

<u>A. INTRODUCTION: STEAM TRACTION</u>	- 1 -
<u>B. A 21ST CENTURY VISION OF STEAM TRACTION</u>	- 2 -
<u>1. THE MAIN COMPONENTS OF THE STEAM ENGINE</u>	- 2 -
1.1 THE FIREBOX	- 2 -
1.2 THE BOILER	- 3 -
1.3 THE REGULATOR	- 3 -
1.4 SUPERHEATING	- 4 -
1.5 THE CYLINDERS, PISTONS AND CYLINDER VALVES	- 5 -
1.6 THE BLASTPIPE	- 5 -
<u>2. HOW THE STEAM ENGINE WORKS</u>	- 6 -
2.1 THE FLOW OF THE STEAM	- 6 -
2.2 VALVE WORKING	- 8 -
<u>3. WHY A COAL FIRED STEAM TURBINE IN A POWER STATION AND AN ELECTRIC LOCOMOTIVE ARE BETTER THAN A STEAM LOCOMOTIVE</u>	- 12 -
<u>3.1 ELECTRIC LOCOMOTIVES</u>	- 12 -
3.1.1 COAL-FIRED STEAM TURBINES	- 13 -
3.1.2 NUCLEAR POWER	- 13 -
3.1.3 RENEWABLE RESOURCES	- 14 -
<u>3.2 ANALYSIS OF THE LIMITATIONS OF STEAM LOCOMOTIVES COMPARED WITH COAL FIRED STEAM TURBINES AND ELECTRIC LOCOMOTIVES</u>	- 14 -
3.2.1 EFFICIENCY	- 14 -
3.2.2 MAINTENANCE	- 15 -
3.2.3 ENVIRONMENTAL ISSUES	- 16 -
<u>3.3 CLEAN COAL TECHNOLOGIES (CCT)</u>	- 17 -
<u>3.4 LOCOMOTIVES IN CHINA</u>	- 18 -
<u>3.5 CONCLUSION</u>	- 19 -

4. MODERN STEAM	- 20 -
4.1 WHERE WE LEFT IT AND WHERE WE CAN TAKE IT	- 20 -
4.1.1 FUEL	- 23 -
4.1.2 FIREBOX	- 23 -
4.1.3 BOILER	- 24 -
4.1.4 FRAMEWORK, DRIVE AND OTHER CONSIDERATIONS	- 24 -
4.1.5 MULTIPLE UNIT CAPABILITY	- 25 -
4.1.6 POWER ACTUATION	- 26 -
4.1.7 THE COMPUTER-BASED INTERFACE	- 26 -
4.1.8 TRACTION CONTROL	- 27 -
4.1.9 BOILER SYSTEMS	- 27 -
4.2 BRITISH EFFORTS TO BUILD A MODERN STEAM ENGINE	- 27 -
4.3 OTHER IDEAS FOR MODERN STEAM ENGINES FROM AROUND THE WORLD	- 29 -
C. OVERALL CONCLUSION	- 30 -
D. REFERENCES	- 30 -

A. Introduction: Steam Traction

A steam engine is a device that converts the potential energy that exists as pressure in steam to mechanical force. The steam engine was not invented by only one person but like all other great inventions and great discoveries, came about after centuries of work by many scientists and engineers.

The steam locomotive was developed in the 1800's to improve the speed of carrying goods on tramways. The age of steam locomotive correlates to the coal era. By the middle of the 20th century however, electric and diesel locomotives began replacing steam locomotives and by the end of the 1970s, most countries had completely replaced steam locomotives in commercial service.

Steam locomotives are still used regularly in some parts of China, where there is a large amount of coal. In some mountainous and high altitude rail lines, steam engines remains to be used since the reduced air pressure in those areas do not affect steam engines much compared to diesel engines.

In this report we will discuss in detail the traditional steam locomotive, explaining the different components and how it works. We will also discuss why it was replaced by the coal powered electric locomotive. Lastly we will look into the new technologies utilised in improving the old steam locomotive to make it more compatible in the 21st century.

B. A 21st Century Vision of Steam Traction

1. The Main Components of the Steam Engine

The steam engine of the locomotive consists of different parts, each with its own important function. We will now consider the main working components found in most steam locomotives.

1.1 The Firebox

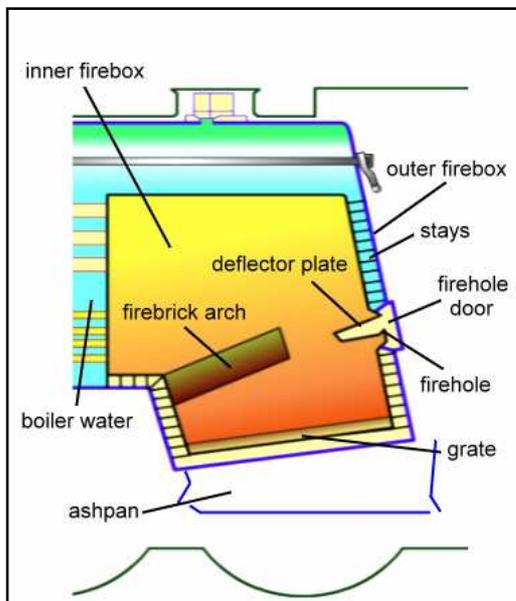


Figure 1a: The firebox

The firebox (*Figure 1a*) is the compartment in the locomotive which houses the fire. It is designed to burn fuel, usually coal, efficiently and to produce sufficient heat to boil water and create steam.

Fireboxes consist of two enclosures, the outer firebox and the inner firebox. The former is usually made of steel while the latter is either made of copper or steel. They are connected by stays, which are bolts that keep the inner firebox rigid within the outer firebox.

Boiler water surrounds the inner firebox to allow maximum benefit from the fire for heating and it also prevents the inner box plates melting due to the intense heat from the fire. The outer firebox is really an extension to the boiler. When the boiler is filled, water will enter the outer firebox legs and cover the roof of the inner firebox.

Primary air is admitted through the grate at the base of the firebox and drawn to the underside of the fire. This is controlled by damper doors in the ash pan. Secondary air is admitted through the firehole and guided towards the fire by the deflector plates. In some cases, secondary air also flows through tubes or hollow stays through the side water spaces.

Inside the firebox, a firebrick arch is positioned over the fire so that the heat from the fire is deflected towards the back of the firebox to ensure the hot gases are distributed towards the tubes more evenly. The hot gases deflected by the brick arch combines with the secondary air to ensure complete combustion. Moreover, the brick arch prevents the cool secondary air from reaching the tubes in the boiler.

1.2 The Boiler

The boiler is the enclosure on a locomotive where steam is produced. It must be filled with water almost to the top. Hot gases from the boiler pass through hollow tubes running the length of the boiler, thus heating the water. When the water boils, the steam it generates forms in the space between the top of the water and the top of the boiler.

Steam will tend to rise to the highest point, which is the steam dome. The amount of steam in the steam dome released to the main steam pipe is controlled by the regulator valve. If more power is needed, more steam is released.

The traditional form of boiler had the same diameter throughout its length and was known as the parallel boiler. A later type was the tapered boiler, which had a narrower front compared to the rear. This allowed more of the water to be at the rear where the greater heat from the firebox was available.

Boilers are insulated and then covered with a thin steel covering. This is done to reduce heat loss. Wood, and then asbestos, was used as the insulating material for many years. In recent years, various forms of natural or man-made insulating materials have been used.

1.3 The Regulator

Once the boiler has generated sufficient steam, it can be used for useful work. A lever is used to control the amount of steam entering the locomotive cylinders. This lever is called the regulator. A regulator valve fitted on top of the boiler and housed in the dome is opened and closed by means of a long shaft connected to a lever accessed from the driver's position in the locomotive cab. The shaft passes through the boiler steam space.

Normally in the United Kingdom, the regulator is mounted on the top centre of the firebox backplate so that it is moved clockwise or anticlockwise to open or close the regulator valve.

If more steam is allowed into the cylinders, more work can be done on the pistons. As a result, more power is produced at the wheels, causing the locomotive to accelerate or pull a larger load.

1.4 Superheating

The steam generated in a boiler is called saturated steam because it is in contact with water. Using the pressure of saturated steam to move the pistons in the cylinder is very inefficient since water will be condensed during the expansion. Condensed steam produces little power.

Superheated steam is steam which has been reheated after its production in the boiler. It has less water vapour and will therefore not condense as rapidly as saturated steam, enabling the power output of a locomotive to be increased up to 25%, thereby increasing the efficiency. It also leads to a 25% saving in coal and 30% saving of water consumption. Basically, superheating increases the heat content and volume of the steam, making it more fluid and using less for a given work output.

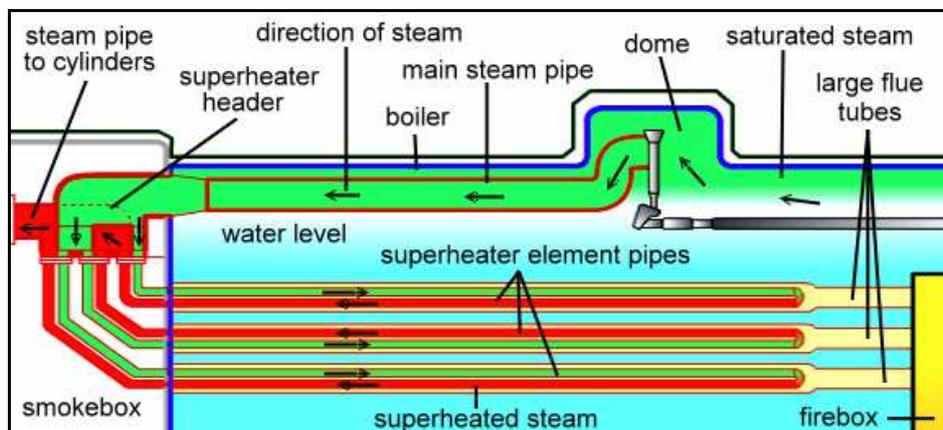
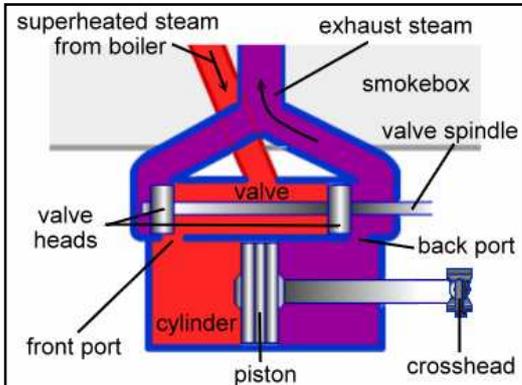


Figure 1b: The process of superheating the steam

Saturated steam from the boiler travels via the main steam pipe to the superheater header, which is a box divided into two separate spaces; one for saturated steam and the other for superheated steam. The saturated steam flows through superheater element pipes situated inside large flue tubes in the boiler where it is heated up. It now becomes superheated steam and its temperature is usually around 320°C to 370°C. The steam then flows through the steam pipes to the cylinders.

1.5 The Cylinders, Pistons and Cylinder Valves



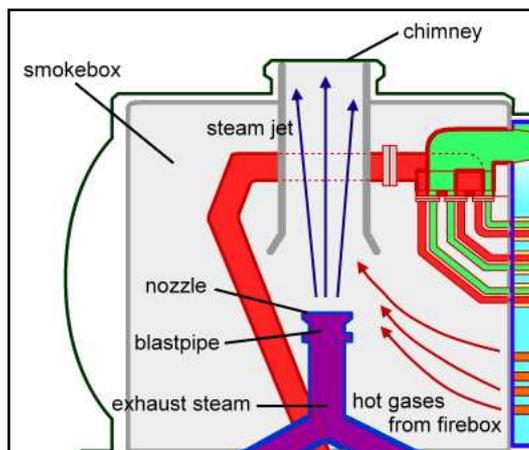
A steam locomotive usually has two, three or four cylinders depending on the design and power requirements. Next to each cylinder is the steam chest containing a valve which controls the flow of steam into and out from the cylinder. Usually the cylinder and the steam chest are designed on the same block as in *Figure 1c*.

Figure 1c: Inside one of the cylinders

A cylinder typically has a port at each end and the valve covers and uncovers these ports so that at one time one port acts as the admission port while the other as the exhaustion port. The fresh steam from the boiler stores a large amount of energy and tends to expand immediately after being injected into the cylinder. The energy from the high pressure steam is converted into mechanical work by pushing against the piston in the cylinder.

1.6 The Blastpipe

The pipe which carries the exhaust steam from the cylinders to the centre of the smokebox (*Figure 1d*) is called the blastpipe. It is vertical and placed at the bottom of the smokebox facing the chimney exit. Other than letting exhaust steam to pass through, the smokebox also draws gases from the firebox to exit through the chimney.



When passing through the smokebox, the exhaust steam creates a draught which draws the smoke and gases along the boiler tubes and pulls fresh air through the grate in the firebox. If more steam is used, there will be a bigger draught and consequently a hotter fire, thus creating a faster steam production.

If the nozzle is narrowed, the steam velocity increases and the draught will be stronger.

Although a high velocity steam jet may create a strong draught, it is uneven. Usually, lumps of half-burned coal will be drawn out with the smoke from the fire when the draught is uneven. Combustion will then be very inefficient as the fuel is not burned properly. A constricting nozzle increases steam velocity, but it also creates back pressure in the cylinder as the used steam cannot escape fast enough.

An ideal steam blast is strong but slow and steady, and provides a fast passage for the steam leaving the cylinders.

2. How the Steam Engine Works¹

In this section, we will take a look at the working principles of the steam engine used in locomotives. Basically, a solid fuel such as coal is burned to heat up water. When it gets hot enough, the water will condense into steam. The pressure of the steam pushes the pistons which consequently move the gears and the wheels, thus moving the locomotive.

2.1 The Flow of the Steam

Figure 2a shows what happens inside a steam locomotive. Solid fuel is burned on the grate inside the firebox. The primary air is admitted below the grate and is drawn to the firebed while the secondary air is admitted through the firehole door. The firebrick arch lengthens the path of the hot gases from the burning of the fuel to ensure complete combustion. The hot gases are then drawn through long tubes in the boiler to the smokebox and out of the locomotive from the chimney.

¹ Refer to <http://www.ee.ic.ac.uk/eee2proj/mfm304/EngineMechanism.html> for animations on how the steam engine works

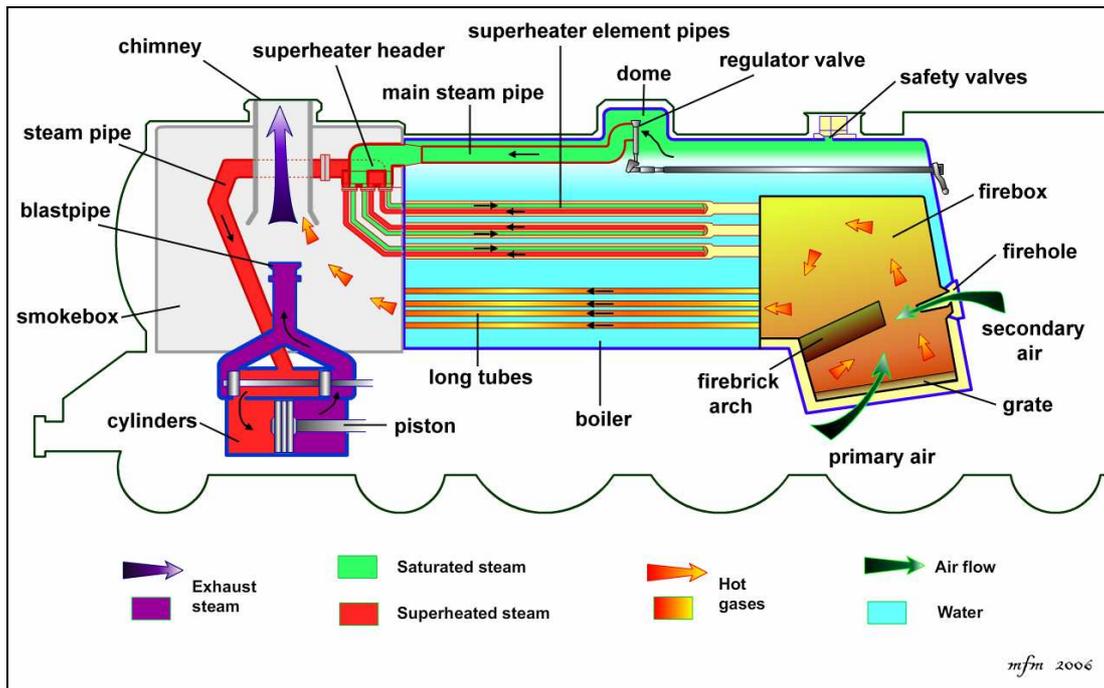


Figure 2a: The steam engine

The heat from the firebox heats up the water in the boiler. Water is also heated by the heat from the hot gases going through the long tubes. As water becomes hotter, it turns into saturated steam which collects above the water. The regulator valve, which controls the passage of the steam to the cylinders, is situated in the dome. There are also safety valves on top of the boiler to release steam if the pressure tends to rise to a dangerous level.

The saturated steam flows through the main steam pipe to the superheater header. It then travels through superheater element pipes in the boiler where it is heated up. After coming out of these pipes through the superheater header, it will have become superheated steam. The extremely hot steam then flows through steam pipes to the cylinders where its pressure moves the pistons which move the wheels of the locomotive.

In the smokebox, exhaust steam passes through the blastpipe to the chimney at high speed due to the confined vent of the blastpipe. This creates a partial vacuum in the smokebox which provides the draw of the air to the firebox and ensures that the hot gases are drawn out of the firebox via the tubes in the boiler.

2.2 Valve Working

2.2.1 Introduction

In a steam engine, the movement of the valve ensures that steam is admitted to and exhausted from the cylinder at the right moment. For a typical cylinder that has two ports, the function of the valve is to admit superheated steam at one end while allowing used or exhaust steam to escape at the other. As a result of covering and uncovering these ports in sequence, the piston is pushed forward and backward by the high pressure steam from the boiler. To regulate the movement of the valve, a mechanical valve gear system is used and this is discussed further in the following subsections.

To know how the valve affects the speed of the locomotive, we have to understand a few terms which are common among steam locomotives operators and enthusiasts. **Lap** refers to the amount of overlap between the valve and the port. In slow moving locomotives, the long lap on the exhaust port gives time for the steam trapped in the cylinder to expand fully to push the piston. On the other hand, on higher speed locomotives the exhaust port is made to open early (short lap) when the valve is in mid-position thus allowing the steam to escape faster. Furthermore, higher speed locomotives also have long **lead** which means that the admission port is already open when the piston is at the end of its movement so there is a sufficient steam pressure that will immediately pushes the piston back to begin its next movement.

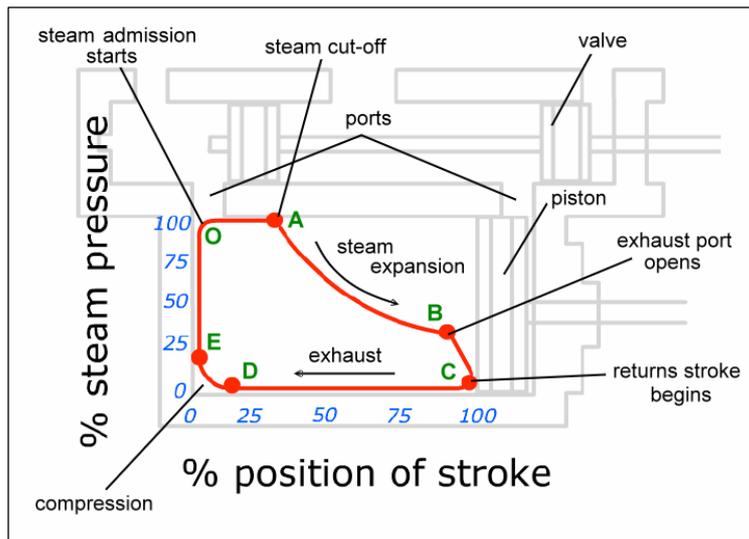


Figure 2b: An indicator diagram for a steam engine

Cut-off denotes the position of the piston, at the moment the valve is closing the admission port. When the engine is working hard and slowly, long cut-off admits steam for most of the stroke of the piston. On fast running locomotives this will cause back pressure to the boiler. To avoid unnecessary back pressure, cut-off is reduced so that steam is

admitted for only 20% of the piston stroke and the remainder of the stroke is due to the expansion of the high pressure steam.

The indicator diagram such as in *Figure 2b* was used by steam locomotive engineers during the steam era to estimate the locomotive's efficiency in converting the steam's energy into useful power at various speeds and cut-offs. The horizontal line OA shows the pressure as the steam enters the cylinder. At cut-off, the pressure drops as the steam expands and does

work to push against the piston. After the exhaust port opens, the line reverses (CD) to indicate the start of the return stroke of the piston. It shows the low pressure as the steam is exhausted. The line DE at the end of the return stroke registers a pressure rise due to the compression of the remaining steam after the exhaust port has closed. As fresh steam is admitted into the cylinder, the pressure rises back to point O and the cycle repeats.

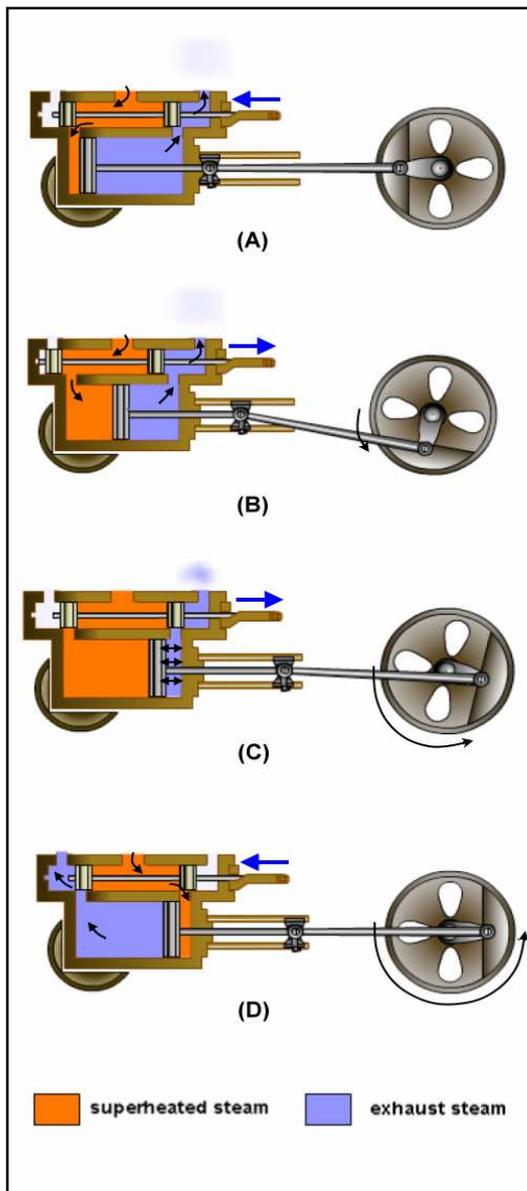


Figure 2c: The working cycle of the valve and piston

2.2.2 Valve-Piston Working

Figure 2c explains graphically how the valve controls the flow of steam in the cylinder. In *Figure 2c (A)*, the opening of the front port allows superheated steam from the boiler to enter the cylinder and push the piston back. As the piston moves backwards, used steam from the previous stroke is exhausted through the back port.

In *Figure 2c (B)*, the valve starts to move backwards while the steam in the cylinder continues to expand and pushes the piston back. The front port opens to exhaust steam (*Figure 2c (C)*) and at the same time the back port closes. This creates some back pressure before the next stroke is made.

The back port opens to allow fresh steam into the cylinder which then pushes the piston forward (*Figure 2c (D)*). A new sweep begins again and the process repeats.

2.2.3 Valve Gear Working – Walschaert system

The locomotive valve gear enables the driver to choose the cut-off of the steam admission and to reverse the locomotives. One of the most common valve gear systems found on UK built locomotives is the Walschaert system, which was first patented in 1844 by Egide Walschaerts, a Belgian engineer. It first appeared on a British railway in 1878. It did not become popular in Britain until the twentieth century but it is now generally regarded as the best valve gear design due to the easy maintenance.

In this system, the fore-and-aft movement of the valve spindle depends on the combined movement of the combination lever and the expansion link. The combination lever motion is worked by the crosshead at the end of the piston rod. It is connected to the expansion link by the radius rod.

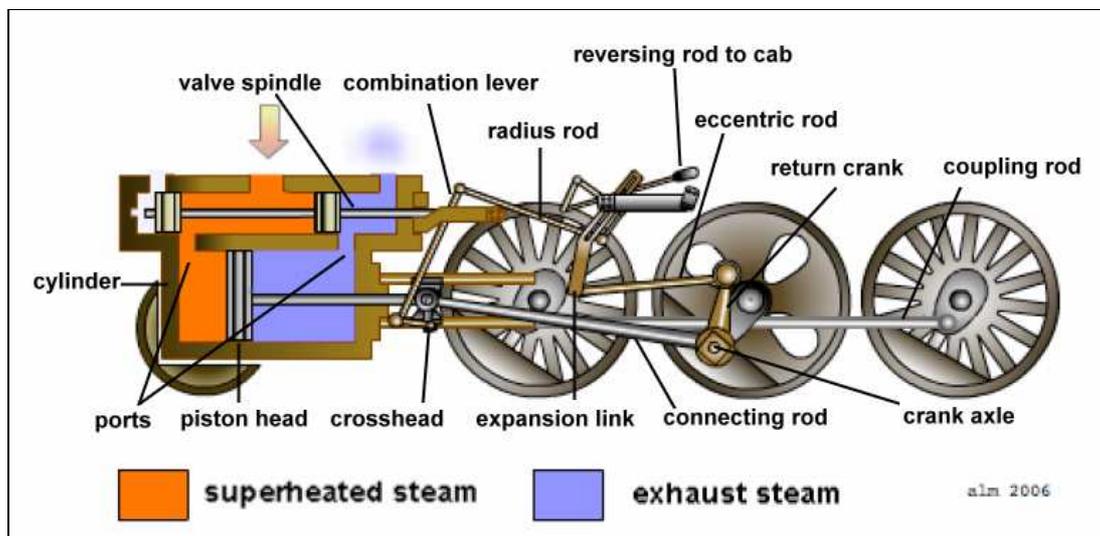


Figure 2d: The Walschaert system

The expansion link movement is obtained from its connection to the eccentric road. The other end of the eccentric road that is attached to the crank axle caused the pendulum-like motion of the expansion link.

By adjusting the position of the radius rod in the expansion link, we can adjust the length of travel of the valve spindle. This can be done by lifting or lowering the reversing rod from the cab. To obtain the maximum valve travel (longest cut-off and maximum steam admission), the radius rod is positioned furthest from the centre of the expansion link. On the other hand, moving the radius rod up and down from one half of the expansion link reverses the movement of the locomotive.

Figure 2e explains graphically the cycle of the Walschaert system. The valve spindle is drawn back as the expansion link pulls the radius rod (*Figure 2e (A)*). This starts to open the admission and the exhaust ports. The radius rod continues to pull the valve spindle backwards (*Figure 2e (B)*). However, its movement is moderated by the forward-moving combination lever. In *Figure 2e(C)*, the combination lever forces the valve to cut steam admission off. The radius rod then moves the valve spindle further forward to begin steam admission at the front port (*Figure 2e (D)*) thus initiating the rear stroke of the piston. *Figure 2e (E)* shows the rear moving combination lever, moderated by advancing radius rod, drawing back the valve spindle. Lastly, the combination lever continues to pull back the valve spindle (*Figure 2e (F)*) to start uncovering the front port for exhaust. The process is then repeated.

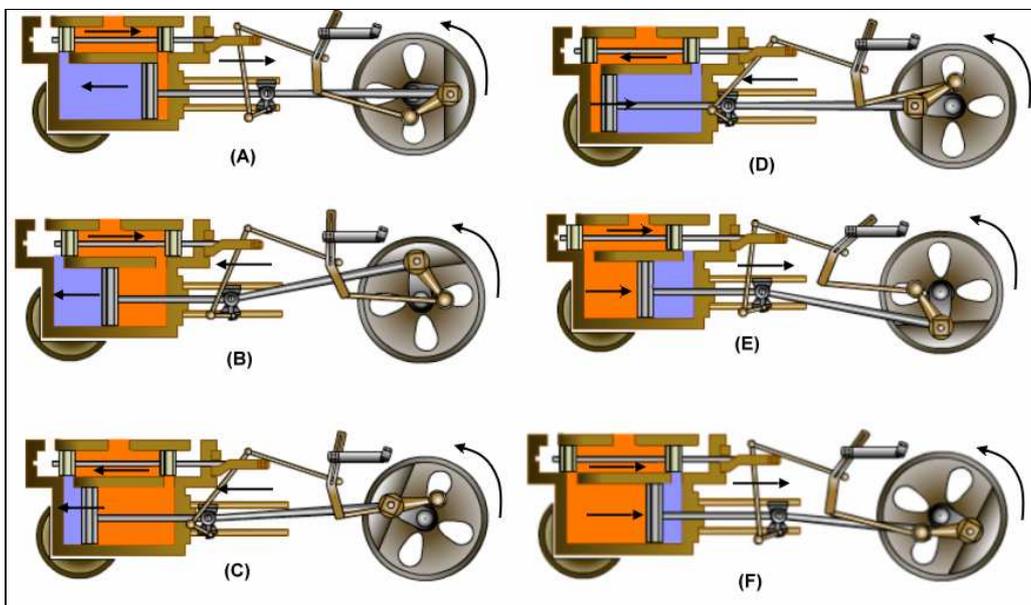


Figure 2e: Cycle of operation of the Walschaert system

3. Why a coal fired steam turbine in a power station and an electric locomotive are better than a steam locomotive

In this section we will compare coal powered stations and electric locomotives to steam train considering economical and technical issues. The basis for one argument is that the power supply in both electric and steam trains are the essentially the same, that is from the burning of coal. At first glance, it could be assumed that if the power was generated on the train it would be cheaper, more efficient, and convenient! From our research and analysis, we disproved such assumptions and found out why the steam locomotive was replaced by other technologies.

3.1 Electric Locomotives

As the name suggests this locomotive is powered by electric motors which draws current from cables overhead, a third rail² mounted alongside the running rail. The locomotive is therefore not self sufficient. The main reason for their introduction was the problem of smoke, (especially in tunnels) caused by steam locomotives.

The Production of Electricity to Drive Electric Locomotives

To produce electricity in large quantities, the most reliable and efficient method is with a turbine. Steam turbines (coal fired or nuclear powered), internal-combustion engines, gas combustion turbines, water turbines, and wind turbines are the most common methods to generate electricity. Apart from coal-fired turbines, we will be looking at various sources of electricity which drive electric locomotives. These alternatives generally provide cleaner ways of producing electricity.

The pie chart in *Figure 3a* shows approximately the percentages of electricity produced in the world in 2000. From the pie chart it can be seen that about two-thirds of electricity is generated from fossil fuels.

² An electrified rail down next to the tracks

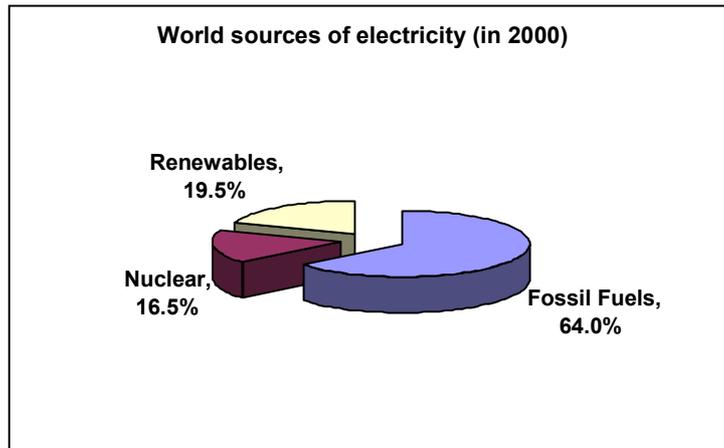


Figure 3a: Pie chart showing world sources of electricity in 2000

We will now explore the different sources of power that can be used to produce electricity to drive steam locomotives:

3.1.1 Coal-fired Steam Turbines

Coal is burnt in large furnaces and the heat generated is used to evaporate water located in boilers, creating steam. This steam expands exerting increasing pressure in the boiler. The steam turbine at the outlet of the boiler converts the energy from the moving steam into mechanical energy. The rotation of the turbine spins a magnet inside a power generator producing electricity.

The main problem with this process is pollution the effects of which will be explained and explored later in this section.

3.1.2 Nuclear Power

The fission (splitting) of the nucleus of an atom releases heat and light energy. Fission of uranium occurs in a nuclear reactor (controlled environment) to generate heat. The heat is then used to produce steam that powers turbines and generators to generate electricity. Nuclear power however had several disadvantages:

The radioactive material generated during fission could be toxic if it is released into the environment. The nuclear waste is stored on the power plant site also raises health and safety concerns.

When all the costs associated with nuclear power are considered, it is currently more expensive than generating electricity from fossil fuels or with many renewable energy technologies. It is therefore not suitable at the moment for driving electric locomotives.

3.1.3 Renewable Resources

Renewable energy resources include the sun, wind, water and biomass (plants and other organic material). Renewable sources are inexhaustible and produce no air pollutants. They therefore provide security and economic advantages. However, they are more financially expensive than using fossil fuels. There is also some difficulty to site and permit wind turbines and other renewable sources. In addition, some renewable energy technologies (from the sun and wind) only generate electricity intermittently.

In summary, though renewable sources provide better economic advantages, at the moment mostly fossil fuels are used in power stations. In the future the goal of alternative energy sources is to replace fossil fuels as energy sources. Judging from the present rate of consumption of fossil fuels, the supplies will eventually run out and the so called alternative energy sources are likely to be the single way of produce electricity.

3.2 Analysis of the Limitations of Steam Locomotives Compared with Coal Fired Steam Turbines and Electric Locomotives

3.2.1 Efficiency

For a steam locomotive, the working fluid of the steam engine is water. Thus a tender³ that carries this fluid along with the solid fuel (coal) is needed. A lot of power therefore is needed to pull the tender along with the storage structures and water processing equipment. Also, solid fuel requires more storage space, which further adds to the power wastage. The large mechanical transmission system causes the mechanical efficiency of the steam locomotive to be low. Additional inefficiencies present were due to poor combustion and engine losses. In practice, a steam engine exhausting the steam to atmosphere will have an efficiency of 5%, but with the addition of a condenser the efficiency is greatly improved to 25% or better.

The electric locomotive on the other hand uses energy the most efficiently due to the low friction of steel wheels on rails, the efficiency and regenerative abilities of electric motors,

³ Attached car to the steam locomotive that carries the fuel and water

and the use of a weightless fuel (electricity), provided transmission losses are kept low through the use of high voltage lines.

Type of locomotive	Thermal efficiency of locomotive (%)	Transport efficiency of energy (tkm/MJ)
Steam locomotive	8.0	1.35
Electric locomotive	25.0	5.25

Figure 3b: Comparison of locomotive efficiencies

The transmission efficiency of electric energy from the plants to the location of use is an important consideration in this respect. Today transmission losses between central power plant and end user are roughly 6%. In the US, thus transmission efficiencies are reckoned to be as high as 94% as of 1998. According to official statistics, transmission losses were 12.1% in 1917, corresponding to an average transmission efficiency of 88%. This means that the amount of useful energy transferred from plant to electric locomotives is comparable to that on steam locomotives and even far better. Furthermore several prototype superconducting systems are now being tested in the US and Europe which will lead to an improvement in the transmission efficiency.

Let us now consider efficiencies at power stations. For instance, in a combined cycle power plant, a gas turbine generator is combined with a steam turbine generator to maximise the efficiency of electricity generation. The burning material is first used to drive a gas turbine can produce 60% efficiency. Capturing the waste heat it can then be reused in the steam turbine. This process is known as cogeneration, which is a process in which the residual steam is used for heating. It is therefore possible to use about 90% of the energy produced by burning fuel, wasting only 10% of the energy produced by the combustion.

Coupled with the measures taken to improve efficiency in the stations electric locomotives are by far more efficient than steam locomotives making them the better alternative.

3.2.2 Maintenance

The steam locomotive was subject to high maintenance and thus needed a lot of manpower to operate and service. British Rail Figures showed the cost of crewing and maintaining a steam locomotive was twice that of an electric locomotive, and the daily mileage achievable

was far lower. As labour costs rose, particularly after the Second World War, non-steam technologies became much more cost-efficient. Traditionally, steam locomotives need careful nurture before and after each journey. It takes a lot of time to light the fire and heat the boilers. Electric locomotives on the other hand can be started and halted by the push of a button.

3.2.3 Environmental Issues

A major criticism of the traditional steam engine was the negative impact on the environment. When the coal burns, it gives off sulphur dioxide, nitrogen oxide and carbon dioxide, among other gases. These gases have the following negative effects:

- Sulphur dioxide (SO₂) is the main cause of acid rain, which damages forests, lakes and buildings.
- Nitrogen dioxide (NO₂) is a major cause of smog, and also a cause of acid rain.
- Carbon dioxide (CO₂) is the main greenhouse gas, and is the leading cause of global warming.
- Small particulates are a health hazard, causing lung damage
- Carbon monoxide (CO) is a poisonous gas and contributor to global warming.

As mentioned earlier, excess smoke was common in steam locomotives. At full output, about 50% of un-burnt carbon was passed into the atmosphere, resulting in a rain of cinders and particulates. Furthermore, water polluted with expelled cylinder lubricant and boiler treatment chemicals was released as steam to the atmosphere and as water from boiler blowdown⁴.

About 80% of global Carbon dioxide emissions come from power plants. Thus power plants are estimated to be responsible for at least half of Global warming. However, it is important to note that due to cleaner coal technologies, there has been a decrease in emissions from Coal fired turbines.

⁴ Blowdown protects boiler surfaces from severe scaling or corrosion problems that can result otherwise.

The Figure below shows a decrease from 1980 to 2002 in the United States:

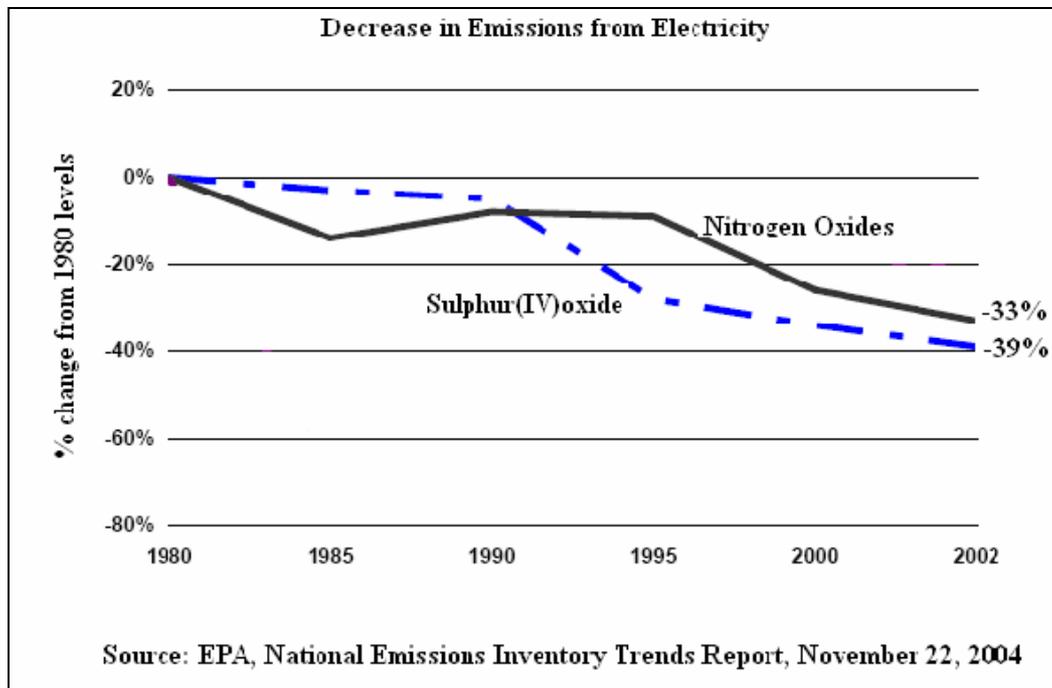


Figure 3c: Decrease in emissions from electricity in the U.S.

3.3 Clean Coal Technologies (CCT)

Some of the processes employed in clean coal technology (CCT) are outlined below:

Coal Washing

Coal contains mineral content that needs to be removed before it is burnt. Removing the unwanted elements, make the coal burn more efficiently. Coal washing involves grinding the coal into smaller pieces and passing it through a process called gravity separation. The coal is then pulverised and prepared for burning.

Gasification

In *Integrated Gasification Combined Cycle (IGCC)* systems, coal is not combusted directly but reacts with oxygen and steam to form a "syngas". This product gas is cleaned and burned in a gas turbine to generate electricity and to produce steam to power a steam

turbine. IGCC's are able to convert coal to electricity at high efficiencies and with low emissions.

Removing Pollutants

1. Sulphur (IV) oxide

Flue gas desulphurisation (FGD) systems are used to remove sulphur (IV) oxide. Wet scrubbers are the most popular FGD system used. This is because they are cheaper and more available than other FGD technologies. A chemical reaction occurs between SO₂ and limestone to form gypsum (a calcium sulphate):
$$\text{SO}_2 + \text{CaCO}_3 + 1/2\text{O}_2 + 2\text{H}_2\text{O} = \text{CaSO}_4 \cdot 2\text{H}_2\text{O} + \text{CO}_2$$

2. Nitrogen oxides

The use of 'low nitrogen oxides burners' is one of the methods to reduce Nitrogen oxides. They restrict the amount of oxygen available in the hottest part of the combustion chamber where the coal is burned hence minimising the formation of the Nitrogen oxides. Low nitrogen oxides burners can be used with other methods like overfire air, reburning or flue gas recirculation. These combinations can achieve up to 74% Nitrogen oxides removal efficiency.

Carbon Capture and Storage (CCS)

This involves capturing the carbon dioxide and storing it deep underground. CO₂ can be pumped into disused coal fields where it gives off methane which can be used as fuel. It can also be pumped into and stored safely in saline aquifers or into oil fields to maintain pressure, making extraction easier.

Due to the scale of the technologies involved, steam locomotives cannot benefit from clean coal technologies and are therefore less environmentally friendly.

3.4 Locomotives in China

To further compare steam locomotives with electric locomotives, we will consider China where at present both technologies are in use.

In China, a system has been setup based on the operating costs and opportunity costs presented by the electric, diesel and steam locomotives. It was concluded that the most economical and rational rail transport structure should be Steam locomotives, for remote inland areas with low transport level. Diesel locomotives for medium level lines and Electric locomotives should be generally adopted for rail lines involving huge volume.

China's present price structure, for transporting equivalent loads, shows that the lowest cost is generated by steam locomotives. Steam locomotives, having smaller traction power, are a technically inferior type of traction but prevent the full use of the railway lines due to limited tonnage, which means that it reduces the operational costs. However, in heavy traffic sections, the opportunity cost related to the affected railway transport capacity exceeds the operating cost saved by steam locomotives, providing a reason for fazing them out.

3.5 Conclusion

It would seem, given the areas of comparison, that electric locomotives are the better choice of railway transportation today. The steam engine appears to be of inferior technology and has no solid grounds on which it is the better option. The use of electricity in transportation has aided the realisation of the Tube railways of cities, and has contributed largely to the successful operation tunnels, such as the (London-Paris) Euro-tunnel. They also have the advantage of being easier to run, much quieter, and very fast. The issue of pollution has also been considered and owing to "Clean coal technology" electric traction is the superior alternative.

The electric locomotive and electric motor coach may be regarded as natural developments that have followed steam traction. However, the question still remains whether or not this would be the case if 21st century technology was adopted and incorporated in the design of a steam locomotive today.

4. Modern Steam

The lack of development of steam locomotives led to the demise of this good old technology. Instead of making improvements in the existing steam technology, engineers were more attracted towards its replacement by diesel or electric traction. However, with the help of the scientific advancements in the past, the steam industry can be revived today and operate at its full potential. A dedicated group of engineers, around the world, firmly believe that steam locomotives can indeed make a comeback and prove to be beneficial both economically and environmentally. In this section of the report, we are going to look at the factors that led to the replacement of steam locomotives in the early 20th century. We are then going to look at the new designs proposed by engineers which incorporate modern technology to improve these century-old locomotives for a better future.

4.1 Where We Left It and Where We Can Take It

There were indeed many problems – both economic and environmental - with the old steam locomotives. Analysing these problems and devising solutions will enable us to make efficient 'modern' steam locomotives that can compete with the diesel or electric locomotives of today.

From the economical point of view the old steam locomotives were not desirable because of high footplate staff costs, maintenance costs and high fuel consumption due to low thermal efficiencies and high carbon loss in the combustion process. Also high risk, stand-by losses and lack of inter-changeable parts made it obvious that these locomotives could not compete in the modern world.

In addition, environmental concerns such as excess smoke and heavy emission of NO₂, CO₂, SO₂ plagued the steam locomotives as mentioned in the previous section.



Figure 4a: Steam engines of the past

The image above describes a steam engine, as portrayed by the media: polluting (notice the black smoke) and suitable for carrying industrial goods only. However all this is to change with the introduction of the modern steam engines. Notice the clean burning of fuels in the modern steam engine (Figure 4b):



Figure 4b: Modern steam engine

By making good use of modern technology we can build an efficient and clean steam engine. Features such as one man operation, minimum servicing requirements and short starting time are desirable from a modern steam engine. For the engine to be efficient it should not only provide high thermal efficiency but also be light weight. It should also provide clean and efficient combustion of fuel, good insulation and should incorporate interchangeable parts. Thus the steam engine can be more efficient and cause lesser pollution.

Now, let us look at how individual parts can be modified to give us a steam engine for the 21st century.

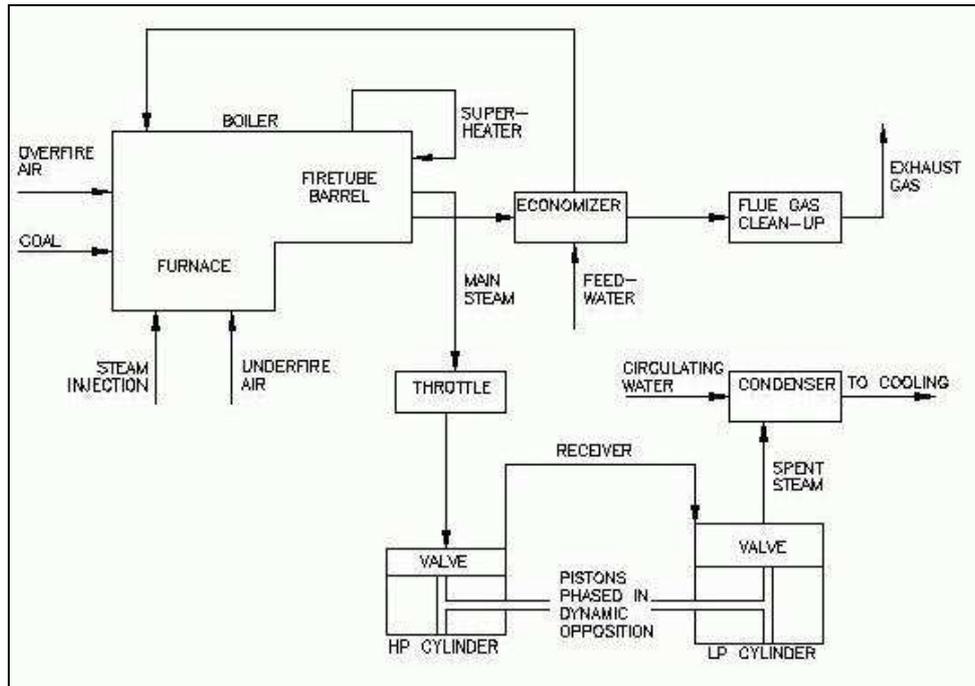


Figure 4c: Flow Chart of a newly designed coal fired steam engine

The flow chart above is from one of a newly designed coal fired steam engine. It will give us an overall view of how a new steam locomotive engine operates.

Coal is deposited on fuel bed in the furnace, and burnt with insufficient slow velocity underfire air to keep the temperature of the coal low. To supplement the relatively low amount of hot gases from incomplete combustion, additional steam is injected into the furnace. At 2nd stage, volatiles (combustible) from coal will be burnt completely with overfire air intake at higher level of the furnace. Hot gases flow through firetube barrel and exchange heat to boiler to generate steam, super-heater feed back is used to generate super heated steam.

Main steam will be fed to the cylinders by the throttle which is controlled by a computer. After passing through the high pressure HP and low pressure LP cylinder, the spent steam will be used to recompress the LP steam or generate auxiliary power where possible. The final cool steam will be condensed and fed to a water treatment unit. The chemically treated water will be circulated back to the boiler to raise steam again.

The exhaust gases will be fed into the economiser where it exchanges its last heat to a small amount of water. The steam raised will be injected back with the underfire air; where the gas will be fed back into the overfire air to make sure carbons and combustible gases are

completely combusted. Finally the gas (mainly CO₂ with very few particulates and other gases), will be cleaned up and released into the atmosphere.

4.1.1 Fuel

There is a proposal of using extra light oil as a fuel for modern steam engines. Unlike heavy oil, light oil does not need to be preheated for use. Therefore heating coils can be eliminated from the design allowing the engine to be light weight and reduce energy consumption. New designs for burning light oil have to be developed because there are none present today. This adds to developments costs and coupled with the fact that oil reserves are depleting rapidly, the choice to use oil as a fuel in the 21st century is impractical. Oil combustion also adds pollutants such as CO₂ to the atmosphere.

Another approach would be to use biomass as the fuel. The argument for biomass is that emitted CO₂ would be reabsorbed by plants and it becomes a part of the carbon cycle, therefore, no 'excess' pollutants are added to the atmosphere. However, using biomass introduces complications to the whole system as it requires changing the firebox and boiler design. Only a few South American countries where "fuel plants" are largely available have actually made use of this technology.

A more realistic design proposes the use of low sulphur coal as the fuel. New steam engine can be designed with new combustion techniques, which can control the emission of pollutants below Environmental Protection agency (EPA) standards. Low cost and high abundance of coal make it the more appropriate fuel in the 21st century. Therefore in this report, we are going to explore the use of coal as a fuel in modern steam locomotives.

4.2.2 Firebox

In the design of a firebox, the main objective is to achieve maximum thermal efficiency. To produce enough heat to raise steam in the boiler more efficiently under the emission constraints, a new firebox with a new gas production technique is developed with 2 stages:

Stage 1: Coal is mechanically distributed across the fuel bed, where it is burnt with little but sufficient air for complete combustion. This is meant to reduce char gasification; however, steam is injected into the furnace to produce more gases with the reduced air intake. Temperature of the burning coal is low in this manner; non combustible ashes (soot) would stay in the coal, where in the old steam locomotive it is discharged into environment.

Moreover, the gas velocity is minimized ensuring fine particles of coal remain. This would greatly reduce the carbon losses; which in old engines could be over 50% at high speed.

Stage 2: Remaining volatile and gaseous products are completely burnt with additional air in the fire box. The emission of harmful gases such as Sulphur oxides and nitrogen oxides are controlled to below EPA emission standards owing to the low temperature combustion technique. Ashes are agglomerated and collected safely instead of discharging it to atmosphere.

4.2.3 Boiler

Again, in order to achieve maximum efficiency, the boiler must be light weight and well insulated. To ensure sufficient water in the boiler, an electronic sensor can be used to maintain a safe water level. However, the sensor must account for various inclinations of the track.

According to a proposal for modern boilers water must be fed into the boiler using a feed pump. The feed pump must be belt driven, taking water from the source tanks. This water is then heated by passing it through the exhaust steam chamber and its entry into the boiler is regulated by a bypass valve. This valve can be automatically controlled using electronic sensors. Wet steam from the boiler is then superheated and is now ready to drive the locomotive.

Good insulation of the boiler is required as locomotives spend most of their time in the shed. Proper insulation of the boilers allows immediate start-up of the locomotive once it is out of the shed. Also by saving all the thermal energy, that would otherwise be lost, the insulation proves to be very cost effective. The development of boiler insulation faded away with the demise of steam locomotives. However, high quality insulation is in use for industrial boilers today and these insulating materials can be used for the modern steam engine.

4.2.4 Framework, Drive and Other Considerations

The overall framework has to be light weight and strong. This can be achieved by having an all-welded frame and using driving axles with hollow shafts. The locomotive suspensions must be of high quality for good shock-absorption and pulling heavy load efficiently. The tractive force must be applied directly to the wheels or through the shortest path possible, so

as to avoid loss of energy. To avoid rolling-back, the hind truck must be equipped with a stabiliser.

Modern steam locomotives must be adaptable with the existing tracks so as to avoid costs of laying new tracks. This can be achieved, more or less, by varying the axle length. The height of the train above the track can be adjusted by changing the diameter of the wheels. Thus modern steam locomotives can be used on existing tracks – making them economically beneficial.

Our next concern is that of safety. Electronic sensors can be used in different parts of the train (as in the boiler) to ensure proper functioning of each part. Any error in any part must be reported to the driver on his display screen. Other safety features must be included in the design such as over-speed trip and roll-back protection.

Also, there must be different sets of synchronised brakes for the locomotive and the coaches. This will ensure safe stopping of the locomotive. To avoid wearing out of brakes, they must be of a high tensile strength and should be well lubricated. The heat produced in the braking process is then cooled using cold water producing steam. A silencer can be used to reduce the noise generated while braking.

It is worth noticing that apart from thermal energy, the modern locomotive will also utilise a fair amount of electrical energy using sensors, controllers and in the display screen of the driver. It is imperative, therefore, for the locomotive to carry a battery as a source of electrical energy. This battery must be kept separate from the steam generator – preferably at the rear of the locomotive. It can be charged mechanically while running using an alternator and using an external charger while in the shed.

4.2.5 Multiple Unit Capability

Multiple unit capability is the ability to use two or more engines connected together under the control of a single driver. This capability is highly desirable in steam locomotives as there is a limitation to the size and pulling capacity of a single engine. Effectively depending on the load required to be moved, more than one engine could be brought together and connected to work as one big locomotive. This sort of capability would make steam engines very competitive and would then be highly desirable for use on heavy duty main lines.

A computer control system would make this kind of multiple unit operation a reality. Attempts at implementing this kind of system were made by Wabco engineers in the 1940's. They designed and patented pneumatic⁵ and electro-pneumatic control systems for the multiple unit operations under a single driver. With the ACE 3000 project this sort of idea was taken one step further where efforts were made to allow multiple unit operations with other steam engines and even diesel locomotives.

It becomes apparent that to be able to have multiple unit capability easily available, provisions must be made for single driver operation of locomotives. For this we must have power actuated locomotive controls, design of computer based interface for locomotive management, automatic control of the boiler systems and traction control.

4.2.6 Power Actuation

Operations such as braking safely, accelerating, steering, reversing had a completely mechanical operation in the traditional locomotives. To accelerate or decrease speed the driver invariably had to use huge levers which were mechanically directly connected to the locomotive. In modern engines this sort of operation must be done away with and computer or electrical control panels must be installed. For example when the driver initiates a command to brake on the control panel, actuators which relay his command will be powered and the brakes will be applied.

4.2.7 The Computer-Based Interface

The driver could have in front of him an interface module rather like a computer screen and also a control panel. This control panel would allow the driver to make instructions to the locomotive while the screen would be the source of feedback to driver regarding engine conditions. The onboard computer would also be used to maintain a database of the performance of the engine and the operating values for various critical components. This could be a source of knowledge, which after careful analysis could tell us how the locomotive could be better run, which components need repair or even how to make improvements to the design.

⁵system moved or worked by air pressure

4.2.8 Traction Control

Inbuilt safety considerations could also be implemented through preinstalled commands for mode of action to be taken by the computer in certain situations. For example in case of braking, the onboard computer should manage the braking force so as to avoid locking the wheels. This would be similar to the anti-lock braking system in automobiles in use today.

4.2.9 Boiler Systems

The boiler system could process in real time the correct amount of fuel required to give the power demanded by the driver. The driver could increase the speed of the locomotive by using his control panel. The onboard computer would get the instructions from the driver and take action based on the operating conditions and also predetermined values to provide right amount of power increase. It would manage air supply to maintain efficient and complete combustion which would allow it to remain within environmentally safe limits.

Microprocessor control of basic operations such as fuel or air supply management and the development of power actuated locomotive controls would greatly help reduce the number of men required for operating the locomotive. As a result, one of the important targets in creating a modern locomotive would be to allow the driver of the locomotive to focus only on the steering of the locomotive rather than also have to be responsible for the efficiency and traction control of the engine. The design and implementation of modern computer controlled actuators and sensors could be used to make the job of the train driver much simpler.

4.3 British Efforts to Build a Modern Steam Engine

In efforts to design and build a modern steam locomotive, various attempts have been made around the world. One such commendable effort was by the A1 Trust. Their desire was to build a modern working model of the original A1 peppercorn design. This was the design made by Arthur Peppercorn, the last Chief Mechanical Engineer of the London and North Eastern Railway (LNER).

Originally there were 49 A1 locomotives operating on the East Coast Main Line in the post war period 1948/49. In a few cases the design of the A1 locomotives, incorporated roller bearings which meant that heavy maintenance was only required after an average of 118,000 miles. Also the design allowed it to run well even on low grade coal. The A1 were

the cheapest locomotives to run compared to other locomotives that were already operating, but unfortunately, in the 1960's there was a rapid move towards diesel engines. This meant that eventually by the end of 1966 all including the last surviving A1 601445 Saint Mungo had been scrapped.

In the 1990's another group of railway enthusiasts came together with the intention of building an A1 peppercorn from scratch. This would become the largest single effort in railway preservation within Britain. There is certain affection towards the appearance and feel of the traditional locomotive, hence the idea remains that however modern the project might be, the overall look of the locomotive should be preserved for sentimental satisfaction. With this in mind, people like Ing. L.D. Porta also made some suggestion for design improvements to the A1 which would enormously increase its efficiency and performance.

The construction of this 50th A1 was undertaken at Darlington. The locomotive has been named the 'Tornado' and numbered 61063. A number of modifications have been planned for the Tornado A1 locomotive. The firebox will be completely made from welded steel. The original had a copper firebox which was riveted. The brake design for the locomotive has incorporated an air braking system as a result of considering the heavy operating conditions on the main line. A vacuum ejector will be fitted to accommodate use with all vacuum braked stock. The tender for the locomotive will be redesigned to eliminate water scoop and increase the capacity to 6000 gallons. Other design modifications suggested by Ing.L.D.Porta include changes to the inside cylinder arrangement, provisions for gas producer combustion system with enlarged combustion chamber, increased boiler pressure capacity. An advanced 'Lemprex' exhaust system would greatly help improve the design of the locomotive. Not all of the suggestions made by Porta were incorporated in the design of the Tornado. But all these changes undertaken ensure that the Tornado engine is thoroughly a modern incarnation of the original A1 design.

Another design for a modern steam engine was proposed by Dr. John Sharpe as a variation for the Beyer-Garratt. This would be a 4000 horsepower engine featuring 2-cylinder compound condensing units utilising a turbo re-compressor between two stages of expansion (see Figure 4d).

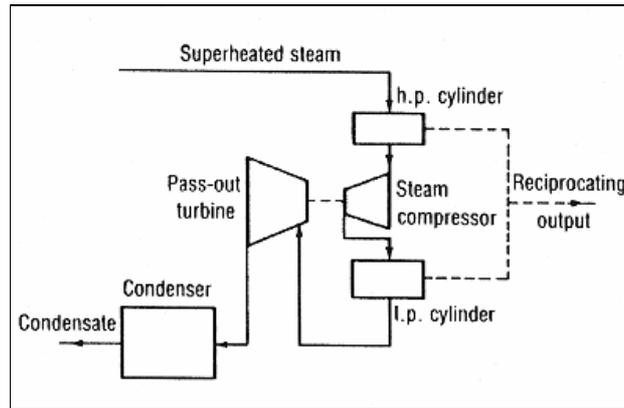


Figure 4d: Flow diagram of a turbo recompressor

In this design, by adding a turbine-driven steam compressor feed back loop in between the high pressure (HP) and low pressure (LP) cylinder, exhausted steam from LP cylinder is fed into the Pass-out turbine to drive the steam compressor, which is used to increase the pressure of the steam from HP cylinder before fed into LP cylinder. This works similar to a turbo charger in use within many modern internal combustion engines to increase power and efficiency. This kind of engine would achieve a thermal efficiency of 15%.

4.4 Other Ideas for Modern Steam Engines from Around the World

In the United States, the National Steam Propulsion Company (NSPC) was formed in 1982 to reintroduce the coal fired steam locomotive back on to the railways of America. The main idea was the use of already existing diesel engine chassis to build the new steam engines. This method would make it easier for the railway to use existing facilities and maintenance operations without having to create too many new specialised processes. This would give the steam locomotive a bigger chance of success through being easily operable on the present railway. The locomotive would use a patented 'Wormser Fluidised Combustion Boiler' which would enable boiler pressure capacity in the range of 1000PSI. This boiler would allow the use of even low grade coal with high sulphur content to be burnt and still meet the environmental limits of the time. It was calculated that such a locomotive could give thermal efficiencies of approximately 18%. But with experience, time and more developments this thermal efficiency could be raised to around 27% in the later versions. The prototype of this kind of locomotive which was first made was called the CE-635 and was rated at 3500 horsepower. Effectively these engines would become desirable because they allowed higher savings on costs over their life-cycle as compared to the diesel while at the same reuse of chassis became a suitable way of recycling existing material.

C. Overall Conclusion

Many efforts have been made to revive the steam locomotive today by making it more environmentally friendly, efficient and economically viable. With the abundance of coal in the world, it could be a reasonable transportation alternative. However, the efforts made so far have not produced results on a commercial scale. We acknowledge that the steam locomotive served its purpose. However, the restoration of the steam locomotive may be somewhat farfetched as other newer technologies are replacing it.

D. References

- *The Railway Data File*; Produced by Eaglemoss Publications; Published by Silverdale Books, 2000
- *How Steam Locomotives Really Works*; A.J. Goldfinch, P.W.B. Semmens
- *Leader Steam's Last Chance*; Kevin Robertson
- *Electric Traction*; Gibbs, George.
- Article - *China's Transportation and its Energy Use*; Li Qunren
- <http://www.nps.gov/stea/locowork.htm>
- <http://www.railway-technical.com/st-glos.html>
- <http://home.new.rr.com/trumpetb/loco/wdiagram.html>
- <http://www.keveney.com/Locomotive.html>
- http://www.trainweb.org/tusp/21_cent.html
- <http://www.trainweb.org/tusp/90s.html>
- <http://news.bbc.co.uk/2/hi/science/nature/4468076.stm>
- <http://www.a1steam.com/hista1.html>
- Papers from <http://homepage.eircom.net/%7Engenerationsteam/index.htm>