BTEC: Mechatronics

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Thermodynamics

Combustion and sustainability of fuels that are used to produce work in mechanical systems

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Report aim

The main aim of the following report is to discuss the sustainability of two different fuels, one of which being solid while the other is liquid, with said solid and liquid fuels being coal and petrol. The comparison is going to be done by testing both fuels using calorimetry with the use of the Thompson calorimeter in order to calculate their individual calorific value. As such, the report is also going to discuss what calorimetry itself is, its uses, and its major parameters. After the results have been acquire, reasoning behind the differences found during the experiment is going be discussed by analyzing the major differences in both fuels and concluding rational reasoning as to why said differences might have occurred while additionally discussing potential sustainability issues with either fuel and its relation to varying industries, which is going to be done in terms of the hazards that both fuel pose onto the environment as well as fuel's current commodity prices. Moreover, potential substitutes for the stated fuels are suggested and how they might be more efficient for the industry.

Contents table

Calorimetry

Calorimetry and the calorific values

From a definition standpoint, calorimetry refers to the measure of change in enthalpy and overall heat transfer in a set quantity of a certain material as to identify said material's combustion efficiency by providing the material's calorific value, which is a constant value given for each material utilized and is measured in Kilojoules per kilogram, which indicates the amount of thermal energy that one kilogram of a given fuel can provide. The calorific value can also be given in two different manners, the net calorific value (NCV) or the Gross calorific value (GCV), with the difference between the two – as stated by (Madhu, 2021) *– being that the NCV to calorific value until the evaporation process ends, while GCV additionally includes the duration when the evaporated water condenses back into liquid form. This also means that the GCV is always slightly higher than that of the NCV since water releases thermal energy during the condensation process according to* (Means, 2019).

The combustion process

The combustion process is the one utilized in emitting energy from fuels and finding out their calorific values. Overall, the process constitutes of heat being applied to the stated fuel while being in the presence of a sufficient quantity of oxygen to release thermal energy, with oxygen being a critical component due to the reaction itself being a process of oxygen reacting with the fuel in the presence of heat adequate to reach the fuel's burning temperature.

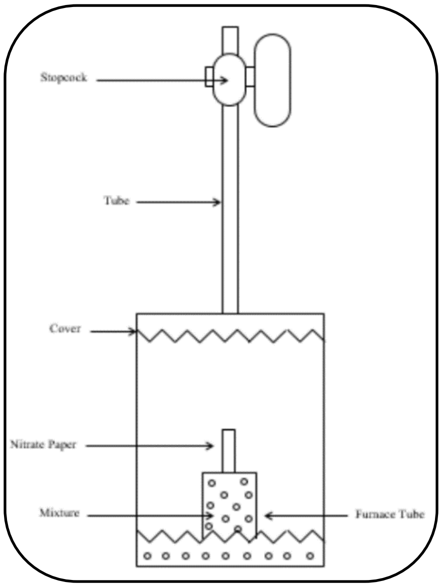
Uses of calorimetry

The most prominent use of calorimetry is to determine the calorific values of fuels, which is the case since said values are utilized on a daily basis in order to determine the optimal fuel for a given process. Additionally, calorimetry is also seen in nutrition as by using a given food as the fuel source for the calorimetry process, the number of calories that said fuel contains can be determined, which assists in calculating the calory consumption of a person.

The calorimeter

What is a calorimeter?

A calorimeter is the apparatus used in calorimetry to measure the calorific value of a given material or fuel, it's a container in which a combustible mixture is placed and combusted to transfer thermal energy to a body of a water, with a thermometer being used to record the change in temperature of said water caused by the combustion of the fuel required for analysis. The overall system has heavily isolated boundaries in order to prevent potential heat loss which would lead to inaccurate calculations. From a thermodynamic perspective, the process occurring within the calorimeter is isochoric as its boundaries do not increase in size, additionally, the system itself is closed, in that it does not allow for any matter to flow through its boundaries, but rather it does allow for the flow of energy – specifically heat energy – by transferring heat to the thermometer. Although there are a variety of different calorimeters from the bomb or coffee cup calorimeter, with the difference between each lying in the way heat is transferred to the water body, however, the one currently available in possession is the ***Thompson calorimeter****, and therefore, it is the one that is going to be analyzed.*



Stopcock	*A valve utilized in order to restrict or block the flow of either liquid or gas, used in preventing the mixture from escaping.*
Tube	*A tube from which mixtures could be added or released depending on the requirements of the process.*
Cover	*The cover is simply utilized to open the calorimeter to either add or clear remains before the main reaction takes place.*
Nitrate paper	*Acts as a timed fuse utilized in starting up the initial combustion of the mixture.*
Furnace tube	*The furnace tube is the container in which the mixture is going to be placed in.*

Experiments

Experiment aim

The main reason the following experiments are going to be done is to compare the results provided from them for analysis between liquid and solid-based fuels, with said analysis assisting in backing up and determining possible reasons as to why a difference in terms of the calorific value and overall efficiency might be seen between the two which would in consequence assist in ascertaining which fuel type would be most suitable while considering environmental drawbacks. The fuels that are going to be utilized for the stated analysis are going to be ***coal*** *and* ***petrol*** *as they deemed to be the most prominent solid and liquid fuel sources utilized nowadays in the industry*

Experiment procedure

Procedure

The process in which the Thompson calorimeter operates is the following: Initially, water at a volume of 2000ml is placed within a measuring cylinder, after which, both the mass of the water to be used and of the fuel is measured while also measuring the initial water temperature, after which, the given quantity of water is placed within a measuring cylinder, thenceforth the fuel is sealed withing the furnace tube while additionally packing nitrate paper that is in contact with the mixture. From there, a thermometer is placed in the measuring cylinder, the stated nitrate paper is lit, and the Thompson calorimeter is placed within the measuring cylinder filled with the body of water while a stop watch is immediately started. Onwards from the stated point, the temperature is measured every second or so until the water stops emitting bubbles, indicating the combustion process has concluded and that the temperature is going to decrease. From there, the calorimeter is moved upwards and downwards to stir the water body, which provides accurate calculation by ensuring heat is not concentrated in one area, which is done while continuously measuring the temperature of the water until the information received is deemed to be sufficient. It should also be noted that the Thompson calorimeter is made out of 300 grams of copper in order to ensure optimal heat conductivity. After the stated procedure is done, enough parameters have been acquired and the following equation is used to calculating the calorific value:

$$C = \frac{m_w \times C_w \times (\theta_{max} - \theta_{min}) + m_{Cu} \times C_{Cu} \times (\theta_{max} - \theta_{min})}{m_{fuel}}$$

Apparatus

- *Thermometer*
- *Stopwatch*
- *Nitrate paper*
- *2000ml of water*
- *Fuel*
- *Thompson calorimeter*

Health and safety precautions

Safety practices

Safety practices should be maintained and applied by every individual working on the experiment or in nearby proximity of it while its occurring. The main issues that should be noted are for all students to maintain appropriate distance from each other, avoid running at all within the lab, for people uninvolved with the ongoing experiment to stay away and not disturb the ones currently taking measurements, slowly move the calorimeter when stirring as to avoid potential spillage of hot water, make sure to not fill the measuring cylinder all the way to the top as the water would flow over when heated, and finally, make sure to check the temperature of the water before physically touching it, and finally, ensure the workspace is cleansed after the experiment has concluded.

PPE

PPE (full form for personal protective equipment) is an essential aspect that should not be taken lightly. The main areas of the body that are placed at risk during the experiment are the hands, arms, and eyes due to the possibly eruption of boiling water. As such, the major protective equipment that should be worn by individuals doing the experiment are the following: Safety goggles, heat-resistant gloves, and long-sleeved outfits.

Figure 1Required PPE for the experiment

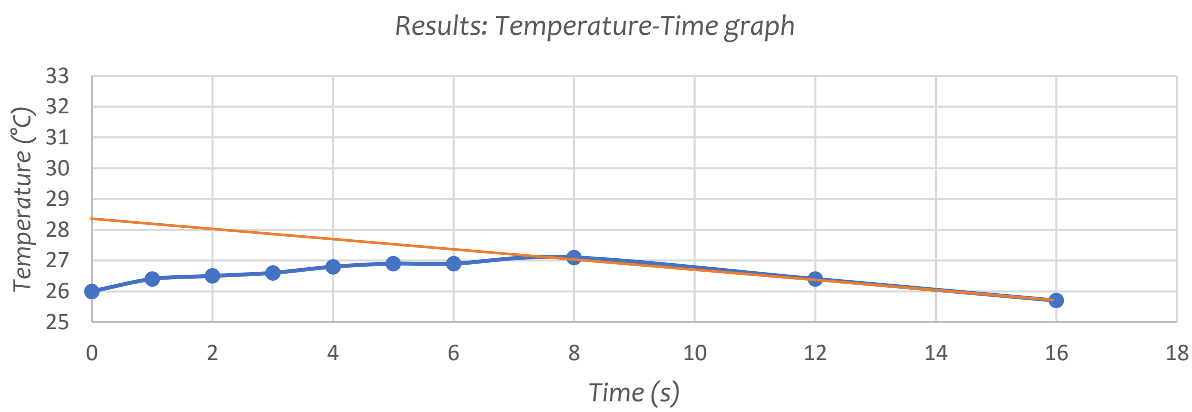
Emergency practices

An important note that both the supervisor and individuals working within the lab should keep in mind is how they are going to react if an emergency were to occur. A major aspects that should be noted is a fire occurrences, as such, students should keep a fire extinguisher near by and be able to know how to use it in the case that an error occurred which resulted in a fire, additionally students should also have an idea of where all the emergency exists are in the case that the fire were to spread rapidly and evacuated was necessary. As well as that, if hot water were to be spilled onto a student that is currently carrying out the experiment, cooling of the burnt area should be done using warm water and emergency services should be dialed if necessary.

Solid fuel results and calculations – Coal

Prerequisites

Before using the coal for the actual experiment, certain prerequisites would have to be met. Initially, 2 grams of coal would have to be provided, pounded until the available coal has turned into a powder. After which, the powdered coal is going to be mixed with potassium nitrate and potassium chlorate, which both assist in the burning process by creating an explosion which would occur when the mixture initially starts to burn. Additionally, due to coal's air to carbon ratio being 11.5:1 and coal constituting of approximately 70% carbon, meaning around 1.4 grams of the 2 grams of coal is actually made from carbon, and therefore 16.1 grams of air would be needed for complete combustion.



Known values

$m_{calorimeter}$ = 300g m_{coal} = 2g V_{water} = 2000ml $C_{water} = 4200\frac{J}{kg{\cdot}K}$ $C_{copper} = 385\frac{J}{kg{\cdot}K}$

θ_{min} = 26°C θ_{exp} = 27.1°C θ_{cal} = 28.5°C

Calculations:

Calculating Θ_{max}:

$$\theta_{max} = \frac{\theta_{exp} + \theta_{cal}}{2}$$ → Middlepoint between maximum temperature from the thermometer and the calorific temperature

$$\theta_{max} = \frac{27.1 + 28.5}{2}$$

$$\boxed{\theta_{max} = 27.8°C}$$

Calculating the calorific value:

$$C = \frac{m_W \times C_W \times (\theta_{max} - \theta_{min}) + m_{Cu} \times C_{Cu} \times (\theta_{max} - \theta_{min})}{m_{fuel}}$$

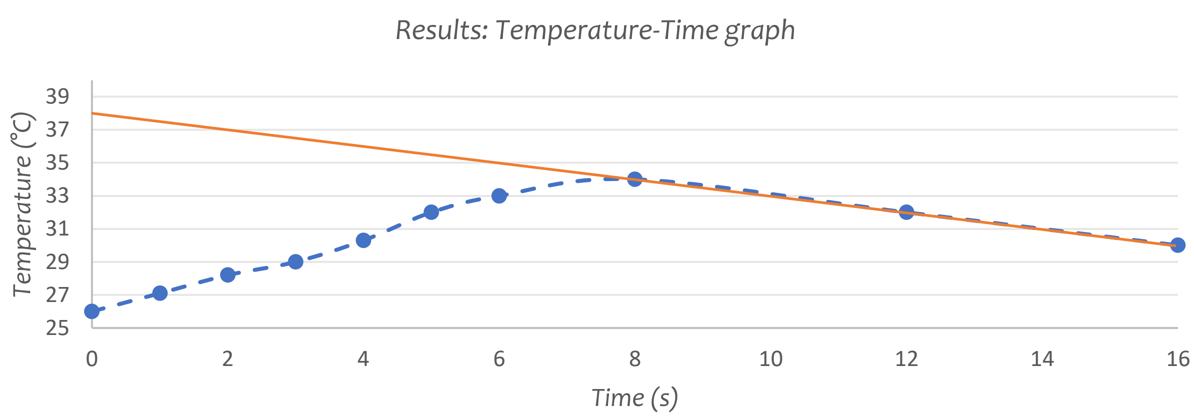
$$C = \frac{2 \times 4200 \times (27.8 - 26) + (300 \div 1000) \times 385 \times (27.8 - 26)}{2 \div 1000}$$ → Substitue values, also, 1kg of water = 1000ml

$$\boxed{C = 7663950\frac{J}{kg} \textbf{ or } 7663.95\frac{kJ}{kg}}$$

Liquid fuel results and calculations – Petrol

Prerequisites

Unlike coal, there aren't steps that have to be followed in order to prepare the liquid for the following experiment. As such, the only prerequisite is to simply have 2 grams of petrol to match the quantity that was utilized for the coal's experiment. Due to petrol's fuel to air ratio being 14.7:1, around 29.4 grams of air would be required to ensure proper combustion of the 2 grams of petrol.



Known values

m$_{Calorimeter}$ = 300g **m**$_{petrol}$ = 2g **V**$_{water}$ = 2000ml **C**$_{water}$ = $4200\frac{\mathrm{J}}{\mathrm{kg{\cdot}K}}$ **C**$_{copper}$ = $385\frac{\mathrm{J}}{\mathrm{kg{\cdot}K}}$

θ$_{min}$ = 26°C **θ**$_{exp}$ = 34°C **θ**$_{cal}$ = 38°C

Calculations:

Calculating Θ_{max}:

$$\theta_{max} = \frac{\theta_{exp} + \theta_{cal}}{2} \rightarrow \text{Middlepoint between maximum temperature from the thermometer and the calorific temperature}$$

$$\theta_{max} = \frac{34 + 38}{2}$$

$$\boxed{\theta_{max} = 36°C}$$

Calculating the calorific value:

$$C = \frac{m_w \times C_w \times (\theta_{max} - \theta_{min}) + m_{Cu} \times C_{Cu} \times (\theta_{max} - \theta_{min})}{m_{fuel}}$$

$$C = \frac{2 \times 4200 \times (36 - 26) + (300 \div 1000) \times 385 \times (36 - 26)}{2 \div 1000} \rightarrow \text{Substitue values, also, 1kg of water} = 1000\text{ml}$$

$$\boxed{C = 42577500\frac{\mathrm{J}}{\mathrm{kg}} \textbf{ or } 42577.5\frac{\mathrm{kJ}}{\mathrm{kg}}}$$

Discussions

Overall results

The main idea that can be taken from the provided results is that petrol has a much greater calorific value in comparison to that of coal, with more energy being able to be extracted from petrol even when the same quantity of coal was utilized. With petrol providing a calorific value of 42577.5kJ/kg, while coal was only able to provide 7663.95kJ/kg, which is approximately a 555% decrease in comparison to petrol.

Potential reasons for inefficiencies

Fuel impurities

A major point that should be taken into account is the quantity and overall percentage of incombustible matter found within the analyzed fuels. In terms of coal, although a large percentage of it is made out of carbon, around 50% of its mass is made on non-organic/non-carbonaceous material as mentioned by (USGS, 2022), which is the percentage of the material that is combustible. This can be additionally backed by the amount of ash was formed where the coal was initially burnt, with said ash being the product of burning the stated non-carbonaceous portion of coal. Therefore, this means that although two grams of coal were utilized, only around 1 gram of which was actually useful in emitting thermal energy. The stated lack of combustible material is just seen in coal specifically, but rather it can prominently noticed in all forms of solid-based fuels, which is the case due to the likelihood of them containing incombustible material being higher than that of liquid based material as fuels such as petrol since liquid purification is able to remove almost 100% of impurities in comparison to coal washing, which removes approximately 45 percent as stated by (Jai, 2020). On the other hand, liquid-based fuels contain very little to no incombustible material, and therefore most of the energy that goes into burning said fuels is thenceforth outputted as thermal energy, which is a major reason as to why petrol's calorific value was higher in comparison that of coal's.

Incomplete combustion

Incomplete combustion refers to when a given fuel is burnt during a lack of oxygen surrounding the combustion system, that is the case since oxygen is a major ingredient in combustion reactions. Although the fuel would nonetheless combust during incomplete combustion, the lack of oxygen means that the amount of oxygen particles would not be sufficient in order for them to complete perform a combustion reaction with each individual particle of the reactants, and therefore a portion of the fuel would go unutilized, consequently decreasing the amount of thermal energy that is going to be produced. In terms of how this can affect the analyzed fuels can be seen when looking at their individual air to fuel ratio, which is the ratio which determines the amount of air that is theoretically required in order to perform a complete combustion of the utilized fuel. A study done by (Liu, et al., 2020) has concluded that the fuel to air ratio of carbon is around 11.5:1, meaning that 11.5 grams of air are required in order to burn 1 gram of carbon seen within coal, while for petrol, the fuel to air ratio is around 14.7:1 in accordance to (CarParts, 2022), meaning that petrol actually requires more oxygen to burn than coal, meaning it is more likely for it to go through incomplete combustion if the environment was air-tight, however, the amount of fuel utilized in both processes is only 2 grams, meaning it is almost certain that incomplete combustion would not occur.

Relationship

As stated, the fuel to air ratio that is provided for both fuels is a theoretical value for how much air would be necessary in order for complete combustion of fuel to occur. However, even though petrol has a higher air requirements, coal is still more susceptible to having incomplete combustion. That is this due to the material impurities restricting the carbonaceous elements from instantly reacting with coal since oxygen molecules would could potentially react with said elements or take longer to reach the combustible material since the incombustible elements might be enclosing the organic elements,

Sustainability

Environmental harm

A major aspect that is generally associated and taken into consideration with fossil fuels – especially in recent times – is their implication on the overall health of the environment and their major contribution to the constantly increasing global warming crisis. With the main emissions that are taken into account being carbon dioxide, monoxide, and sulfur dioxide.

Coal	*Petrol*
In terms of carbon dioxide emissions, coal produces around 2.42kg of carbon dioxide per one kilogram of coal that is burnt as mentioned by (360 Energy, 2020)*, which is a relatively average amount, however, other issues that make burnt coal emissions dangerous is the emissions of sulfur, which – in accordance to* (Winterbone & Turan, 2015) *– emits much more sulfuric acid in comparison to that of natural gasses, therefore contributing to acid rain. Additionally, the leftover ash from burning the incombustible elements found within coal is generally disposed off by coal powered power plants, and they do so by throwing the stated ash it into waterways, consequently harming wildlife and contributing the water pollution.*	*When it comes, petrol is relatively similar to that of coal with emission of around 2.3kg of carbon dioxide per kilogram of petrol according to* (Natural Resources Canada, 2014)*, which is still bad as it is merely 5% smaller in terms of emission. However, while still contributing to the emission of sulfur into the atmosphere, petrol produces less sulfur in comparison to that of coal by a significant amount as mentioned by the* (Energy Information Administration, 2018)*. It should also be noted that unlike coal, petrol is burns and evaporates entirely, meaning the disposal of leftover waste from utilized petrol should not be an issue that power plants which utilize the fuel should worry about, therefore decreasing possible environmental harm from waste.*

Cost

Although the environmental impacts fuels are very significant point when it comes to the sustainability of fuels and the ability to continuously utilize them in the coming future, the cost at which said fuels are acquired and sold is also relatively important from both the industry's and consumer's standpoint, and instability of such a point is nevertheless a major drawback to the overall sustainability of the fuel. In terms of the price of both provided fuels, coal is undoubtedly cheaper in comparison to petrol due to its abundance and the overall process of obtaining it being relatively easier as mentioned by (Metcalfe, 2019)*. This point is further backed by current commodity market, showing petrol prices at around 3.45USD per liter while coal is around 325USD per ton as of April 28th, 2022. When the stated quantity of petrol is converted to reflect the amount of gallons equal to 1 ton of petrol, it comes to around 325, from there it can be deduced that petrol is priced at around 1121USD per ton of petrol by multiplying 345 with the current USD/gallon with the gallons that make up one ton of petrol. The stated price of petrol is around 345% higher than that of coal for the same amount of fuel, therefore making it petrol a much harder fuel to sustain in terms of expenditures.*

Coal prices over the last year (USD/Ton)	***Petrol prices over the last year (USD/Gallon)***
 Figure 2 Coal commodity prices graph (April 28th, 2022)	 Figure 3 Petrol commodity prices graph (April 28th, 2022)

Potential substitutes

Biodiesel

Biodiesel is one of the major biofuels currently utilized in the market. The fuel constitutes of many natural and organic components such as vegetables oils, yellow grease, used cooking oils, or animal fat as stated by the (U.S Department of Energy, 2022)*, making it a cheaper alternative to the analyzed fuels as mentioned by* (Kotrba, 2021)*and possess a gross calorific value of biodiesel is around 37.27 MJ/kg according to* (Elsayed, Matthews, & Mortimer, 2003)*. Although the fuels components are clean, burning biodiesel emits CO2 nonetheless, however, said CO2 emissions are absorbed feedstock seen within biodiesel as in accordance to* (Energy Information Administration, 2020)*by the , and therefore risk of polluting the environment is minimal if biodiesel were to be used, however, this also poses a significant issue with the fuel, in that if it were to produce in quantities similar to that of petrol, potential risk of damaging food supplies is being ran on the report of* (Hill, Nelson, & Tilman, 2006)*, therefore restricting the fuel from being used in major power plants and notably limiting it to relatively small operations.*

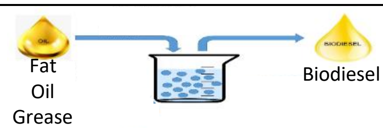


Figure 4 Biodiesel's components

Hydrogen

Hydrogen as a fuel source can be utilized in a variety of ways, two of which being hydrogen utilized as a combustion agent and hydrogen being used as a reactant to be utilized within power cells. The difference between the two being that in the first example, hydrogen is combusted in the presence of oxygen, just as petrol or coal is, while the second is an electrochemical reaction between hydrogen and oxygen which converts chemical energy to electrical as well as slight amount of heat. There are two major advantages related to using hydrogen as a fuel alternative, the first being the fact that hydrogen possesses the highest known calorific value of at around 120-142 MJ/kg according to (World Nuclear, 2022)*, with the second being that the byproducts of combusting hydrogen are heat and water only as stated by* (Argonne National Labratory, 2016)*, making it an environmentally friendly fuel source. However, the major drawback of hydrogen stems from its price, while although the gas itself might be cheaper, the logistics of transporting and storing hydrogen and its overall production makes it more expensive according to* (Barnard, 2021)*.*

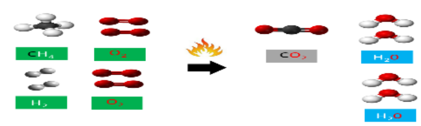


Figure 5 Hydrogen combustion emissions

Nuclear power

Nuclear power generation stems from utilizing a radioactive material, with the one most prominently used being Uranium 235 in order to generate heat. This process is done by extracting neutrons from specific materials during the startup of a nuclear reactor, which are then shot at the Uranium, due to the nature of radioactive elements such as uranium, when this occurs, the Uranium splits into several different lighter elements and shoots neutrons in a process called nuclear fission, when procedure takes place, both radiation and thermal energy are released from element, and therefore providing energy. A significant point that should be made about nuclear power is that it does not produce any negative emissions to the atmosphere, however, the nuclear element utilized as the core does have to be entirely replaced in the span of three to six years, and when that does happen, nuclear waste is disposed of in underground repositories as stated by the (World Nuclear Association, 2022) *as nuclear was is incapable of being recycled, and although the manner in which it is disposed is relatively safe there is a chance that it could be harmful if not monitored correctly. The major drawback that prevents nuclear energy from being as prevalent in comparison to petrol or coal is the capital expenditures required in setting up nuclear reactors, however, after a nuclear reactor has been set-up, the maintenance and sustainability costs are relatively much cheaper and more economical in the long term according to the* (World Nuclear Association, 2008)*. In addition, it should be stated that due to the large infrastructure required nuclear energy as well as the risk taken when untrained people handle radioactive material, it would most likely never be utilized in smaller processes such as transportation or individual buildings, but rather be used for more significant power generation, and examples of which – as mentioned by the* (World Nuclear Association, 2021) *– being supplying power for entire cities, desalination, oil refining, synthetic oil production, and more.*

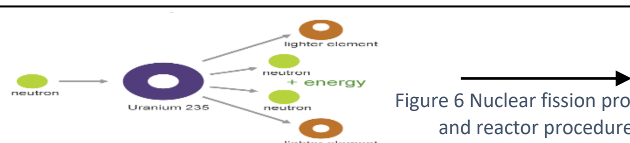
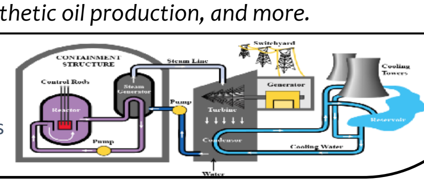


Figure 6 Nuclear fission products and reactor procedure



Resolutions

Conclusions

Out of the two analyzed fuels, it can be clearly noted that petrol is the more efficient one, with its calorific value being significantly higher than that of coal's, with the reasons for its inefficiency stemming from the quantity of incombustible elements found within its constituents, which affects it's performance in two different ways, the first of which being that although a given quantity of coal might be utilized, only a certain fraction of it might be useful for the purpose of generating thermal energy, as the other section is composed of the stated incombustible elements, the other reason for coal's inefficiency is that there is a higher chance of incomplete combustion to occur due to the quantity of air being used to maintain the combustion process potentially not being useful for the stated purpose since the combustible portion of the coal might be enclosed within the non-carbonaceous portion, essentially blocking oxygen from maintaining combustion, therefore potentially causing incomplete combustion and inefficiency as the utilized quantity of air might not react with each individual combustible element.

In addition, petrol is also superior in terms of environmental friendliness since although the overall effects of both fuels in terms of emissions are similar, coal - due to it being a solid fuel - leaves residue after it has been burnt in the form of fly ash, making its overall environmental harm more significant due to inefficient and harmful disposal of the stated residue. However, the major advantage of utilizing coal by the industry is that it is significantly cheaper with its commodity prices by as far as 350% cheaper than that of petrol's for the same quantity in terms of weight, making it far more sustainable when it comes to maintaining operating expenditures.

Verdict

Altogether, it can be concluded that petrol is the better fuel source in comparison to that of coal due to its higher efficiency in providing thermal energy, since although coal is cheaper by a very significant amount, the quantity of coal required in order to produce a set amount of energy would be higher compared to the required quantity of petrol, therefore forcing the user to purchase a higher amount of coal and thus increasing the price, which in consequence also increases capital expenditures for the storing and logistics of the stated higher quantity, which are expenditures that would be less costly if petrol were to be the fuel of choice.

Additionally, the stated characteristics of petrol and coal directly reflect onto how solid and liquid fuels perform, indicating that in general liquid fuels are superior due to them not leaving residues – at least not in solid form – after they have burnt. Additionally, because of the levels of impurities within them being easier to purify and are generally lower, they are able burn quicker, easier, and have a lower chance of going through incomplete combustion.

Overall, even when considering all the advantages that the are provided by either solid of liquid fossil fuels, finding better alternatives that are more environmentally friendly and improving on the ones that are currently being used in the industry such as the ones stated is the path that should be followed going forward in the fuel production industry, as although utilizing fossil fuels might be more economical in the short-term, they significantly worsen the climate change crisis, in addition, some of the stated substitutes considerably better fuels however they are not utilized at an industry changing scale due to the lack of funding and consideration that is being put into at least when compared to that of the funding being put into acquiring and refining fossil fuels.

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"We must trust to nothing but facts: these are presented to us by nature and cannot deceive. We ought, in every instance, to submit our reasoning to the test of experiment, and never to search for truth but by the natural road of experiment and observation."

-Antoine Lavoisier

Inventor of the calorimeter