International Baccalaureate

Chemistry Extended Essay

Investigation of the Combustion Reaction of Cotton Satin Fabric Using Different Boron Compounds as Fire Retardants

"Does changing the type of boron compound (Boric acid, Borax pentahydrate, Borax decahydrate, Sodium pentaborate, Sodium metaborate) affect the rate of reaction of combustion of 25.00 cm^2 cotton satin fabric pieces using the impregnation method at 50.0±0.5℃ and burned after at room temperature?"

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Introduction

1.1 Research Question

"Does changing the type of boron compound (Boric acid, Borax pentahydrate, Borax decahydrate, Sodium pentaborate, Sodium metaborate) affect the rate of reaction of combustion of 25.00 cm^2 cotton satin fabric pieces using the impregnation method at 50.00℃ and burned after at room temperature?"

1.2 Context

Boron has recently been brought to use in especially space industries because it has the highest volumetric heating value between all common metal fuels even though it is presented as a metalloid in the periodic table. This way it helps the start of the ignition reaction to occur faster and reach high energy levels with minimal time, especially when using its hydro-boron compounds. The reason for this is because hydrogen has highest energy per mass of the fuel. When combined with elements like boron it obtains a higher density than in gaseous form, so with borons' high energy output and low weight, the new compound becomes the most ideal fuel within the current elements considering that it is neither highly toxic or radioactive.

In addition to this boron also has a significantly high gravimetric heating value, just behind beryllium which comes at first place. In comparison to magnesium and aluminum, which are the most common metal fuels used, boron nearly has twice the energy of both these elements' fuels with a value of 58.83 kJ/g[1]. This makes it suitable to be used as an additive to liquid fuels along with its non-toxic properties and low volume consumption.

Although boron has a high potential in the industry, it still has a big problem which is the existence of naturally occuring oxide layers covering its particles. As the name suggests these oxide layers form when boron compounds are introduced to open air. These layers result in borons ignition and combustion to be delayed and increases the time it takes for boron particles' full energy to be released.

This idea was expanded upon and two methodologies were considered for decreasing the thickness of the oxide layers. However, both desired mechanisms and gears that could not be achieved with the laboratory equipment at hand. Because of this, a different approach was initialized. It was decided that rather than decreasing the thickness of these oxide layers, they were utilized to be used as fire retardants for the combustion of a commonly used fabric. This way, whether fire resistant clothes and fabrics could be obtained was observed. This idea is solely supported by the fact that, the boron compounds increase the time for the combustion to occur. By this, any fiber or fabric introduced to boron compounds would have a longer time in combustion.

Background Information

The experiment was conducted using an impregnation method, in which each compound is dissolved at different containers and the cotton satin pieces are drowned so that they absorb the dissolved boron compounds. Then to get rid of the water, they are heated as water evaporates. This methodology was chosen to be used, for its ability to obtain as many data as possible for checking any errors and having an understanding on the topic more easily. Dissolving was held at 50°C because of each compound having a low dissolving rate at room temperatures. These five compounds were chosen to be experimented for their solubility levels inside water at a

specified temperature and because of their accessabilities, as boron can be considered valuable. After the main experiment ends a shorter one will be conducted for the compound with the longest times for combustion at different temperatures (30.0°C, 40.0°C, 50.0°C, 60.0°C, 70.0°C). To achieve a better understanding, information about each of these compounds are given in Appendix 1.

2.1 Hypothesis: As the solubility of the compound increases, more boron will be impregnated into the cotton satin fabric because more boron ions will be dissolved and present inside the solution. The reason behind this idea is explained in detail in the appendix part.

On the other hand, as a counter hypothesis as the solubility increases more boron will result in the fire will ride the fabric faster and will decrease the time it takes for the fabric to fully burn down.

Experimental Variables

3.1 Independent Variable

Independent Variable	Effect on the Experiment
The type of boron compound Boric Acid(H_3BO_3) Borax Pentahydrate($Na_2B_4O_7•5H_2O$) Borax Decahydrate($Na_2B_4O_7•10H_2O$) Sodium pentaborate decahydrate ($NaB_5O_8•10H_2O$) Sodium metaborate tetrahydrate($NaBO_2•4H_2O$)	Each boron compound has a different molecular structure which changes its solubility in water. In the method, if there are more boron percentile impregnated inside the cotton satin fabric, then the combustion time should increase because of boron atoms own naturally occuring oxide layers delaying the fabric to burn.

Table 1: Independent Variable and Its Effect on the Experiment

3.2 Dependent Variable

Dependent Variable	Method for Measurement
Combustion reaction rate	The impregnated cotton satin fabric is held at a constant angle and a timer is started when the fire jumps to the fabric. The timer is stopped when even smoke is not observed.

Table 2: Dependent Variable and Its Method for Measurement

3.3 Controlled Variables

Controlled Variables	Reason for Control	Method of Control
The angle at which the fabric is held	The fabric is burnt from one side and it is observed as it slowly progresses. If the fabric is held at a vertical angle, the fire will ride up on the fabric and make it combust quicker.	The fabric should be harder to handle after the impregnation process. This will make it easier to stabilize it with a clamp on a horizontal level. The clamp was arranged so that it would effect the experiments less by compressing a portion of the fabric lightly.
The temperature of the water baths	As the temperature of the water increases the overall molecular motion will increase and more solute particles will be pulled thus increasing its ability to dissolve more solute particles.	The water baths have their own settings for precise temperatures to keep them constant. The temperature of all water baths were all checked to prevent errors.

The windiness of the laboratory	The wind can both increase and decrease the rate at which something combusts. It can supply oxygen to the fire and if it is strong it can take away heat from the fire so that it cannot continue to burn.	The flow of air throughout the experimentation was disabled by closing any means of air to escape or enter like doors and windows.
The volume of the cotton satin fabric	If the volume of the cotton satin fabric is increased, there would be more matter for the fire to combust and therefore this will lenghten the time it takes for the fabric to burn.	Each fabric was labelled and cut precisely using a kind of stitching machine beforehand. Because each sample was cut from the same source, their heights are the same therefore it does not have any effect on the experiment and the volume can be mentioned as area.
Flow rate of the flame	Same amount of flow rate is obtained for each of the combustion reaction obtained by same heat source and angle of handling.	

Table 3: Controlled Variables with Their Reason for Control and Method of Control

Safety Precautions

4.1 Risk Assessment

The experimentation process does not have any risk involving interactions other than combustion. Because the combustion is not big scaled it is easy to control and prevent any health injuries and experimental issues from occuring. This is done by first obtaining the following protective equipment for your own protection:

- Oven gloves
- Lab coat
- Plastic gloves
- Protective glasses

Other necessary gears could be:

- Fireproof table clothing
- Metal tray for collecting ash and residue
- Fire extinguisher

Other than protection from the combustion, guarding oneself from the boron compounds is also obliged. The compounds are not seen in a great amount to cause severe or lethal health problems however it is still important to avoid any direct contact of them with the skin and eyes while also any inhalation or swallowing of the compounds should be prevented as they can still cause irritation, coughing, difficulty in breathing, vomitting and diarrhea [4]. If any of these issues listed occurs, do the following:

- For eyes, flush them with lukewarm water for about 10 minutes, hot water is **NOT** recommended as it can cause further damage.

- For skin, if it does not have any reaction to it, rinse it for 15 minutes. If it does have any reactions such as swelling, becoming red, burning and so on and do not try to remove any crust of the boron compound off of your skin forcefully. You can try to wash the area with soap and water and applying moisturizer to prevent it from drying.
- For inhalation, take the person affected to a well-ventilated area to allow fresh air to clean up the lungs.
- For swallowing or consuming, do **NOT** induce any type of vomiting as it can cause more problems. Identify what you've consumed so as to give the medical personnel has knowledge of how to approach your situation.

Medical attention for each issue is mandatory.

4.2 Ethical Implications and Environmental Issues

One ethical implication could be the possible harm to living organisms or the environment during and after the experimentation process. The use of cotton satin fabric pieces is a non-hazardous material. However, there is still the handling of the boron compounds which may pollute the seas and the soil to an extent that it becomes poisonous to living organisms by changing the concentration of substances in the environment. To prevent the mixing of waste chemicals, the waste produced was thrown into a chemical collecting container and then was got rid of in appropiate methods.

Looking at the experiment economically, boron being found commonly in the region, it still holds a value. For this it can be said that each boron compound may be expensive. To decrease the cost, the investigation was done with the smallest amounts possible and each equipment was used for the slightest possible times.

Methodology

5.1 Materials

Materials	**Amount required**	**Uncertainties**
Cotton satin fabric 5.00x5.00 cm^2	25 + 20 for additional experiments	$\pm 0.02\ cm^2$
Metal tray	A single metal tray	-
Boric acid	5.00 grams for each trial	±0.01 g
Borax pentahydrate	5.00 grams for each trial	±0.01 g
Borax decahydrate	5.00 grams for each trial	±0.01 g
Sodium metaborate tetrahydrate	5.00 grams for each trial	±0.01 g
Sodium pentaborate decahydrate	5.00 grams for each trial	±0.01 g
Water bath		-
Electronic timer	A single electronic timer	±0.2 sec
Thermometer		$\pm 0.5^0C$
500 ml Beaker	Minimum 5 for maximum time, maximum 25 for minimum time	±1 ml
Distilled water source	About 100 ml for each trial, 5.5 L in total	-
Tweezer	A single tweezer	-
Clamp	A single clamp	-

Burner	A single burner	-
Digital weight	A single digital weight	±0.01

Table 4: Materials with the amounts required including the uncertainties

5.2 Procedure

1. Fill 100.00ml of the beaker with distilled water.
2. Obtain the metal tray and put the burner on it.
3. Put the beaker inside the water bath and wait for the temperature to fully reach 50.0C°.
4. Carefully insert 5.00gram Boric Acid into the beaker. Wait for an hour for it to fully dissolve inside water.

   Note: All boron containing chemicals were specificaly chosen to be dissolved inside water. If you observe any characteristics that do not belong to dissolution like compounds creating a layer under the water or above it, retry this step. Also the 1 hour wait time was chosen so that the conditions of the amount of compound that can dissolve in water at 50.0°C is met.
5. During this time calculate the weight of the fabric.
6. After waiting, put the cotton satin fabric inside the solution until it is completely submerged in it. Wait another hour for the fabric to fully absorb the solution.

   Note: Again as in the 4th step, the hour is predicted to be enough for the fabric to fully absorb the solution as it is in a relatively higher temperature than room temperature.
7. After 1 hour get the fabric outside the solution with a tweezer. Put the fabric inside the oven for 45.0 minutes at 70.0℃ so that all excess water inside the fabric are dried out.
8. Calculate the weight of the fabric by a digital weight.
9. Stabilize the fabric horizontally using a clamp so that the fire doesn't ride up and decrease the burning time. Put the clamp on top of the burner inside the metal tray.
10. Increase the level of the burner so that the tip of the flame is just under the fabric, this can vary between 0.1-0.5 cm depending on the source. Be sure not to change the level throughout the whole experiment so that it does not increase the error. Prepare the fabric and the timer for combustion.
11. Start the timer when any fire is observed on the fabric. This experiment should be stopped when a light gray smoke escapes the fabric.
12. Stop the timer when you fully observe that the combustion of the fabric has stopped, no further smoke comes out of it.

    Note: Until now the fabric will combust from the tip of the burner flames and the combustion will rise to the whole fabric. Because we want to fully observe the effectiveness of the compound as a flame retardant, we take the time it takes until no smoke is observed. Smoke is chosen as the indicator because there may still be molecules present in the fabric that hasn't reacted yet and therefore the low energy release could not be building up into a fire, while it may be seen as smoke.
13. Write the data on the timer.
14. Repeat steps 1-11 with same concentrations of Boric Acid 4 times.

15. Repeat steps 1-12 with different compounds (Borax Pentahydrate, Sodium Metaborate Tetrahydrate, Borax Decahydrate, Sodium Pentaborate Decahydrate) 4 times.
    Note that this whole process can be made time efficiently by doing 2 or more measurements at a time. So that when waiting for a singular fabric value you will wait for the same time with more measurements.

5.3 Additional Experimentations

1. Use the strongest compound of boron that acted as a flame retardant at different temperatures (30.0°C, 40.0°C, 50.0°C, 60.0°C, 70.0°C). This process will be done with using the same methodology and twice for each temperature.
2. Burn both a fabric without any solution impregnated inside it and burn another that was drowned inside water and put inside the oven for evaporation. Calculate the data of both of these for preliminary purposes.

5.4 Qualitative Observations and Results of Preliminary Experimentations

Qualitatively the experiment had no issue handling. During the water bath process, some water vapour was seen on the sides of the beaker as the temperature inside was higher than room temperature and made the water inside the bath vaporize. The molecules that clinged to the walls of the beakers, condensed into liquid water and created steam. This could have resulted in an error in the experiment, however the water levels were checked to make sure it did not create a problem that could harm the results of the experiment. The fabric itself gave a dark black smoke when burnt and the ones with boron impregnated onto gave a more greyish-white smoke.

Also for the main and the first additional experimentation's both had a fogginess inside the soutions that resembles the presence of residue which was wanted as each compound was being observed at its full capability. For the main experiment, the fogginess decreased as solubility increased whereas in the first additional experiment fogginess decreased as the temperature increased.

From the preliminary experiments, 5 cotton satin fabrics were dumped inside into just water and were burned after drying them inside the oven. Another 5 was burned without any applications onto them. This was done so as to optimize the time inside the oven needed for full evaporation. The times for combustion for both tests were needed to be about the same, along with no weight difference between the initial and final calculations were observed. When the time was taken as 45.0 minutes, average times of the dry fabrics was 30.0 seconds, of the soaked fabrics was 30.6 seconds. No weight change was also observed and thus 45.0 minutes were taken for the oven time.

Calculations and Analysis

6.1 Raw Data Table of Initial and Final Weight with Time

	Trial No.	Initial Weight of the fabric (g) ±0.001	Final Weight of the fabric (g) ±0.001	Time (s) ±0.2
Boric Acid	1	0.389	0.400	37.6
	2	0.353	0.356	50.1
	3	0.394	0.400	52.9

	4	0.360	0.370	45.6
	5	0.382	0.385	44.3
Borax Pentahydrate	1	0.393	0.404	60.7
	2	0.384	0.391	55.4
	3	0.390	0.402	56.8
	4	0.367	0.378	54.4
	5	0.390	0.401	56.6
Borax Decahydrate	1	0.376	0.383	54.2
	2	0.389	0.391	45.4
	3	0.378	0.391	55.4
	4	0.376	0.388	45.2
	5	0.390	0.403	57.3
Sodium Pentaborate Decahydrate	1	0.373	0.391	106.8
	2	0.376	0.398	85.8
	3	0.366	0.371	76.6
	4	0.397	0.403	78.3
	5	0.389	0.393	83.0
Sodium Metaborate Tetrahydrate	1	0.362	0.370	81.9
	2	0.404	0.409	78.9
	3	0.396	0.403	88.1
	4	0.368	0.396	112.9
	5	0.376	0.380	72.5

Table 4: Raw Data Table of Initial and Final Weights of the Fabric After the Impregnation Process with Each Boron Compound and Their Combustion Times

From this table, sodium metaborate is the most capable as a fire-retardant just by looking at their time values. However, this can be also referenced more scientifically. Through calculations we can determine the effective heat of combustion in this experiment. This value, along with each compounds relative limiting oxygen index will give a more reliable data set for observation.

Limiting oxygen index (LOI) for each compound is different. This gives the minimum amount of oxygen required in the system for a fire to lead into a stable combustion. In normal conditions, with atmospheric air as the oxygen supply the LOI of most fires are about %16. This means that the air surrounding the burning specimen needs to be at least %16.00 oxygen [3]. For normal cotton satin fabric this value is %18.65[5] percent. Cotton satin fabric impregnated with boric acid, borax pentahydrate, borax decahydrate, sodium pentaborte decahydrate and sodium metaborate tetrahydrate the LOI is %19.0, %42.0, %37.0, %40.0 and %42.5 respectively [3], These values could be caused by either the oxide layers or the water molecules both of which help inhibit the burning of any compound. This way more oxygen may be needed to fuel the fire in order to burn them. It can also be affected by temperature however, it is constant all through the experiment as each sample is burned at room temperature, 25.0℃ [6].

For calculating the effective heat of combustion (EHC), the total heat released is divided by the mass of final fabric, as EHC unit is $MJkg^{-1}$. To find the total heat released we can use the combustion enthalpy of each trial which is $kJmol^{-1}$ then rearrange the values according to our samples. The ΔH_C° values of boric acid, borax pentahydrate, borax decahydrate, sodium pentaborate decahydrate and sodium metaborate tetrahydrate are -181.2, -1056.6, -3387.2

-3567.8 and -6686.8 $kJmol^{-1}$[3] respectively. The combustion enthalpy of a substance gives how much energy is released for one mol. To change this according to our trials we can find how much mol of both boron compounds and the fabric is used in each trial then divide the combustion enthalpies to that value.

As an example first trial of boric acid with 0.389 g initial and 0.400 g final masses is used. The difference is 0.011 g which gives the boric acid amount impregnated inside the fabric. The combustion enthalpy for boric acid was -181.2 kJ for a single mol. To find the effective heat of combustion we can give this value in grams. The molar mass of boric acid is 61.83 $gmol^{-1}$. This makes:

$$\frac{181.2}{61.83} = 2.931\ kJg^{-1}$$

This is equal to $MJkg^{-1}$ as both energy in joules and weight in grams is multiplied by 10^{-3}. This will then give the megajoule released for each kg of boric acid. If we multiply $0.011x10^{-3}$ kg with this value we find the total heat released from the combustion of boric acid for this sample which is $3.22x10^{-5}$ MJ. Then we divide this value to the total mass present in the sample, final mass, in kg. Which is:

$$\frac{3.22 \times 10^{-5}}{4.000 \times 10^{-4}} = 8.06 \times 10^{-2} MJkg^{-1}$$

Then we also need to find their percent of mass that has penetrated the fabric to understand how much affect the boron compounds made individually. This can be achieved by dividing the boron weight by the final fabric weight and multiplying by 100 to obtain a percentage value. Using the same trial:

$$Percent\ Mass\ of\ Penetration\ by\ Fabric = \frac{0.011}{0.400} \times 100 = 2.75\%$$

For this sample, the EHC is obtained as $8.06 \times 10^{-2}\ MJkg^{-1}$ and the percent mass of penetration of boric acid found inside the fabric is 2.75%.

The uncertainty of this sample for EHC is %1.3 as boric acid for this sample has an uncertainty of %0.8 and mass of fabric has %0.5. The uncertainty for mass of penetration is %9.3 as the mass lost has %9 uncertainty and final mass has %0.3 uncertainty. The uncertainties of processed data is given in the appendix section.

Below the EHC, LOI and the boron compound mass of penetration of each compound in each trial is listed.

During the calculation, uncertainties, standard deviation values were all used to work uncertainty which can be seen at appendix.

6.2 Data Table of EHCs, LOIs and Percent Mass of Penetration by Fabric for All Trials of Each Boron Compound

	LOI (%)	Trial No.	EHC ($MJkg^{-1}$)	Percent Mass of Penetration by Fabric (%)
Boric Acid	19.0	1	$8.06x10^{-2}$	2.75
		2	$2.47x10^{-2}$	3.65
		3	$4.39x10^{-2}$	1.50
		4	$7.92\ x10^{-2}$	2.70
		5	$2.28\ x10^{-2}$	0.78
Borax Pentahydrate	42.0	1	$9.88\ x10^{-2}$	2.72
		2	$6.49\ x10^{-2}$	1.79
		3	$1.08\ x10^{-1}$	2.98
		4	$1.06\ x10^{-1}$	2.91
		5	$9.95\ x10^{-2}$	2.74
Borax Decahydrate	37.0	1	$1.62\ x10^{-1}$	1.83
		2	$4.54\ x10^{-2}$	0.51
		3	$2.95\ x10^{-1}$	3.33
		4	$2.75\ x10^{-1}$	3.09
		5	$2.86\ x10^{-1}$	3.23
Sodium Pentaborate Decahydrate	40.0	1	$4.26\ x10^{-1}$	4.60
		2	$5.12\ x10^{-1}$	5.53
		3	$1.25\ x10^{-1}$	1.35
		4	$1.38\ x10^{-1}$	1.49
		5	$9.42\ x10^{-2}$	1.02
Sodium Metaborate Tetrahydrate	42.5	1	1.05	2.16
		2	$5.93\ x10^{-1}$	1.22
		3	$8.42\ x10^{-1}$	1.74
		4	3.43	7.07
		5	$5.11\ x10^{-1}$	1.05

Table 5: Boron Compounds With Their Own LOI, EHC Values and Percent Mass of Penetration by Fabric Within the Cotton Satin Fabric Along with Their Mean

Uncertainty calculations and %Uncertainty values are give and calculated in the Appendix part.

The EHC values can be easily seen to increase from bottom to top. Looking at their percent mass of penetrations meanwhile, they are distributed evenly and this should result in a similar mean value all throughout the experiment. To see this even more clearly and evaluate better, mean values are obtained.

6.3 Processed Data Table of Mean LOI, EHC and Percent Mass of Penetration by Fabric of Each Boron Compound

Mean	Boric Acid	Borax Pentahydrate	Borax Decahydrate	Sodium Pentaborate Decahydrate	Sodium Metaborate Tetrahydrate
LOI (%)	19.0	42.0	37.0	40.0	42.5
EHC ($MJkg^{-1}$)	$5.03x10^{-2}$	$9.54x10^{-2}$	$2.13x10^{-2}$	$2.59x10^{-1}$	1.28
Percent Mass of Penetration by Fabric (%)	2.28	2.63	2.40	2.79	2.74
Time (s) ±0.2	46.1	56.8	51.5	86.1	86.9

Table 6: Processed Data of Each Boron Compound Stated Given with Their LOI, EHC and Percent Mass of Penetration by Fabric in Mean Form

Conclusion

From Table 6, the most optimal compound to be used as a fire-retardant, the LOI value must be high and EHC must be low. This gives that the oxygen needed for combustion is high and that its ability to burn is low. However when looking at **Table 6**, we see that both LOI values and EHC values increase accordingly. For boric acid, the EHC is $5.03x10^{-2}$ and LOI is %19.0, meanwhile for sodium metaborate decahydrate EHC is 1.28 and LOI is %42.5. Because of these results, the time should be the key factor for the result of our experiment. The longer the time that took for the combustion of the fabric is for compounds sodium pentaborate decahydrate and sodium metaborate tetrahydrate with only a 0.8 seconds difference. While the others are below this value with 34.6 seconds difference or higher.

This proves our hypothesis to be partly true, as solubility increases the ability of a boron compounds ability to be a fire retardant also increases. This is because the highest solubility in water at 50.0°C was that of sodium metaborate tetrahydrate but its ability to act as a fire retardant was the greatest not because of its solubility rather it was caused by its oxide layers. When each compounds combustion enthalpy is considered, the highest is that of sodium metaborate tetrahydrate. This means that more energy is released out of 1 mol of this compound when combusted in comparison to others. While more energy may be released during combustion, the percentage of boron being high in its structure may have inhibited the ability for it to burn instantenously and distributed the energy to the entirety of the combustion process, the total time.

As it was discussed before, the most effective compound would have been put through another experiment with varying temperatures (30.0°C, 40.0°C, 50.0°C, 60.0°C, 70.0°C). The result is given below.

7.1 Data Table of EHCs and Percent Mass of Penetration by Fabric for Sodium Metaborate Tetrahydrate for Each Temperature

Mean	30.0°C	40.0°C	50.0°C	60.0°C	70.0°C
EHC (MJ/kg)	$9.49x10^{-1}$	$7.77x10^{-1}$	$9.59x10^{-1}$	$9.61x10^{-1}$	2.17
Percent Mass of Penetration by Fabric (%)	1.96	1.60	1.98	1.98	4.48
Time (s) ±1	38.8	52.8	64.3	101.2	100.1

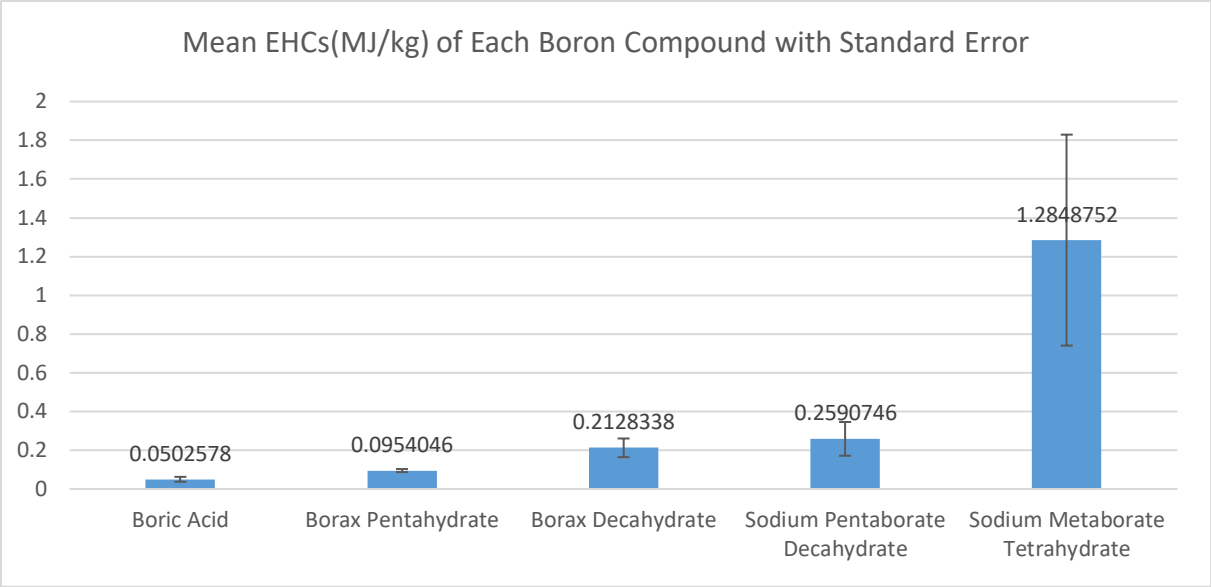
Table 7: Mean Data of EHCs and Percent Mass of Penetration by Fabric for Sodium Metaborate Tetrahydrate in Each Temperature Sample

The LOI was not given on the table as it should be constant for each sample because the same compound, sodium metaborate tetrahydrate, was used. The mass of penetrations of 30.0°C, 50.0°C, 60.0°C are near same. Other than that, 40.0°C has a lower mass of penetration meanwhile 70.0°C has a much higher mass of penetration. The same issue for EHC and LOI values both increasing is present. However, the results can again be achieved by looking at their time values which shows the most as 60.0℃ with 1.1 seconds longer than the second longest 70.0℃ with 100.1 seconds. The results of the main and side experiment both have the same issue with them. This reoccuring problem may be explained by the errors in our experiment.

Evaluation

Overall the experiment was a success for understanding and differentiating each boron compound and find the most suitable for fire-retardant purposes, sodium metaborate tetrahydrate. This result was expected in the hypothesis section. Although solubility is a small factor for these results, the main affector was the boron content. Sodium metaborate tetrahydrate ($NaBO_2•4H_2O$) has more boron in its structure than sodium pentaborate decahydrate ($NaB_5O_8•10H_2O$) in terms of percentage. Another factor may be that it also has less water molecules which increase the inhibition of fire. For further exploration sodium metaborate tetrahydrate has higher thermal stability meaning it is more effective at higher temperature than other boron compounds.

During the experiment, some uncertainty values have been obtained due to various reasons. One uncertainty that can be evaluated further is for the mean EHC of the main experiment:



Graph 1: Mean EHC of Each Compound wih Their Standard Error

Looking at this graph, the reliability for borax pentahydrate is the highest as error bar is the smallest for this value in terms of percentage. However the longest error bar is for sodium metaborate tetrahydrate. Each compound has a slight increase in its uncertainty except sodium metaborate tetrahydrate. These are rather small uncertainties in comparison to the actual values, however knowing that our EHC values were not expected, this uncertainty proves that they are at the very least near the actual values. Also by looking at the uncertainties for the side experiment we can see that they are also within the desired range again proving that the results are not derived much. Nevertheless, these uncertainties could've been decreased for future experimentations so as to reach the actual value by managing systematic and human-made errors.

Some human-made errors that could've been observed in this experiment. The stopping of the timer, the volume of water and the weights of both the fabric and boron compounds being wrongly calculated are some examples. These could've been neglected by using more precise equipment. Other ways an error could've occurred was from the system itself. The fire may have rode up the fabric as each trial cannot be made using the same angle, the water may have not fully dissolved the boron compound even with waiting for an appropriate time, as well as each machinery used may had some problem with it that gave off wrong data. There may also be inaccuracies caused by not perfectly handling the controlled variables. None of these can be fully controlled but their effects can be decreased. There were many attempts to do this and they were successful however none of them can be fully controlled and identified which harms the reliabity of the experiment.

While this methodology could be a good way to draft the approximate values for each compound, it still has some weaknesses. The biggest example to give is the correlation between LOI and EHC values. This was a continuing question in the experiment as in both the main and side experiment this was clearly observed. This may again be because of unkown abilities of the boron compounds or because the ability of the naturally occurring oxide layers to inihibit the fire. Even though the second is the more probable, either way this is a big problem in the conducted experiment and can to be indentified with a more precise methodology like using a bomb calorimeter or doing the experiment in a more suitable laboratory. Another effective

method would be to use a more mechanical one, like some types of doping. These would decrease the human-made error as well as increase the reliability of the results. Both were considered however were not done because the experiment would be expensive and exceed the budget of an experiment done at high school levels as it would need more equipments and more samples of the boron compounds.

The results from this experiment can be used to understand which compounds to cover or apply similarly on fabrics. This could be made so that for firefighters or any other fire related occupations could use these sorts of fabrics to delay the fire from spreading so as to obtain more time to have for safety. While there are some other ways to create fire resistant fabrics, this is another method to actually reach the same result and it may actually be more economical than most methodologies with small scale burning the material and also if made efficient with more people can be also very good for time-management.

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Appendix

Chemical and Physical nature of independent variable- structure of the compound used

2.1 Boric Acid($B(OH)_3$)

Boric acid has a molar mass of 61.83 $gmol^{-1}$. It is the most known compound form of boron and can even be easily made at home by mixing borax or colemanite borate mineral with any mineral acid, sulfuric acid(H_2SO_4) and hydrochloric acid(HCl). While it is given as H_3BO_3 in most researches, this resembles that boric acid acts like phosphoric acid(H_3PO_4) which is a Brönsted acid and therefore $B(OH)_3$ shows the molecular structure more clearly. It can also be named as ortoboric acid and is found as “sassolite” mineral in the nature. It is mainly used as fireproofing agents for wooden and glass structures as well as making fireproof paint[2]. Boric acid has a solibility of 10.27% in water at 50°C[3].

$$2B(OH)_3 \xrightarrow[-2H_2O]{} 2HBO_3 \xrightarrow[-H_2O]{} B_2O_3$$

Boric acid, by losing the hydrate water molecules bonded to its structure depending on the temperature can turn into metaboric acid and boron trioxide respectively.

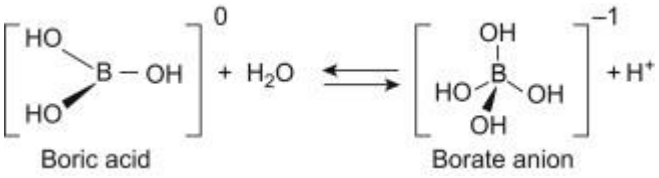


Figure 1: The Dissolution Reaction of Boric Acid

While dissolving in water, boric acid dissolves by forming hydrogen bonds with water molecules. These hydrogen bonds cause boric acid to dissociate into H^+ and $[B(OH)_4]^-$ ions. This is also dependent on the acidicity, pH, and the concentration of the solution. As boric acid is a very weak acid, at low concentrations it may not fully dissociate and may not produce the given ions. Instead it dissociates into H_2BO_3 and H^+ ions and no further dissociation is observed. The combustion reaction of boric acid is given below:

2.2 Borax Pentahydrate($Na_2B_4O_7 \cdot 5H_2O$)

Borax pentahydrate, also known as tincalconite, is a salt used in the cleaning sector as well as a buffer solution. Its molar mass is 291.3 $gmol^{-1}$. It has a solubility of 14.85% at 50.0°C.

$$Na_2B_4O_7 \bullet 10H_2O \underset{5H_2O}{\longleftrightarrow} Na_2B_4O_7 \bullet 5H_2O$$

It is formed according to this equation, by dehumidifying tincal ($Na_2B_4O_7$•$10H_2O$) or putting newly synthesized borax decahydrate crystals in 50℃ and then again in room temperature.

$$\mathrm{Na_2B_4O_7 \bullet 5H_2O}_{(s)} + H_2O_{(l)} \rightarrow \mathrm{2Na^+}_{(aq)} + \mathrm{[B_4O_7]^{-2}}_{(aq)} + \mathrm{5H_2O}_{(l)}$$

Borax pentahydrate dissociates into sodium and borate ions that become surrounded by water molecules, which form a hydration shell around each ion. These shells help stabilize the ions and prevents them from returning back into solid salt form. Adding acid to the solution will react with borate ions and form boric acid which will reduce the solubility of borax.

2.3 Borax Decahydrate($Na_2B_4O_7$•$10H_2O$)

Borax decahydrate, also known as sodium borate decahydrate or tincal, is a salt used in the cleaning and cosmetic sector. Has a molar mass of 381.4 $gmol^{-1}$. If it is put in phosporus pentoxide or sulfuric acid without any applications at 50.0℃, it transforms into amorphous borax which then returns back into borax decahydrate form after contacting water. It is formed by purifying tincal just like borax pentahydrate. The similarities between two compounds can be seen clearly as the only difference is the existence of 5 more water molecules. Has a solubility of 8.78% at 50.0°C[3].

$$\mathrm{Na_2B_4O_7 \bullet 10H_2O}_{(s)} + H_2O_{(l)} \rightarrow \mathrm{2Na}_{(aq)} + \mathrm{[B_4O_7]^{-2}}_{(aq)} + \mathrm{10H_2O}_{(l)}$$

As it can be seen clearly, the same reaction with borax pentahydrate occurs. The same principles of water molecules protecting the ions and boric acid formation also apply to this reaction.

2.4 Sodium pentaborate decahydrate(NaB_5O_8•$10H_2O$)

It has %21.72 solubility in water at 50.0°C[3] and molar mass of 385.2 $gmol^{-1}$. Looking at its molecular formula, the compound has the presence of 10 water molecules which is the most found in the given compounds with the other being borax decahydrate. It is used as a pesticide and again in the cleaning industry.

$$\mathrm{NaB_5O_8 \bullet 10H_2O}_{(s)} + \mathrm{4H_2O}_{(l)} \rightarrow \mathrm{Na^+}_{(aq)} + \mathrm{B(OH)_4^-}_{(aq)} + \mathrm{5[H_2BO_3]^-}_{(aq)}$$

The crystals of sodium pentaborate decahydrate contain ionic bonds between Na^+ and $(B_5O_8)^{-2}$ ions. While the formula is given as NaB_5O_8•$10H_2O$, the water molecules are actually hydroxyl groups covalently attached to boron atoms which may be misleading. The dissolution is given above however the number of moles of water reacted may change accordingy to temperature, pressure and concentration because the degree of hydration of $\mathrm{B(OH)_4^-}_{(aq)}$ depends on these conditions.

2.5 Sodium metaborate tetrahydrate ($NaBO_2$•$4H_2O$)

It is a synthetic boron compound highly demanded for its abilities as a fire retardant.It has a molar mass of 137.86 $gmol^{-4}$. It is highly soluble with most solvents and has a solubility in water at 50°C of %34.10[3]. From its molecular structure and formula, it contains 4 water molecules which is the weakest among all four boron compounds that are hydrated. It also has

a single boron atom in its molecule. For this fact its molecule size is very small in comparison to others and therefore has the most solubility at same temperature.

$$NaBO_2 \bullet 4H_2O_{(s)} + 4H_2O_{(l)} \rightarrow Na^+_{(aq)} + BO^-_{2\,(aq)} + 4H_2O_{(l)}$$

A White crystalline compound highly soluble in water dissociating accordingly to the equation. The ionic bonds that hold the crystals together are broken and new ionic bonds are formed between Na^+ and $(BO_2)^-$ and water molecules. From this $(BO_2)^-$ is a weak Lewis base and reacts with water to form boric acid and hydroxide ions:

$$(BO_2)^-_{(aq)} + 4H_2O_{(l)} \rightarrow H_3BO_{3\,(aq)} + OH^-$$

2.6 Hypothesis: The more boron atoms that stick to the fabric cause more delay by their naturally occurring oxide layers preventing the combustion of the cotton satin fabric and this way be a more usefull source for fire retardants. From this, it is predicted that sodium metaborate tetrahydrate will have delay the combustion the most.

	Boric Acid		Borax Pentahydrate	
	EHC ($MJkg^{-1}$)	Mass of penetration (%)	EHC ($MJkg^{-1}$)	Mass of penetration (%)
Mean	0.0502578	2.26	0.0954046	2.628
Variance	0.000800799	1.34425	0.000306227	0.23167
Std. Dev.	0.028298399	1.159417957	0.01749935	0.481321099
Std. Error	0.012655429	0.518507473	0.007825947	0.215253339
%95 conf. Interval	0.024804185	1.016255974	0.015338574	0.421888792

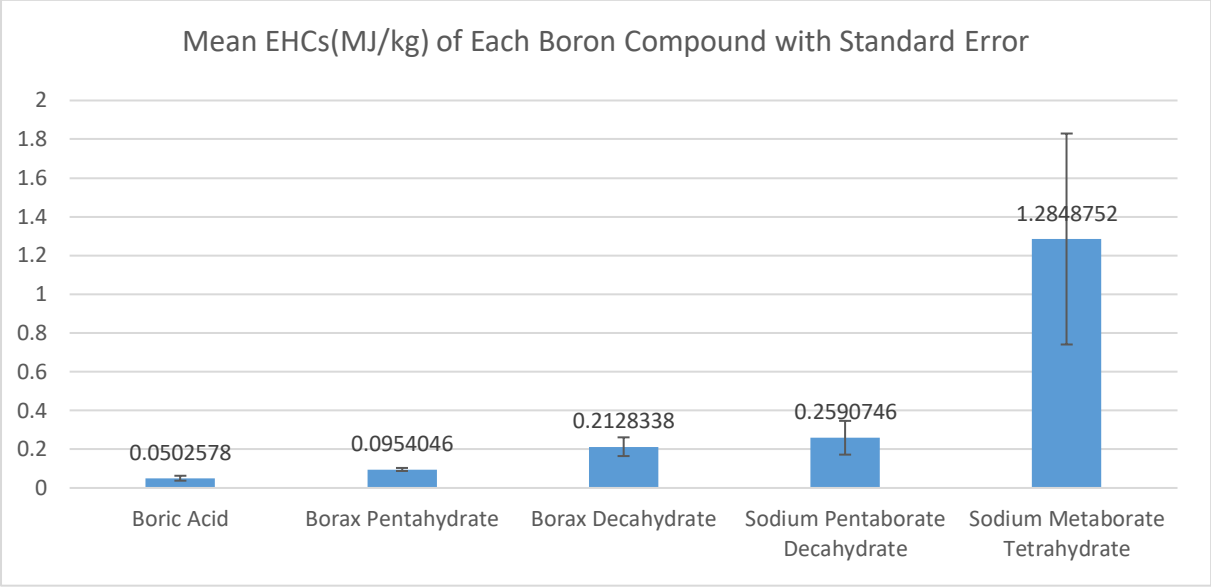
Appendix Table 1: Mean, Variance, Standard Deviation, Standard Error, %95 Confidential Interval of Boric Acid and Borax Pentahydrate-These values are recorded by ignoring the decimal digit numbers

	Borax Decahydrate		Sodium Pentaborate Decahydrate	
	EHC ($MJkg^{-1}$)	Mass of penetration (%)	EHC ($MJkg^{-1}$)	Mass of penetration (%)
Mean	0.2128338	2.398	0.2590746	2.798
Variance	0.011655383	1.48172	0.037955667	4.41997
Std. Dev.	0.107960101	1.217259216	0.194822141	2.102372469
Std. Error	0.048281225	0.544374871	0.08712711	0.940209551
%95 conf. Interval	0.094629462	1.066955141	0.170765998	1.842776858

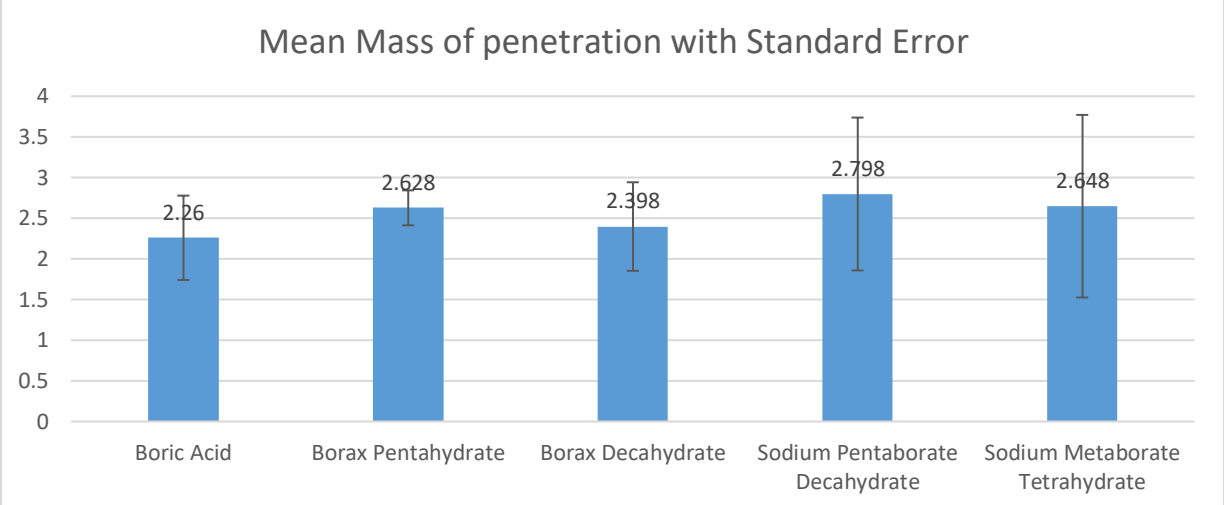
Appendix Table 2: Mean, Variance, Standard Deviation, Standard Error, %95 Confidential Interval of Borax Decahydrate and Sodium Pentaborate Decahydrate

	Sodium Metaborate Tetrahydrate	
	EHC ($MJkg^{-1}$)	Mass of penetration (%)
Mean	1.2848752	2.648
Variance	1.482392012	6.30237
Std. Dev.	1.21753522	2.510452151
Std. Error	0.544498303	1.122708333
%95 conf. Interval	1.067197064	2.200467897

Appendix Table 3: Mean, Variance, Standard Deviation, Standard Error, %95 Confidential Interval of Sodium Metaborate Tetrahydrate



Appendix Graph 1: The Mean EHC of Each Boron Compound with Their Standard Error



Appendix Graph 2: The Mean Mass of penetration of Each Boron Compound with Their Standard Error

	30.0°C		40.0°C	
	EHC ($MJkg^{-1}$)	Mass of penetration (%)	EHC ($MJkg^{-1}$)	Mass of penetration (%)
Mean	0.948744645	1.956001913	0.777206459	1.602346141
Variance	1.07617e-05	4.57427e-05	0.008168522	0.034720291
Std. Dev.	0.003280507	0.006763336	0.090379876	0.186333817
Std. Error	0.002319669	0.004782401	0.063908224	0.131757905
%95 conf. Interval	0.004546468	0.009373333	0.125257816	0.258240749

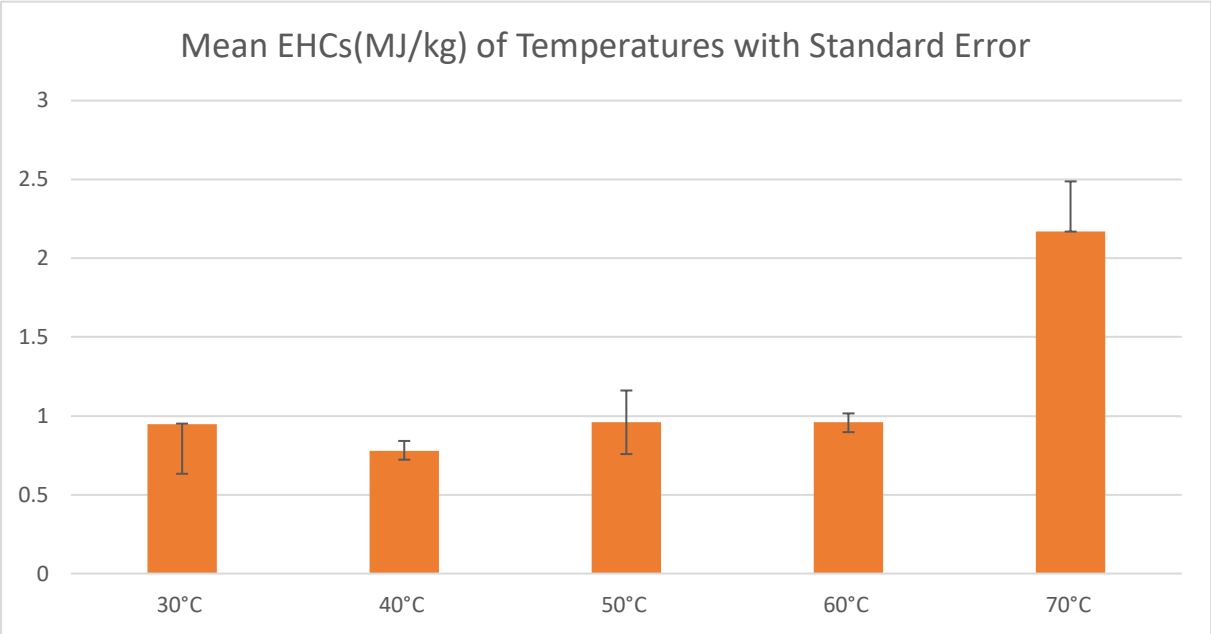
Appendix Table 4: Mean, Variance, Standard Deviation, Standard Error, %95 Confidential Interval of Sodium Metaborate Tetrahydrate in 30°C and 40°C

	50.0°C		60.0°C	
	EHC ($MJkg^{-1}$)	Mass of penetration (%)	EHC ($MJkg^{-1}$)	Mass of penetration (%)
Mean	0.959443039	1.978058511	0.9606045	1.980453752
Variance	0.081255821	0.345377752	0.006092203	0.025895002
Std. Dev.	0.285054067	0.587688482	0.078052568	0.16091924
Std. Error	0.201563664	0.415558511	0.0551915	0.113787086
%95 conf. Interval	0.395057521	0.814479714	0.108173352	0.22301859

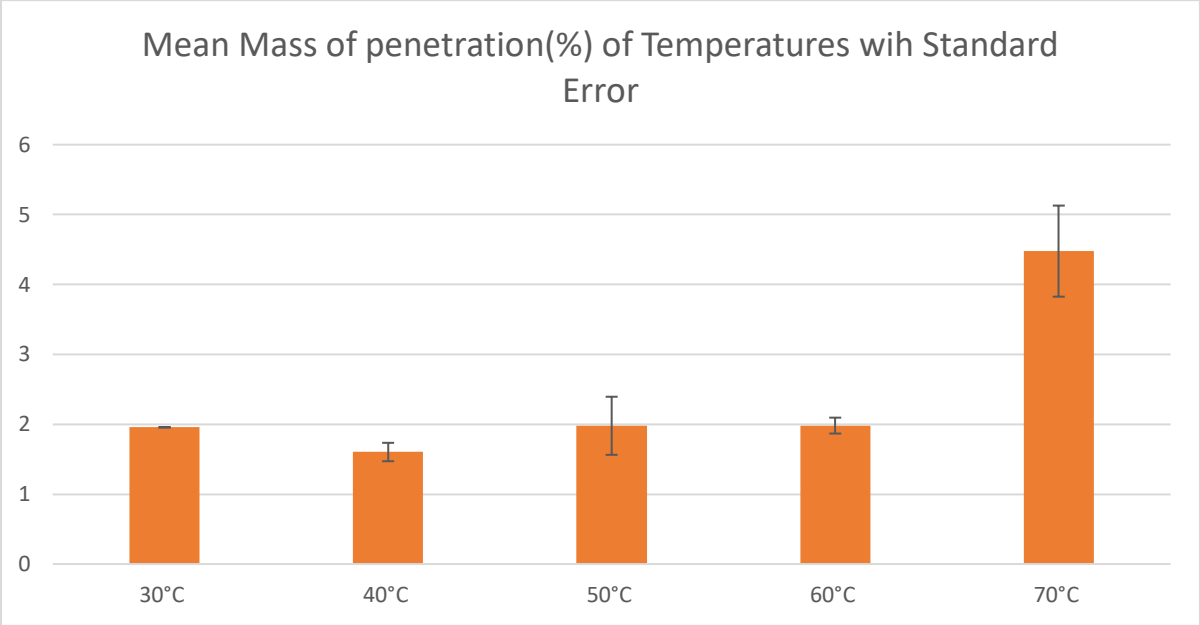
Appendix Table 5: Mean, Variance, Standard Deviation, Standard Error, %95 Confidential Interval of Sodium Metaborate Tetrahydrate in 50°C and 60°C

	70.0°C	
	EHC ($MJkg^{-1}$)	Mass of penetration (%)
Mean	2.1714	4.47667087
Variance	0.199712	0.848993779
Std. Dev.	0.446891486	0.921408584
Std. Error	0.316	0.651534258
%95 conf. Interval	0.619348619	1.276983681

Appendix Table 6: Mean, Variance, Standard Deviation, Standard Error, %95 Confidential Interval of Sodium Metaborate Tetrahydrate in 30°C



Appendix Graph 3: The Mean EHC of Each Temperature with Their Standard Error



Appendix Graph 4: The Mean Mass of penetration of Each Temperature with Their Standard Error

Error Calculations were made by using Microsoft Excel[7]. The standard error gives the "±" error value of each sample.