Current Advances in Heat Loss Modelling of Industrial Boilers

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Abstract

Industrial boilers are especially important mechanical systems that are used for various operations in industry. Their main objective is to heat up water to elevated temperatures to either convert it to steam through the evaporation process which is mostly used in power generation plants or provide elevated temperature water as output to the other parts of buildings or plants such as paint plants in automotive industry companies. Efficiency is a key aspect in boilers due to the high demand in production that they need to fulfil. Through numerous factors, boilers experience heat/energy losses which be monitored and rectified through several ways identified in this paper.

This study focuses on a boiler used at Sasol Synfuels Power Station which uses Pulverized coal as the fuel to fire it up. Dry flue gases, moisture content formation of water from hydrogen, radiation, convection, fly and bottom ash are the factors that contribute to heat losses in boiler and later causes the efficiency of the boiler to decrease. In this scenario, heat losses increase in a period of 5 days of study and causes a decrease in efficiency from of 91.05% to 87.08%. This is determined with the use of data collected and the application of specified formulas. Another leading factor to this efficiency decrease is the increase of the Gross Calorific Value from 14322 KJ/kg and end point of 14279 KJ/kg. To improve the heat losses in this boiler, a feasible reactive maintenance strategy must be chosen and improvements such as using an air preheater is considered because it decreases the flu gas temperature. Gross Calorific value must be increased to attain increasing efficiency.

Keywords
Boiler, heat losses, heat transfer, energy, maintenance, mathematical modeling, dry flue gases, gross calorific value

1. Introduction
The 19th century also known as the period where the industrial revolution brought in with a lot of possibilities in the engineering field which meant that the transition of theoretical scientific ideas would finally come to practice and be used in human beings' everyday lives. A scientific theory of heating water and turning it into steam was now an engineering problem which then led to the design and manufacturing of complex machinery, capable of heating water in a much more efficient way. Boilers are core mechanical components in energy generation systems which release an output of elevated temperature steam to the generator to later produce electrical power (Patro, 2016).

Due to the elevated levels of thermal energy in boilers, combustion efficiency plays a key role in controlling the fuel consumed during operation (Faizal M., 2009). For a specified process that a boiler will undergo, thermal energy facilities are selected for the boiler to operate under enormous weather conditions and under full capacity loads. However seasonal weather changes affect the thermal energy which will be induced in the boiler, which is greatly affected by the excess air ratio unit load and fuel lower heating value varying from90.3% - 92.3% for wide range of above variables (Faizal M., 2009). The calorific value of the fuel used plays a vital role in the efficiency of the boiler. The quality of the fuel used also pays a role in the efficiency which is determined by the amount of ash is contained, i.e. if the fuel contains a lot of ash, the quality becomes low which will required the boiler to use a large furnace for the same amount of work (Patro, 2016).

2. Literature Review
2.1. Types of boilers

Boilers are categorised into the fire tube and water tube units which are then classified by their heat sources. The purpose of these boilers is to convert the chemical energy in fuel into thermal energy that can be used to generate steam or hot water (Elie Tawil P.E. & LEED AP, 2017). Boilers are classified by their type of pressure (high or low) and whether they are hot water or steam boilers. By definition high pressure boilers are steam boilers that operate at a pressure greater than 15 psig and this is due to the increase in pressure which means the increase of both the flue gases and the water temperature, and later causes the heat losses in the boiler to increase (Dukelow, 1991).

There is a combustion chamber inside the boilers which needs to fulfil two processes to generate steam or elevated temperature water. Combustion must occur in a way that oxygen will mix with the fuel used in the specific boiler. From then on, thermal energy is transferred to steam or elevated temperature water by the heated gases during the combustion process.

2.2. Fire Tube Boilers

The first boiler manufactured was the fire tube boiler which was used to power up steam trains and ships, and they constitute the largest share of small to medium sized industrial units (Thompson, 2019). Fire tube boilers have tubes which are arranged in series inside a water-filled outer shell in order to have fluidity of hot combustion gases (Elie Tawil, P.E., LEED AP, 2017). The water inside the tank is heated up by the elevated temperature gases flowing through the tubes as shown on Figure 1. The outer shell of Fire tube boilers is not thick since these types of units are used for applications which have low pressures. Modern day Fire Tube boilers still use the same design as that of the initial boilers whereby spherical pressure vessels were mounted over the fire with flame and hot gases around the boiler shell (Dukelow, 1991). However, this design has come in with improvements which includes pressure vessels which consists of longitudinal tubes which allow flue gases to flow within them. The purpose of this improvement is to increase and have a better heat transfer area which influence the increase of the heat transfer coefficient.

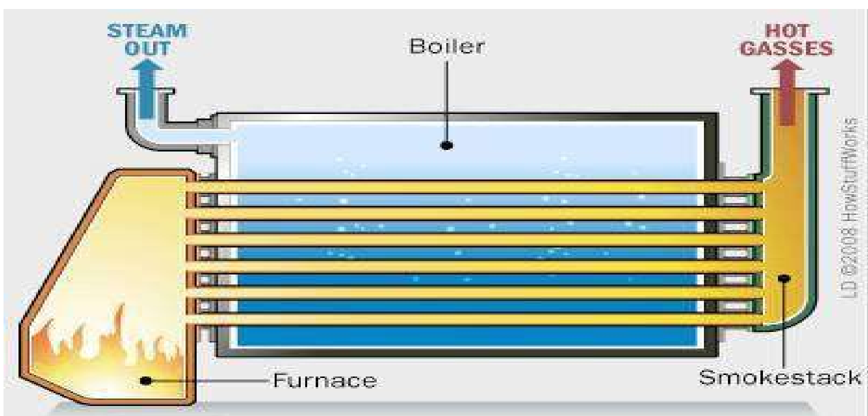

Figure 1. Fire Tube Boiler (Faizal M., 2009)

Fire tube boilers come in with certain advantages about its usability which include its price, its ability to meet the demand of steam which fluctuates and its size (They're very compact). On the other hand, the disadvantages are that the output steam can never reach very high temperatures because water and steam are stored in one vessel, the steam is not very dry and that the steam drum is always under pressure and this might lead to explosions which could cause very severe accidents (Abbas H., 2021). These types of boilers are used in small scale environments.

2.3. Water Tube Boilers

In Water tube boilers, elevated temperature gases flow through the tank which consists of tubes filled with water. The water flowing through these tubes is heated by these elevated temperature gases which converts this water into steam or elevated temperature water and this can be seen on Figure 2. The tubes extend between an upper header, called a steam drum, and one or more lower headers or drums. (Elie Tawil P.E. & LEED AP, 2017). The upper drum is filled with half steam and half water while the lower drum(s) is filled with water.

There sometimes can be a formation of mud sludge due to the boiler gravitates which is drawn off from the lower drum. These types of boilers are easily designed for greater or less volume using the same boiler convection heating surface, water tube boilers are particularly applicable to solid fuel firing. They are also applicable for a full range of sizes and for pressures from 50 psig to 5000 psig (Dukelow, 1991). These types of boilers are used in large power plant where very high-pressure applications occur (Abbas H., 2021; Adoh J.O., 2019).

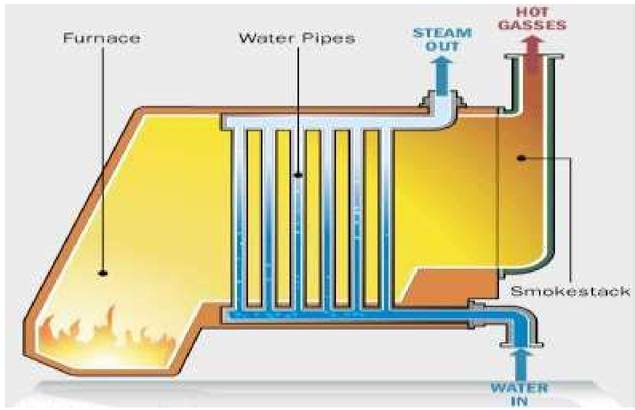

Figure 2. Water Tube Boiler (Faizal M., 2009)

2.4. Boiler operations

Water is the most effective medium in terms of cost and usability when converting/transferring heat during the process of combustion. For this process to take place, water must be heated up/boiled to extremely elevated temperatures which would play a vital role in increasing its volume. When water's volume is increased to above a thousand times, there tends to be an explosive force produced which makes the boiler an extremely dangerous mechanical equipment to be used which should have proper safety measures clearly indicated when using it. Heat can be transfer is a couple of forms which are namely radiation, convection and conduction.

Radiation is the transfer of heat from an elevated temperature body to a low temperature body by means of a conveying medium, but without these bodies' physical being in contact. Convection us the transfer of heat by a certain fluid (air or water), while conduction is transferring heat between bodies of different temperatures through physical contact of those bodies. In the boiler, there's a component known as the heating surface and is known to be any metallic part of the boiler which contributes to evaporation process (The process of making steam). This heating surface plays a vital role in how efficient a boiler can become.

The boiler system comprises of feed water system, steam system and fuel system (Jain, 2012). The first component used is the fuel system since it needs to start up or fire up the boiler so that the heating process of water can take place and for this to take place, the type of fuel (coal, gas, etc.) used is also especially important. The main item in the boiler being water is supplied by means of the feed water system which is an automated process conducted to meet the requirements of steam needed to be produced. During the evaporation process, the stem produced is collected and controlled by the steam system which uses specified pipes to direct this steam to the required output point.

When this steam is flowing, various valves and pressure gauges are used to check and regulate this steam. This whole boiler system comprises of a lot of components, some of the being valves of assorted designs which are used to access the boiler for maintenance purposes. The abovementioned components in the boiler system need to work effectively to produce a highly efficient boiler which has a particularly good evaporation ratio. However, if it happens that the combustion is poor and there are problems with heat transfer, then the efficiency of the boiler reduces and this happens over time and if the maintenance done is poor.

Boiler feedwater must be free from contaminants which can affect the whole operation of the boiler (Sajath, 2020). Firstly, the water used in the boiler must meet certain required standards which are for the boiler's safety and operability purposes. Normal water must be purified to the required standards in processes such as the one remove oxygen and minerals from water. Besides oxygen and minerals, there are other contaminants which should also be removed to achieve high quality water to be used in the boiler. These contaminants are shown on Table 1.

Table 1. Common pollutants in water (Azeem, 2010)

Name	Description
Iron and Manganese	Can exist in water as a dissolved cation but readily precipitates and cause discoloration and fouling
Turbidity	A finely suspended matter which appears as muddy or cloudy which does not settle.
Colour	Generally due to decayed organic matters
Total Suspended Solids - TSS	Exist in water as suspended particles. They can be mineral or organic particles, can be removed by filtration.
Total Dissolved Solids – TDS	There are scale forming and non-scale forming dissolved solids in water. The principal ones are calcium and magnesium carbonates and sulphates which form scales when heated.
Hardness	Calcium and Magnesium salts which are mainly responsible for scale formation.
Alkalinity	Bicarbonate (HCO_3) and Carbonate (CO_3) and Hydroxyl (OH) ions which cause the alkaline situation of the water
Silica	Most detrimental impurity in water. Usually exist in water as an anion or as a colloidal suspension
Dissolved gases	Oxygen and Carbon dioxide which dissolved in water. These gases are the main contributors to corrosion.

The boiler consists of components which are included in the abovementioned sub systems which are namely the burner, economizer, combustion chamber, heat exchanger and controls. The burner mixes the fuel and oxygen together and, with the assistance of an ignition device, provides a platform for combustion. This combustion takes place in the combustion chamber, and the heat that it generates is transferred to the water through the heat exchanger. Controls regulate the ignition, burner firing rate, fuel supply, air supply, exhaust draft, water temperature, steam pressure, and boiler pressure (Azeem, 2010). In boilers which only produce heated water instead on converting it to steam, a process of pumping this water to the desired output point (which can be other equipment being fed by the boiler) takes place.

2.5. Boiler maintenance

Asset management is the core fundamental of engineering in industry since each equipment used must be 'everlasting' and this is done in a way popularly known as maintenance. In engineering terms, maintenance is a way of applying engineering concepts and principles to keep equipment reliable and available by way of optimizing them. This maintenance activity is then used to take diligent care of assets used in industry which are known as equipment. Boilers form part of assets in organizations since they play a vital role in contributing to the probability by way of being productive in whichever process is used in that specific company.

With this in context it can be said, proper machine maintenance is fundamental towards maximizing profit and reducing the cost of production in boiler operation. The type of maintenance adopted by a manufacturing firm is a major factor in determining the reliability of a production process (Adoh J.O., 2019). However, when deciding on the type of maintenance to practice, it is very vital to keep in mind the importance of the required availability together with the safety of the personnel doing labour.

Prescriptive industry practices have long traditionally dictated the type of maintenance to be used on plant equipment to acquire reliability. Indeed, statutory inspection under the regulator legislation has long been a requirement for boilers, pressure systems and other critical equipment (Hamata, 2006). These prescriptive practices lack in some areas such as not really focusing on analysing the threats to plant the integrity of the plant, the boiler's risk and the consequences that arise from failures coming from boilers. Risk-based maintenance has been introduced to control and minimise the probability of failure of plant boilers. A supporting factor to this is the introduction of non-destructive testing methods in boilers, more specifically in boiler tube.

Maintenance includes keeping physical components in good working order and within design specifications. This includes cleaning heat transfer surfaces, controls tuning and maintaining insulation. Before boiler tune-ups, system diagnostics should be performed and any deficient equipment brought back to specifications. Changes to design specifications can be made, but all implications of the change must first be considered (An In-Depth Examination of an Energy Efficiency Technology, 1997). Most importantly maintenance is done to prevent unnecessary heat losses that are probable to occur during the operation of the boiler. If proper maintenance is conducted, poor, loss in production volume can be prevented on a huge scale for that specific industrial environment.

These heat losses are prevented to occur by performing proper maintenance in heat surfaces by increasing the air-fuel ratio which occurs in the burner. This insulates tubes, pipes and steam vessels which minimizes leakages and pressure of steam in the boiler provided the loads are kept at the required standard. Among many aspects which could be used, Risk Based Maintenance (RCM) is mostly used when maintaining boilers and it does a particularly excellent job. The Risk Based Inspection and Maintenance (RIMAP) standard (2008:12) defines Risk Based Inspection (RBI) as an optimal maintenance business process used to examine equipment such as pressure vessels, heat exchangers and piping in industrial plants. In Europe, most power plants have now adopted the RBI method as part of their statutory obligation (Sihanda, 2016).

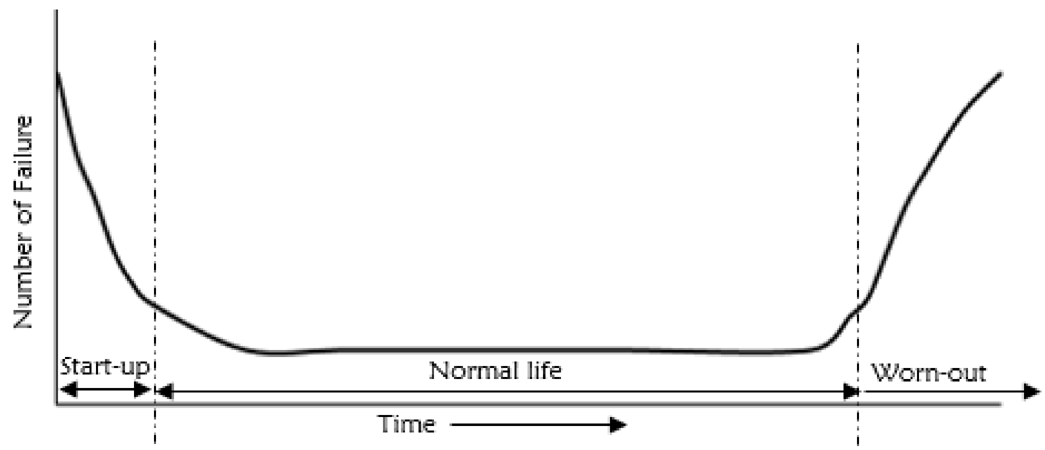

Figure 3. Bathtub Curve (Ahmed S. Kh. R. Q. Alazemi, 2019)

Maintenance of a boiler like any other asset can be represented in its life form of when it is most likely to experience failure with the use the bathtub curve as shown on Figure 3. As seen from the bathtub curve, it can be noted that there is a greater risk of failure at the beginning of the life of an asset and towards the end.

2.5.1. Maintenance strategies

There are various strategies which can be used to maintain boilers to prevent or rectify failure upon occurring. The following are the strategies which can be used to keep the boiler in operation when needed;

2.5.2. Reactive Maintenance

Reactive maintenance is the intervention done after a boiler fails. A boiler will operate and fail without any maintenance personnel noticing and decide to act and rectify the failure by intervening and repairing the boiler. This strategy is the simplest way of maintenance but has a lot of disadvantages with regards to production. This is because it does not require any monitoring of the boiler, but rather wait for the boiler to malfunction/fail. The bad side of this strategy is that it contributes a lot of downtime which varies based on the type of failure in place at the time. It is by no means the most effective maintenance.

Taking a reactive approach in boiler maintenance can be quite costly to the business in terms of boiler downtime, parts and labour costs for repairs, and reduced service life for the boiler (Ahmed S. Kh. R. Q. Alazemi, 2019). Figure 4 shows the likelihood of failure if reactive maintenance is used for boilers, this means that if the reactive strategy is used, failure is more frequently experienced and this increase the cost of maintaining the boiler.

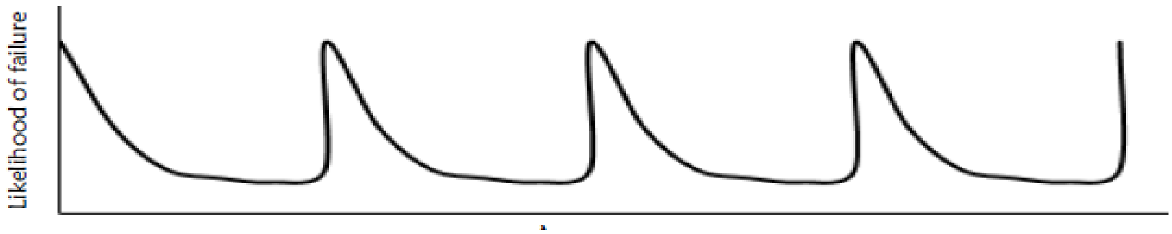

Figure 4. Lifetime likelihood of failure under reactive maintenance (Ahmed S. Kh. R. Q. Alazemi, 2019)

2.5.3. Preventive Maintenance

Preventive maintenance is the intervention done on equipment (boiler in this case) before failure occurs due to certain monitoring conducted on the equipment and after noticing the risk posed by the probability of failure. PM includes painting, lubrication, cleaning, adjusting, and minor component replacement to extend the life of equipment and facilities (Jain, 2012).

This is the better option as compared to reactive maintenance pertaining to avoiding downtime since this comes with reduced breakdown rate and avoid excessive depreciation of assets. The law of preventive maintenance strategy is that the higher the value of plant assets and equipment (per square foot of plant), the greater will be the return if there is a preventive maintenance strategy (Jain, 2012). Amongst other advantages of this strategy, it minimizes the cost of maintenance while improving the reliability of the boilers.

Figure 5. Lifetime likelihood of failure under preventive maintenance (Jain, 2012)

Under this strategy the likelihood of failure is reduced to a minimum and it becomes steady over time as shown in Figure 5. An optimal preventive maintenance strategy should include (Jain, 2012):

- Non-destructive testing.
- Periodic inspection.
- Pre-planned maintenance activities.
- Maintenance to correct deficiencies found through testing or inspections.

2.5.4. Condition-Based Maintenance

Condition based maintenance is a strategy used in industrial boilers to manage its wellbeing and from this it is determined when to maintain it only when needed. This is done in convenient times, increases the safety of boilers and reduces the cost of maintenance in boilers. This strategy optimizes trade-off between maintenance costs by increasing availability and reliability while eliminating unnecessary maintenance activities.

In this strategy, the boiler is maintained based on the required output it needs to give for production to not have downtime and lose out on volume (Mushiri T., 2018). It has some features which are data acquisition, and it involves several types of information: Vibration, Temperature, Pressure, Speed, Voltage/current, Stress/strain/shock, position and particulate count/composition (Figure 6).

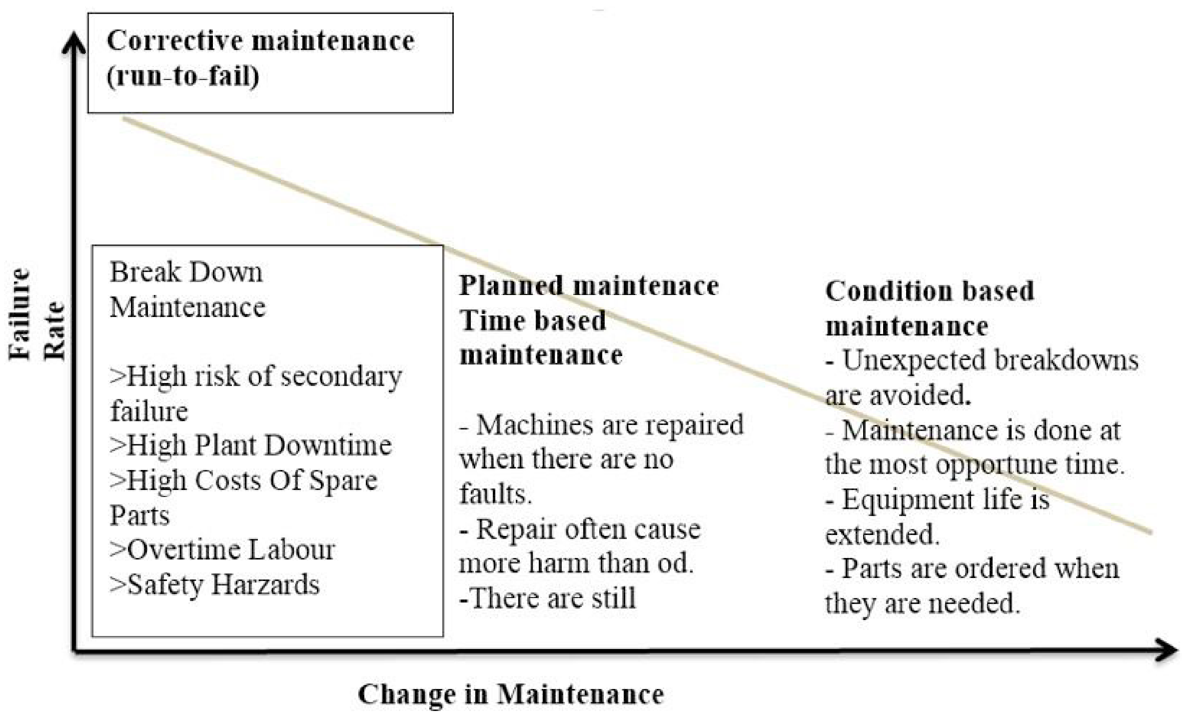

Figure 6. Change in Maintenance against Failure Rate (Mushiri T., 2018)

2.6. Current maintenance practices

Ensuring safety of the boiler, providing a user-friendly way of operating it, ensuring the deterioration rate does not become on the negative side and ensuring that the boiler achieves the required availability and efficiency are the most core fundamentals of maintaining a boiler and these should be properly practices. In modern day industry, a strategy which integrates significant risk assessment is used to achieve the required reliability rate of boilers. The prioritization of the equipment is based on the total risk in terms of economic, safety and environment. Scheduling maintenance is enhanced to optimize the inadequate risk (Fuzi N.F.A., 2020). This is known to be the Risk Based Maintenance Method.

2.6.1. Risk-Based Maintenance (RBM)

The risk-based maintenance (RBM) procedure is a mechanism to plan an effective maintenance scheduling with minimal expected failure of the machine (Fuzi N.F.A., 2020). This strategy is used to maintain a boiler so that reliability can be achieved at a very cost-effective value. The risk or probability of failure is reduced therefore preventing failure at a much-optimized cost. Nowadays organizations want to achieve a lot but in very cost-effective ways and it is known that maintenance is a luxurious process to have, so using RBM comes in with an advantage of saving organizations cost on maintenance. The process used for RBM is shown on Figure 7 and this is measured or can be calculated using the following equation;

Risk = Probability of failure × Consequences of Failure (Fuzi N.F.A., 2020) (3.1.)

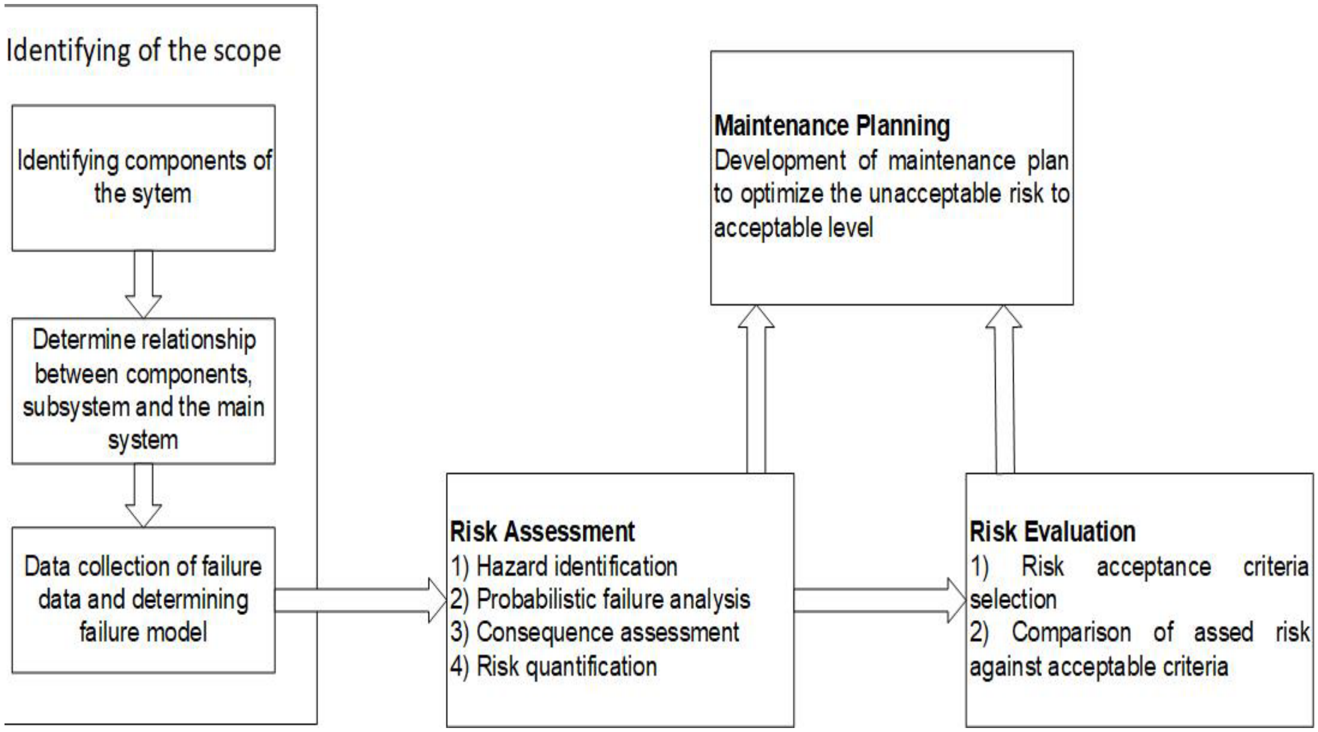

Figure 7. Risk-Based Maintenance Methodology (Fuzi N.F.A., 2020)

3. Methodology
To improve the Heat Losses in Industrial Boilers, theoretical scientific approaches are researched and implemented. These are factors that will assist by way of modelling heat losses acquired in the boiler with the use of mathematical formulas. The methods outlined will improve the boiler's energy performance by producing positive output results as required by the next in line mechanical equipment Turbine as per the complete system's requirements.

3.1. Heat Transfer
Heat transfer deals with the transmission of thermal energy from higher- to lower level by any one or a combination of the three classical modes, namely, conduction, convection, and radiation. These are not complex processes to transfer heat, but their complexity arises when different modes (dynamic conditions, irregular shape, etc.) occur simultaneously. Due to many dynamics and variables involved in heat transfer, it is not specifically considered as exact science (Rayaprolu, 2009). The following are the processes of heat transfer which occur in boilers;

3.1.1. Conduction
It is the transfer of heat between two or more bodies using physical contact. This transfer occurs in substances when energy flow is occurs without the movement of molecules due to lattice vibrations and flow of free electrons. Heat flow from flue gases to water/steam across the metal wall in a boiler, loss of furnace heat to the surrounding atmosphere through insulation, and heat loss from hot steam/water pipes through insulation are all examples of conduction (Rayaprolu, 2009).

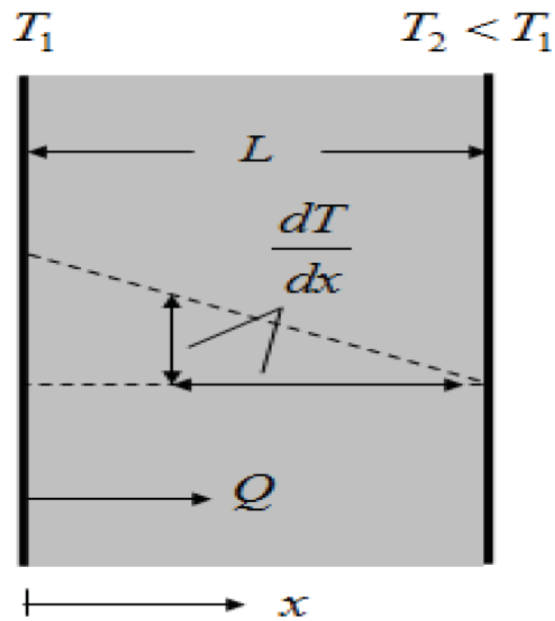

Figure 8. Conduction (Long, 2009)

Figure 8 shows the key quantities that are needed to be considered in the conductive process of heat transfer and from this diagram the rate of heat transfer can be determined using the following equation;

$q_k = -kA\frac{dT}{dx}$ (Kreith F., 2011) (3.2)

3.1.2 Convection

Convection is the flow of energy from the surface to the surrounding fluid due to conduction and mixing of fluid molecules (Rayaprolu, 2009). The convection mode of heat transfer consists of two mechanisms operating simultaneously (Kreith F., 2011), which are the natural and forced convections. In natural convection, the fluid motion is driven by density differences associated with temperature changes generated by heating or cooling. While in forced convection the fluid motion is driven by some external influence (Long, 2009).

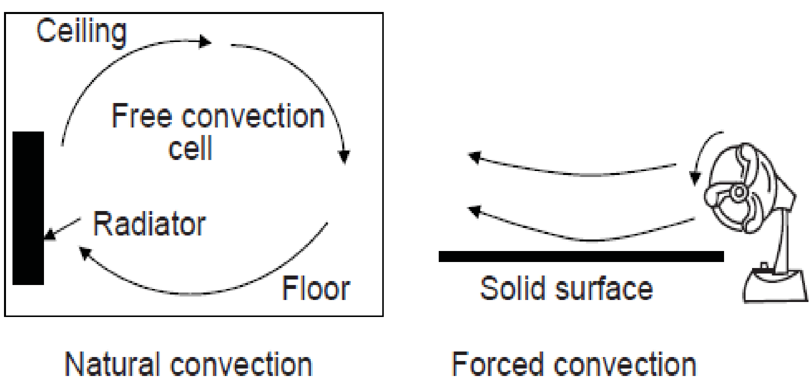

Figure 9. Convection (Long, 2009)

Figure 9 shows the convection process that occurs during the heat transfer in boilers and this heat (Q) can be calculated using an equation governed by Newton's law as follows;

$Q = h_cA(T_1 - T_2)$ (3.3)

3.1.3 Radiation

Radiant heat transfer is the main kind of heat transfer in furnaces and combustion chambers and accounts for 90–98% of the total heat transfer in steam boiler fireboxes (Makarov, 2018). Radiation occurs when the is heat is transferred by means of electromagnetic forces whereby the sun acts as the source of supply and this takes place between surfaces with different temperatures facing each other. The heat radiation is a result of internal energy transformation of bodies into energy of electromagnetic modes. As thermal beams hit on other body their energy is partially absorbed again turning to the internal. It results in a radiant heat exchange between bodies (Maximov, 2008).

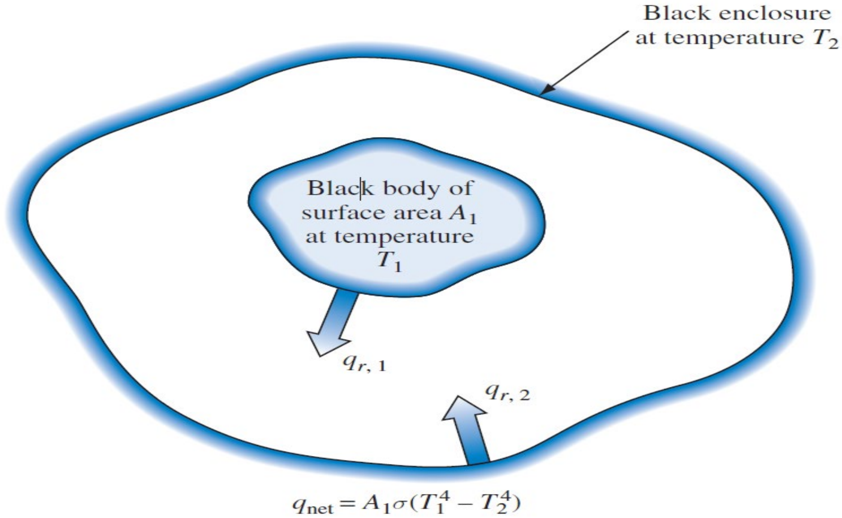

Figure 10. Radiation between body 1 and enclosure 2 (Kreith F., 2011)

Figure 10. shows the radiation process that occurs during the heat transfer in boilers and this heat (Q) can be calculated using an equation governed by Newton's law as follows;

$$q_r = \sigma A_1 T_1^4 \quad (3.4)$$

3.2 Current mathematical modelling of boiler heat transfer

In the process of operation, study and maintenance of heat and power equipment at thermal power stations, it is necessary to assess the effect of different mode changes on the conditions and indicators of operation of both certain units and their assemblies (Galyanchuk, 2020). For heat transfer in boilers, the equations used must be formulated in a steady state manner. Mathematical models for conventional boilers are usually based on empirical equations corresponding to each region of the boiler: the economizer, the boiler and the superheater (Dumont, 2004). The model starts off with the heat flux (q) equation of the furnace wall;

$$q = H_{ext}A(T_w - T_1) \text{ (Xie, 2021)} \quad (3.5)$$

Where:
H_{ext} – wall heat transfer coefficient
T_w – surface temperature of the wall
T_s – temperature of fluid (steam or water)

The utilization of this equation can be used with actual data received from the plant boiler and through a validation process. In this validation process, the boiler's steam operating data can be used to determine the saturated steam and water enthalpies, and from this the flow rate of the feed water can be determined to finally be calculated the heat absorption of the furnace;

$$Q_{wall}^{DCS} = \dot{m}_{feed}(h_{sat,v} - h_{econ}^{out}) \quad (3.6)$$

3.3 Heat Losses in Boilers

The amount of heat losses in power boilers has a considerable influence on their capability to process energy. The improvement of energy processing efficiency is achievable through the optimization of coal incineration processes, obtaining higher steam parameters and the minimization of static heat losses (Kocot, 2017). Heat losses can be caused by several factors such as poor installation, lack of insulation and overall bad technical condition of boilers and their components. Heat losses can be caused by several factors and they are depicted below;

3.3.2 Heat losses due to dry flue gases

Heat is lost in the "dry" products of combustion, which carry only sensible heat since no change of state was involved. These products are carbon dioxide (CO2), carbon monoxide (CO), oxygen (O2), nitrogen (N2) and sulphur dioxide (SO2) (Azeem, 2010). The formation of this gas occurs when there is energy loss which enters the boiler as combustion of air and exit at an extremely elevated temperature. This energy is well associated with nitrogen and when exiting the boiler at an elevated temperature, the systems lose energy.

3.3.3 Heat losses due to Moisture in Fuel

When the moisture enters the boiler with fuel, it leaves as saturated vapour. (Harimi, 2008). Moisture is brought to a boiling point and during this process, sensible heat arises which is used to make up moisture loss.

3.3.4 Heat losses due to Incomplete Combustion

Product formed by incomplete combustion could be mixed with oxygen and burned again with further release of energy. Such products include carbon monoxide, hydrogen and various hydrocarbons and are generally only found in flue gases. Carbon monoxide is the only gas whose concentration can be determined conveniently in a power plant test (Harimi, 2008).

3.3.5 Heat losses due to Moisture in Combustion Air

Vapour which passes through the boiler acts as humidity and is superheated and it can be found using the psychometric charts.

3.3.6 Heat losses due to Radiation and Convection Heat Losses

A portion of heat from combustion escapes from the wall of the furnace without being absorbed by the boiler water. Heat loss from this occurrence is controlled through proper insulation techniques and the maintenance of insulation layers (Azeem, 2010). The factor affecting these losses is the external surface of the boiler when it is in operation.

3.4 Current mathematical modelling of boiler heat losses

Heat losses that occur in boilers can be due to the following factors;

3.4.2 Heat loss in dry flue gas (H_{LG})

The loss in this energy can be determined using the following equation;

$$H_{Lg} = \frac{m_{fg} \times C_p (T_f - T_a)}{\text{GCV of fuel}} \tag{3.7}$$

Where;
H_{Lg} – Heat loss due to dry flue gas
mf_g – Mass of dry flue gas per kg of fuel as fired
C_p – Average specific heat capacity of flue gas
T_a – Average inlet air flue gas temperature
T_f – Average exit air flue gas temperature
GCV – Gross Calorific Value

3.4.3 Heat loss due to formation of water from H_2 in fuel (H_w)

To determine this loss the following equation is used;

$$H_{Lmf} = \frac{9 \times H_2 \times [584 \times C_p(T_f - T_a)]}{\text{GCV of fuel}} \times 100 \tag{3.8}$$

Where;
H_{Lmf} – Heat loss due to moisture in fuel
H_2 – Hydrogen content in fuel
C_p – Average specific heat capacity
T_a – Average inlet air flue gas temperature
T_f – Average exit air flue gas temperature
GCV – Gross Calorific Value

3.4.4 Heat loss due to moisture in fuel (H_{Lmf})

The same Specific Heat Capacity for Hydrogen is also used for this section's calculations which is to determine the Heat loss due to moisture in fuel.

$$H_{Lmf} = \frac{M \times [584 + C_p(T_f - T_a)]}{\text{GCV of fuel}} \times 100 \tag{3.9}$$

3.4.5 Heat loss due to moisture in air (H_{La})

Formula (3.10) is used to calculate heat loss due to moisture in air with the use of the calculated m_{air} as follows:

$$H_{La} = \frac{m_{air} \times humidity \times C_p(T_f - T_a)]}{\text{GCV of fuel}} \times 100 \tag{3.10}$$

3.4.6 Heat loss due to partial conversion of *C* to *CO* ($H_{C,\,CO}$)

In this regard, Heat loss of a combination or product of two elements (Carbon and Carbon monoxide is determined with the parameters provided

$$H_{C,CO} = \frac{\%CO \times C}{\%CO \times (\%CO_2)_f} \times \frac{5744}{\text{GCV of fuel}} \times 100 \tag{3.11}$$

3.4.7 Heat Loss Due to Radiation and Convection ($H_{R,\,C}$)

Two factors are considered in this section which are Radiation and convection, their heat loss is determined with use of the collected data for temperature difference on the appendices section. These losses are casted into the surrounding boiler house.

$$H_{R,C} = 0.548 \times [(T_s/55.55)^4 - (T_a/55.55)^4] + 1.957 \times (T_s - T_a)^{1.25} \times \sqrt{\frac{196.85V_m + 68.9}{68.9}} \tag{3.12}$$

3.4.8 Heat Loss Due to Unburnt in Fly Ash (%)

These are the losses where lesser amounts of Carbon are left in the Ash and this amounts to potential heating of the fuel which generates a loss. For this to occur, ash should be analysed to determine Carbon content.

$$H_{FA} = \frac{Total\ ash\ collected\ /\ kg\ of\ fuel\ burnt \times G.C.V\ of\ fly\ ash \times 100}{\text{GCV of fuel}} \tag{3.13}$$

3.4.9 Heat Loss Due to Unburnt in Bottom Ash (%)

These are the heat losses to be determined and they are for the unburnt amount of Carbon left in ash.

$$H_{BA} = \frac{Total\ ash\ collected\ per\ kg\ of\ fuel\ burnt \times G.C.V\ of\ bottom\ ash \times 100}{\text{GCV of fuel}} \tag{3.14}$$

3.4.10 Boiler Efficiency using Indirect Method (η)

For determining boiler efficiency, formula (3.15) is used. This is the Indirect method applied in this research which outlines and breaks down all the affected Heat losses alongside other aspects.

$$\eta = 100 - (H_{LG} + H_W + H_{Lmf} + H_{La} + H_{C,CO} + \%H_{R,C} + H_{FA} + H_{BA}) \quad (5.15)$$

Table 2 shows the heat losses for the 5 days of investigations and it is seen that theses heat losses keep on increasing due to the decrease value of Gross Calorific Value.

Table 2. Pulverized Coal Heat Losses and Boiler Efficiency

Component	**Day**				
	1	**2**	**3**	**4**	**5**
H_{LG}	4.91%	4.89%	4.96%	4.97%	4.95%
H_w	1.39%	1.39%	1.39%	1.39%	1.39%
H_{Lmf}	0.07%	0.07%	0.07%	0.08%	0.08%
H_{La}	0.18%	0.18%	0.18%	0.18%	0.18%
$H_{C, CO}$	0.69%	1.82%	2.87%	3.79%	4.60%
$H_{R, C}$	0.19%	0.19%	0.19%	0.19%	0.19%
H_{FA}	0.12%	0.12%	0.12%	0.12%	0.12%
H_{BA}	1.41%	1.40%	1.41%	1.41%	1.40%
η	91.05%	89.94%	88.81%	87.87%	87.08%

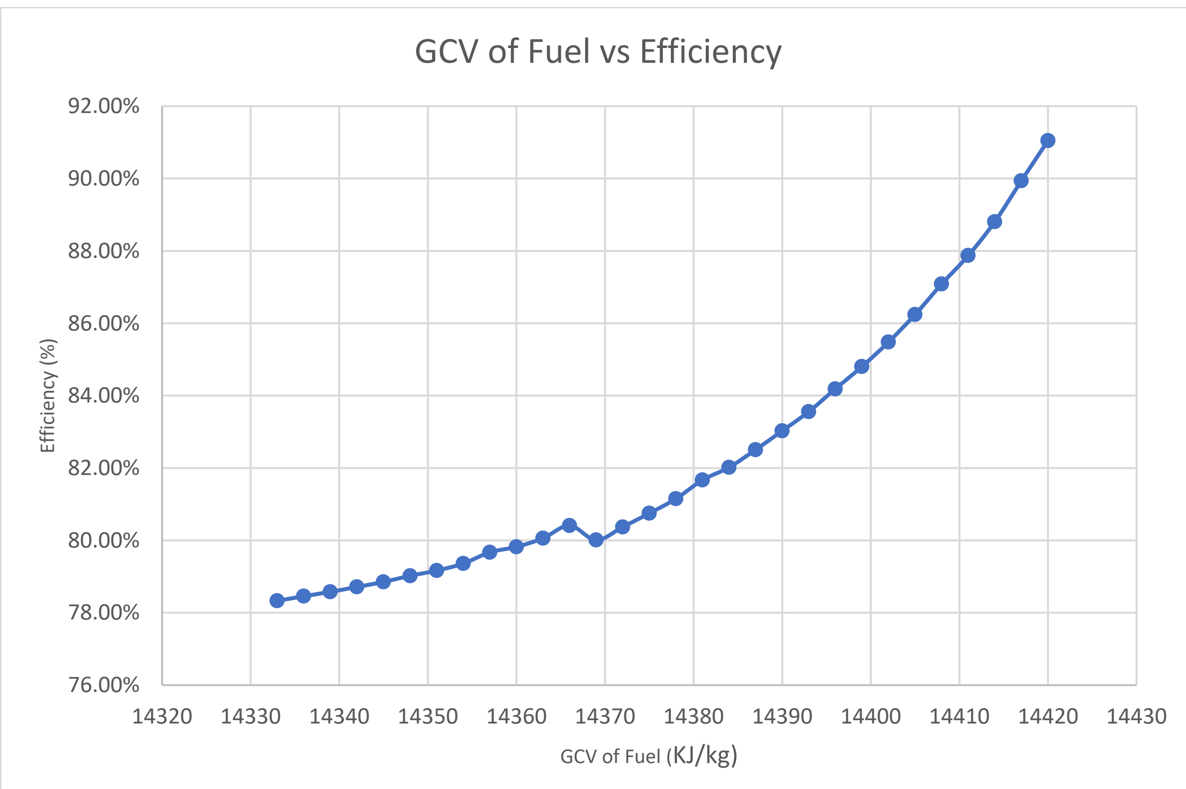

Figure 11. GCV of Fuel vs Efficiency Pulverized Coal

4. Discussion

Upon the research of industrial boilers, it is proven in this study that there are several factors (Gross Calorific value, moisture content, Excess Air, boiler cleaning) which affect the heat losses occurring in boilers. By affecting the heat losses, the efficiency of the boiler is also drastically affected and cannot give the required output for production purposes. With the boiler types used in industry and based on their operability, there are also certain preferred maintenance strategies which can be used to achieve reliability of boilers at cost-effective margins. This study mentions three maintenance strategies which are reactive, preventive, condition-based and risk-based maintenance practices.

These strategies are used based on their effectiveness on boilers and how they could contribute profitably on production. The suitable strategy needs to be used based on the environment and nature of the business. Properly maintained boilers have less risk of experiencing heat losses which arise from various aspects. The potential savings can be done by improving the condition of the electrical system, boiler exhaust gas, combustion system, steam distribution, or the implementation of new energy user equipment (Djayanti, 2019).

Heat transfer and combustor are the main parts that contributed loss of energy and that the method of heat recovery from flue gas is one of the effective ways to save energy in a boiler (Kumar, 2017). It is seen from the study that heat losses can be based on dry flue gases, moisture in fuel, incomplete combustion, radiation and convection, etc. To successfully complete the objective of this study, these heat losses should be prevented by way of modelling them using mathematical equations and/or formulas. Heat transfer plays a vital role in this study because from this phenomenon it can be identified which aspects or components need to be carefully investigated. Flue gas temperature should be 100C or 200C more than the temperature inside the boiler. It should not exceed this limit, if so then it will be lost through dry flue gas (Kaliappan, 2015).

Figure 11 shows the Direct Proportionality between the GCV and efficiency of boiler. If the GCV increases, the efficiency of the boiler also increases, if there is a decrease in the GCV, the efficiency follows the same pattern. It is seen from the results that the GCV in this paper decreases and so does the efficiency form a percentage of 91.05% to 87.08% as shown on Table 2.

The starting point of the graph represented on Figure 11 starts off from the right-hand side at the highest efficiency value (91.05%) to the lowest efficiency values (87.08%), meanwhile the starting point on the GCV value is 14322 KJ/kg and end point of 14279 KJ/kg.

5. Conclusion

Boiler performance is evaluated by determined the boiler efficiency which is a key factor and this is affected the heat losses experienced in the boiler. It can be said that several types of boiler heat losses account for its overall efficiency (Chayalakshmi, 2015). Based on this study, very tedious mathematical manipulation will be an especially useful tool when modelling the heat losses in boilers. Heat transferred by conduction, convection and radiation will later form or cause losses which will be classified as flue gas losses, losses due to unburned CO, losses due to enthalpy and unburned combustibles in slag and flue dust and losses due to radiation and convection (Celen, 2017).

Fuel consumption directly impacts the heat losses, as it increases, the efficiency also increases. The Gross Calorific Value is shown to decrease in this regard for both coal types used and it is seen that the Heat losses also decreases, causing the boiler's efficiency to also decrease. The graphs of Gross Calorific Value vs the Efficiency of the boiler demonstrate this as it can be seen on both Figure 11 that as the Efficiency decreases, the GCV also decreases. The relationship between these 2 factors is shown to be directly proportional to each other.

To improve these losses, a maintenance strategy to be chosen will be influenced by the cost an organization is willing to spend. For example, if reactive maintenance is used, then the organization must be willing to cater for all the downtime that will come with it. Another factor to consider is the type of fuel that will be used because is directly related to the heat losses that will be experienced by the boiler in use (Kumar, 2017).
The following recommendations are made to improve the Heat losses in boilers:

- Use Air preheater to decrease dry flu gas temperature.
- Reduce Radiation and Convection heat losses.
- Increase Combustion Air Temperature.

- Increase Gross Calorific Value of the coal used which will cause heat losses to be minimal and thus causing the boiler efficiency to be at the maximum possible value.

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