1.3 Foam Product at Coverage Level 4

Figure 6 shows the heat release rates from three experimental burns with a feather moss fuel bed treated with the Foam Product at coverage level 4.

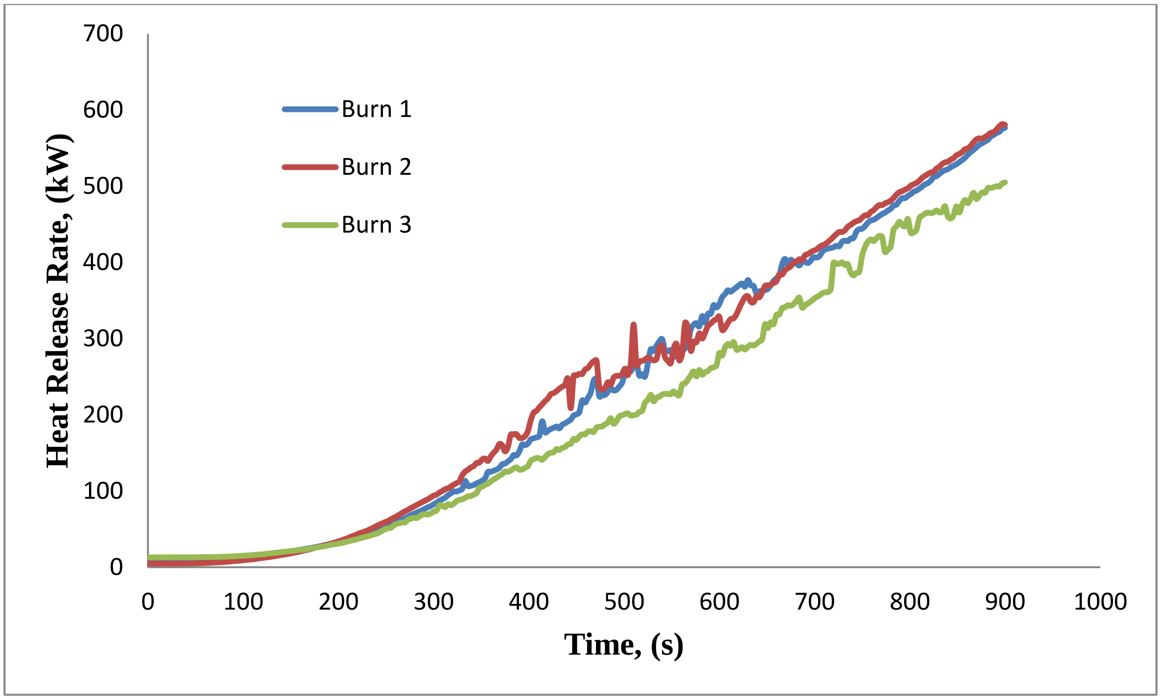

Figure 6: Heat release rate of three experimental burns with a feather moss fuel bed treated with the Foam Product at coverage level 4.

The maximum standard deviation among the three sets of data was found to be 60 kW at 510 seconds where the average heat release rate was 260 kW. This represents a maximum percentage deviation of 23.1% during the burn cycles.

5.1.4 Gel Product A at Coverage Level 4

Figure 7 shows the heat release rates from three experimental burns with a feather moss fuel bed treated with Gel Product A at coverage level 4.

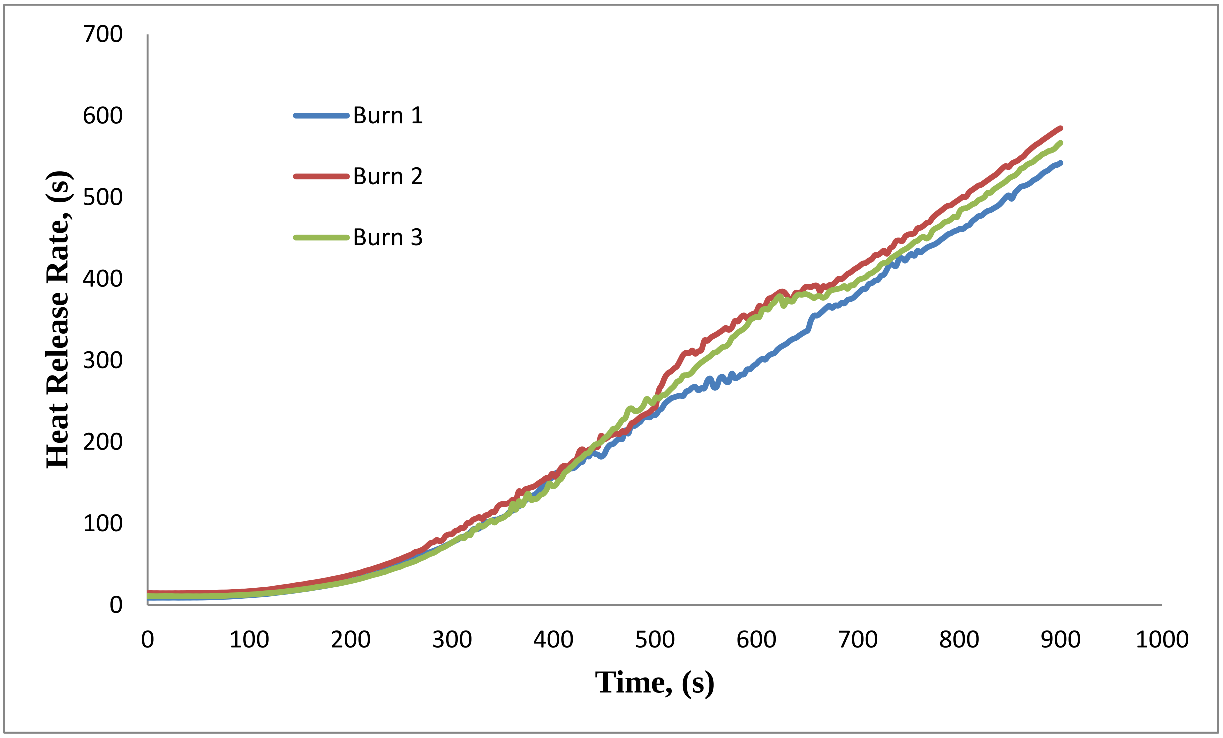

Figure 7: Heat release rate of three experimental burns with a feather moss fuel bed treated with Gel Product A at coverage level 4.

The maximum standard deviation among the three sets of data was found to be 25 kW at 621 seconds where the average heat release rate was 294 kW. This represents a maximum percentage deviation of 10.7% during the burn cycles.

5.1.5 Gel Product B at Coverage Level 4

Figure 8 shows the heat release rates from three experimental burns with a feather moss fuel bed treated with Gel Product B at coverage level 4.

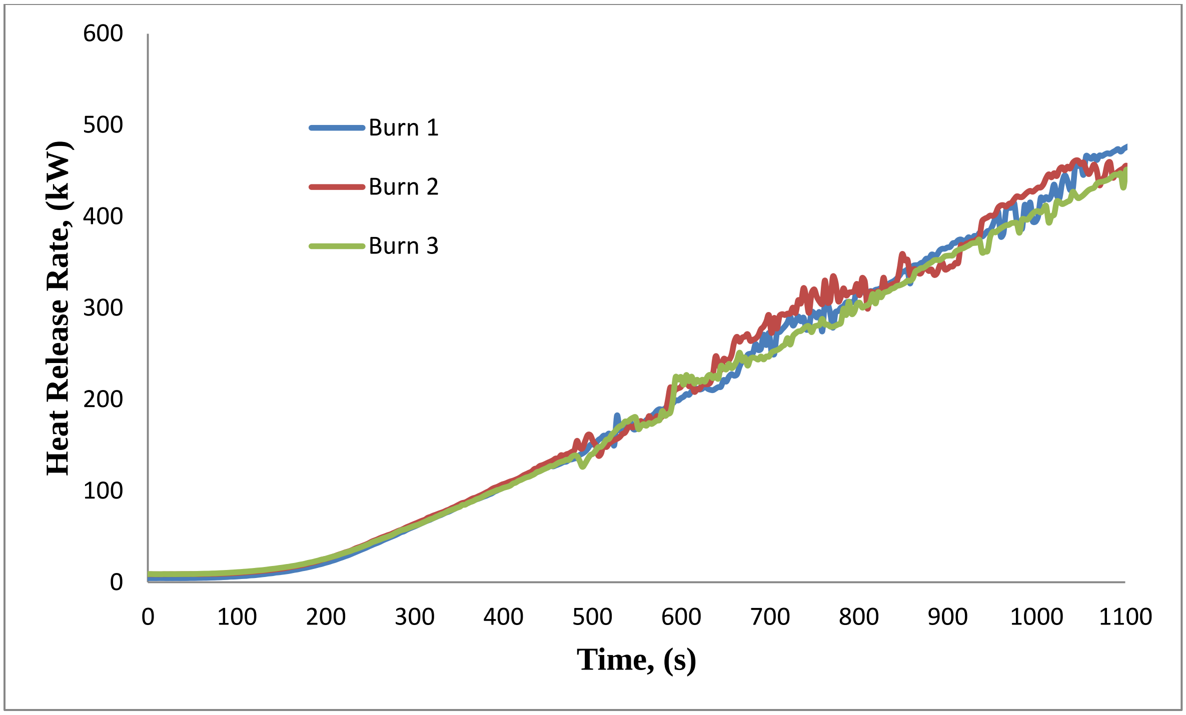

Figure 8: Heat release rate of three experimental burns with a feather moss fuel bed treated with Gel Product B at coverage level 4.

The maximum standard deviation among the three sets of data was found to be 32 kW at 771 seconds where the average heat release rate was 297 kW. This represents a maximum percentage deviation of 10.8% during the burn cycles.

5.1.6 Gel Product C at Coverage Level 4

Figure 9 shows the heat release rates from three experimental burns with a feather moss fuel bed treated with Gel Product C at coverage level 4.

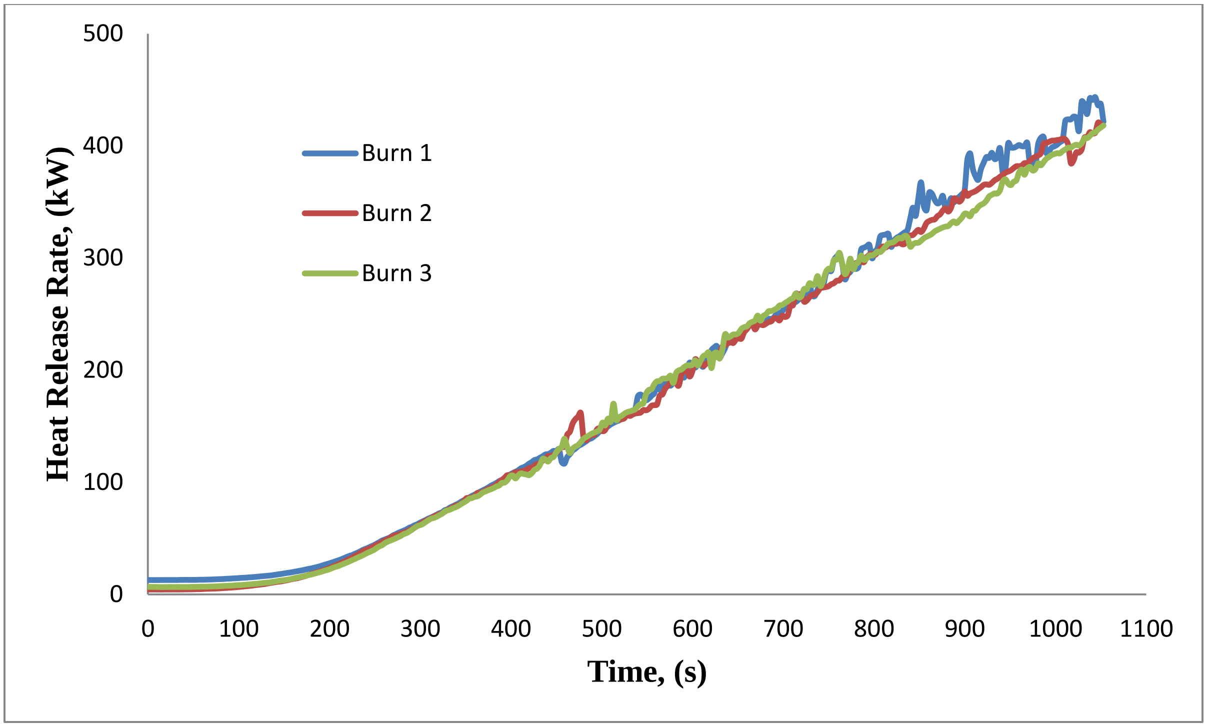

Figure 9: Heat release rate of three experimental burns with a feather moss fuel bed treated with Gel Product C at coverage level 4.

The maximum standard deviation among the three sets of data was found to be 23 kW at 1029 seconds where the average heat release rate was 412 kW. This represents a maximum percentage deviation of 5.6% during the burn cycles.

5.2 Performance Evaluation of Treatments

To evaluate the performance of the different fuel treatments, the average heat release rates from the three experimental burns for different fuel treatments were calculated. Figure 10 shows six different average heat release rates, each corresponding to a different fuel treatment.

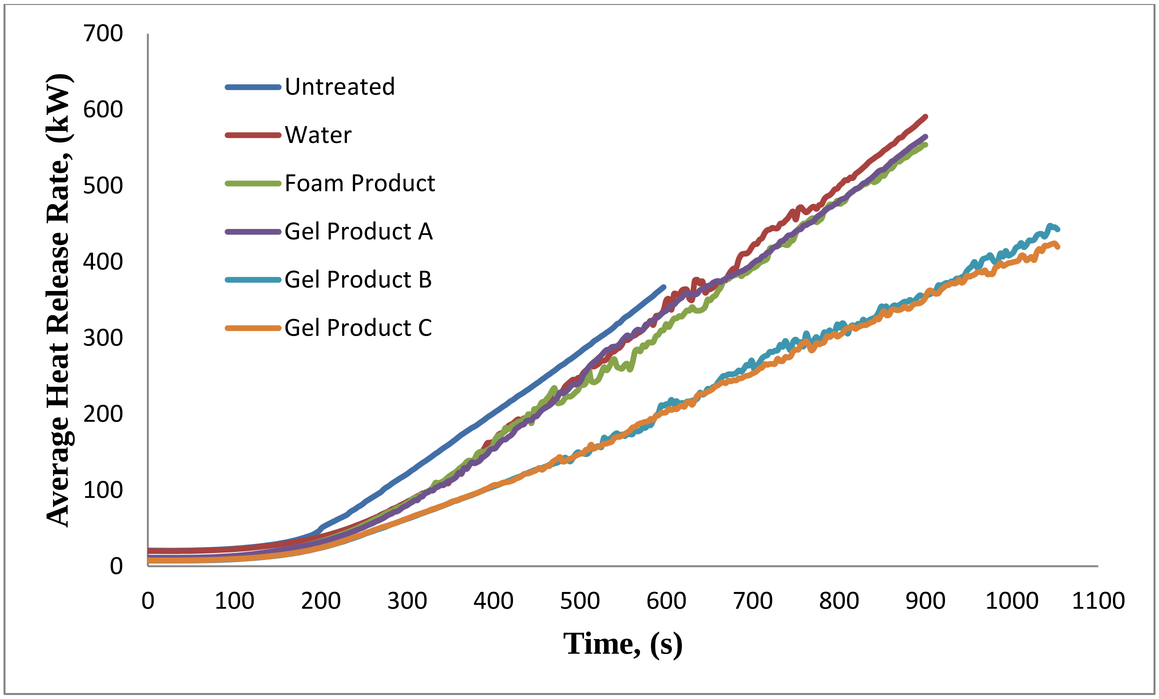

Figure 10: Comparison of average heat release rates between different fuel treatments

The experimental burns with untreated fuel lasted for a duration of 10 minutes, water, Foam Product and Gel Product A treated fuels burned for 15 minutes, and Gel Products B and C, for 18 minutes. This difference is due to the combustion process ending at different times for different treatments.

5.2.1 Untreated versus Treated Fuels

Figure 11 shows the difference in heat release rates between treated and untreated fuels. At around 200 seconds, a sudden rise in average heat release rate is observed in the untreated fuel. This rise in the heat release rate can be seen within the black circle in Figure 11. This is indicative of the onset of the combustion process in the untreated fuel. In comparison, a sudden rise of average heat release rates is not observed for any of the treated fuels. This implies that the treatment of fuels results in the absence of a singular moment of combustion, while allowing a more gradual combustion process when heat is applied. In addition, it can be seen that the average heat release rate for the untreated fuel at any given moment between 200 seconds and 600 seconds is higher than the average heat release rate for any of the treated fuels. This implies that the treatments were effective in reducing the heat release during the process of combustion, and were therefore effective.

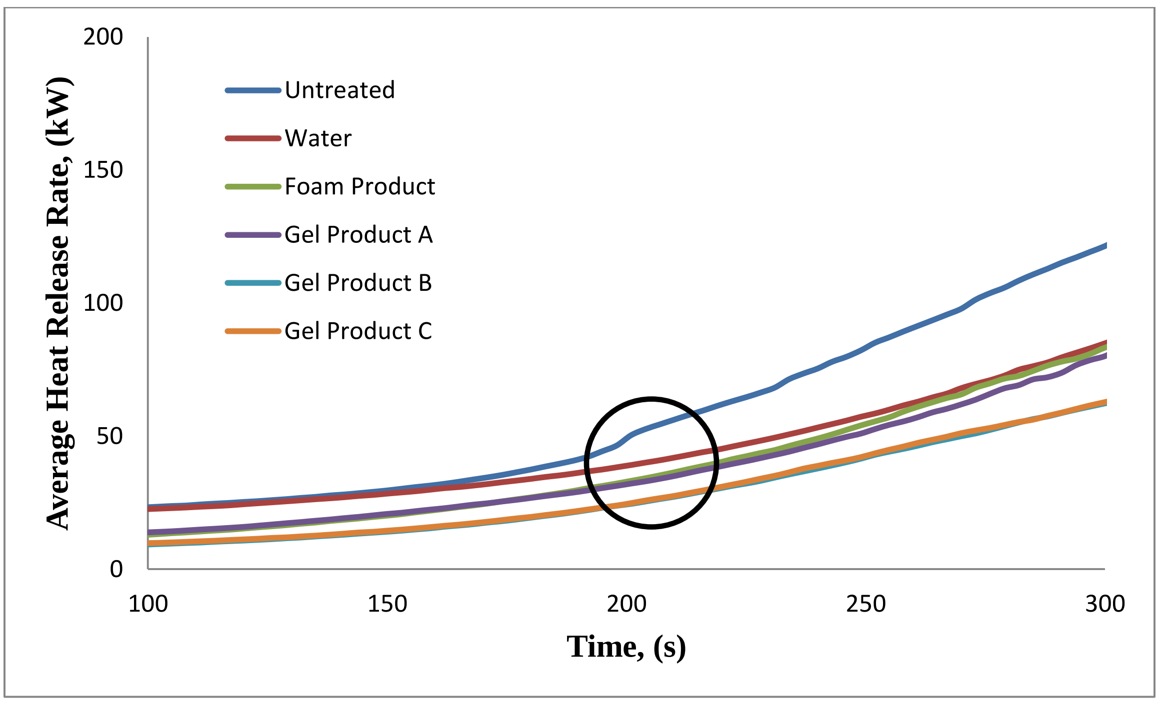

Figure 11: Onset of combustion process in the untreated fuel in comparison to the treated fuels

5.2.2 Comparison of Treatments

Figure 12 presents the average heat release rates of the different fuel treatments: water, Foam Product, and Gel Products A, B, and C. The time frame chosen for Fig. 11 is between 200 and 900 seconds. The time frame between 0 and 200 seconds has been excluded from Fig. 11 since the average heat release rates for the different treated fuels was approximately the same for this duration, as shown in Fig. 10.

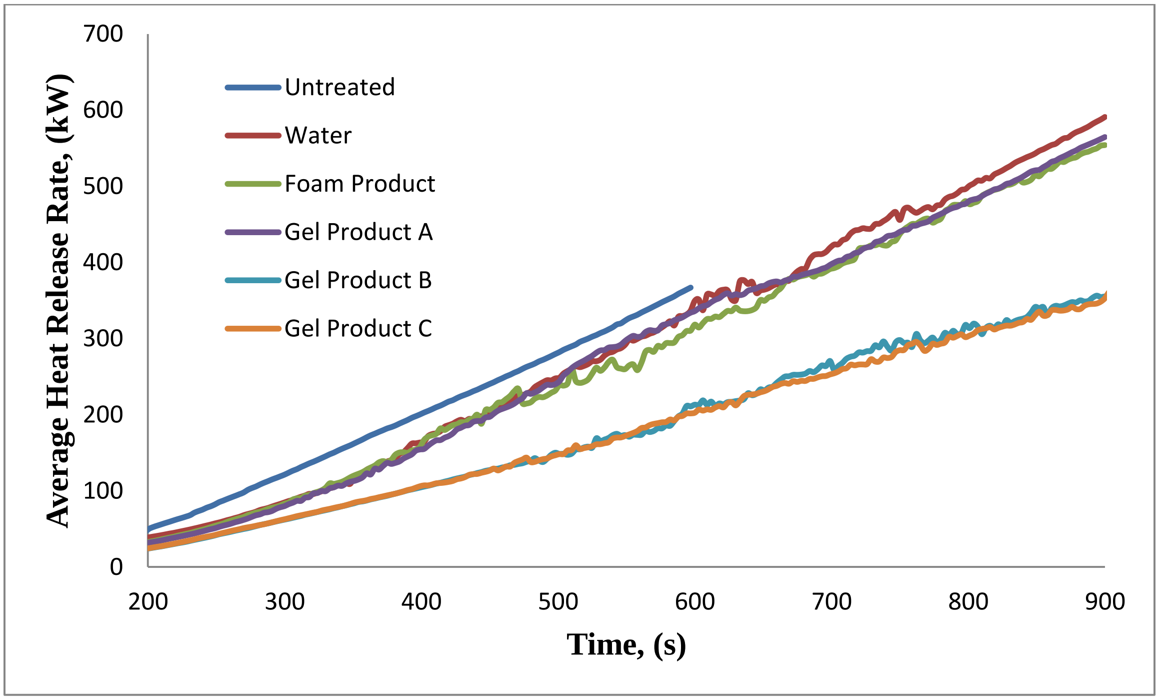

Figure 12: Comparison of average heat release rates between water, Foam Product, Gel Product A, Gel Product B, and Gel Product C.

The average heat release rate of water at coverage level 4 was used as a control measure to gauge the relative performance of the fire chemicals. The performance of the fire chemicals was evaluated in terms of percentage increase or decrease in average heat release rates in comparison to the average heat release rate of water-treated fuels. This percentage value was calculated at five locations on the time scales of 300, 450, 600, 750, and 900 seconds. Table 3 shows the relative performance the fire chemicals are these five time locations.

Treatment	Foam Product	Gel Product A	Gel Product B	Gel Product C
300 seconds	1.91%	5.67%	26.58%	26.02%
450 seconds	-1.39%	3.13%	37.45%	37.78%
600 seconds	8.92%	3.87%	38.99%	42.03%
750 seconds	4.04%	3.40%	34.60%	37.51%
900 seconds	6.24%	4.45%	39.85%	40.27%

Table 3: Relative performance of fire chemicals in comparison to water-treated fuel beds

The following inferences can be drawn from Table 3:

1. Use of all four fire chemicals resulted in lower average heat release rates in comparison to use of water, indicating that they are more effective than water in suppressing combustion.
2. The Foam Product resulted in higher heat release rates in comparison to the three gel products. This implies that the gel products were more effective at suppression combustion of the fuel than the Foam Product.
3. Gel Product A's performance was only marginally better than the Foam Product.
4. Gel Product B and Gel Product C produced significantly lower heat release rates in comparison to water, the Foam Product, and Gel Product C. This implies that Gel Product B and Gel Product C were the most effective at suppressing the combustion of the fuel for the different fuel treatments that were tested.
5. The performance of Gel Product C was marginally better than Gel Product B.

6.0 CONCLUSION

The objective of this study was to develop a test methodology to evaluate the performance of wildland fire chemicals. A custom-built thermal calorimeter, known as the "Thermal Canister" was developed by Anderson [1] using a one-dimensional heat conduction model based on uniform heating of a rectangular-shaped body. The purpose of the canister was to estimate the heat release rate produced during the combustion of vegetative fuels, which would be used as a means to evaluate the performance of the fire chemicals. Modifications to the mathematical model and experimental design were made to produce more accurate estimates of the heat release rate.

Feather moss was selected as the vegetative fuel to be used in the experiments due to its ability to absorb and retain water and water-based fire chemicals efficiently. Six different fuel treatments were selected to validate the performance of the experimental assembly as well as evaluate the relative performance of the treatments. The different fuel treatments selected were: untreated fuel (no water/chemicals), water at coverage level 4, Foam Product at coverage level 4, Gel Product A at coverage level 4, Gel Product B at coverage level 4, and Gel Product C at coverage level 4.

Experimental burns for each treatment type were carried out three times to evaluate the repeatability of the Thermal Canister. The maximum standard deviation from the three sets of heat release rates for different treatment types was calculated and expressed as a percentage of the corresponding average heat release rate values. It was found that the maximum percentage deviation of heat release rate values was lesser than 11% for all treatment types, except for the Foam Product which was found to be 23.07%. The low percentage standard deviations of the heat release rates suggested that the test methodology was able to produce repeatable results.

The heat release rates obtained from the experimental burns were used to evaluate the relative performance of the fire chemicals. It was found that all fire chemicals produced lower heat release rates than water, implying that they were more effective at suppression the combustion of the vegetative fuel. Data also showed that the three gel products performed better than the Foam Product. Gel Product B and Gel Product C produced significantly lower heat release rates than all other treatments, suggesting that the two gels were more efficient at suppressing the combustion of the vegetative fuel.

7.0 REFERENCES

[1] S. Anderson, "Quantification of Performance of Wildfire Chemicals using Custom-Built Heat Flux Sensors", University of Alberta, MSc. Thesis, 2015.

[2] R. Klopfenstein, "Air Velocity and Flow Measurement using a Pitot Tube", ISA Transactions, 37 (1998) 257-263.

[3] P. Kundu, I. Cohen, D. Dowling (2012), "Fluid Mechanics", Fifth Edition, Chapter 16, p. 803.

[4] S. Anderson, R. Refai, A. McDonald, "Error Reduction in the 'Thermal Cube' Heat Flux Sensor Used in Wildland Forest Fires", American Society of Thermal and Fluid Engineers, (2015), #TFESC-12598.