# THE POTOMAC’S ENGINES

## A NOTE FOR DOCENTS

Prepared for the Potomac Association
by Les Dropkin, September 2003

# The Potomac's Engines

When the Electra was built for the Coast Guard in 1934 as one of the 18 cutters making up the Thetis class, she was equipped with twin Winton 158 - 6 marine diesel engines. She continued to be powered by the Winton engines throughout the years that followed until her restoration, when the twin Enterprise DMG - 26 engines we now see replaced the original Wintons. Although somewhat less powerful than the original engines, they are very similar in their operation. Both the Winton and the Enterprise engines can be described as being twin, independent, direct reversing 6 cylinder marine diesel engines.

This note has been prepared to explain these terms, to identify the main engine components and to discuss how these engines work. This is a note, not a manual. The reader is a docent, not an engineer. Its object is to give the docent a reasonable comfort level when showing the engine room to our visitors.

## Some Basic Ideas

If fuel is burned in the open, such as in a camp fire, the heat energy is almost wholly dissipated and there is very little energy available to do work as a result of the combustion of the fuel. On the other hand, there are devices such that the result of the burning creates energy that can be used to perform work; such a device is called a heat engine. Among the various kinds of heat engines that have been invented are those where the combustion takes place internally in a confined space. Specifically, we will focus in on those heat engines where air has been sufficiently compressed to raise its temperature to a point where the introduction of an appropriate fuel will cause combustion. Such an engine is called a Compression Ignited, or CI, heat engine – it is more commonly called a Diesel engine. Of course there are many types of Diesel engines for all sorts of purposes, but our interest is in the two marine Diesel engines of the Potomac. These main engines of the Potomac are referred to as medium speed engines; their function is to provide the power to turn the propellers.

Clearly there are some general questions that have to be answered at this point: What is the nature of the "confined space"? How does the air get into that space? How does it get compressed? How is the fuel introduced? What happens to the combustion products? etc.

The "confined space" of our engine is a vertical hollow cylinder supplied with a cylinder lining. It is closed at the top by the cylinder head. The bottom is closed by the piston - a plug that, although closely fitting, can still move up and down within the cylinder. That is, the fit is loose enough to allow the piston to move, but tight enough so that virtually no air in the cylinder can leak past it.

## Action Inside The Cylinder

The sequence of events occurring inside the cylinder is controlled by three valves located in the cylinder head: air inlet, fuel injection and exhaust. There is also a starting air valve, but we will ignore it for now. The air inlet and exhaust valves are located on the center line of the cylinder, with the injection valve somewhat to the back.

Let us view the action starting at a point when the air inlet valve is open and the piston is moving downward. Air is drawn into the cylinder by suction. The action here is the same as that, for example, which occurs when filling a hypodermic syringe. After the air inlet valve closes the air will be compressed by the piston as it now moves upward. As a result of this compression, the temperature in the cylinder will have risen to about 1000 degrees Fahrenheit, a temperature just above the combustion point of the diesel fuel, a light hydrocarbon distillate oil. After the fuel injection valve opens it remains open for a short time while fuel is introduced into the cylinder. Combustion begins immediately because of the high temperature of the compressed air. The burning is very efficient, in part because the fuel enters in the form of a fine spray. As a result of the combustion, which continues for a while after the fuel valve is closed, the gaseous mixture in the cylinder expands, creating a very high pressure. To withstand these very high pressures requires that the engines have a very robust construction. This pressure forces the piston to be driven down. Finally, the exhaust valve opens and the upward push of the piston gets rid of the combustion products. With the closure of the exhaust valve the cycle of events is ready to repeat itself.

Several points can be noted from the foregoing description:

- During the course of our engine's cycle the piston goes through four strokes – down, up, down, up. Engines such as the Winton 158 – 6, or the Enterprise DMG – 26, are therefore called four – stroke engines. Sometimes one sees them called, somewhat erroneously, four – cycle engines. There are also two – stroke Diesel engines; their inner workings are rather different however.
- The events during these four strokes are usually referred to as intake; compression; expansion or power; and exhaust.
- It is only the expansion stroke that provides the energy to drive the engine.

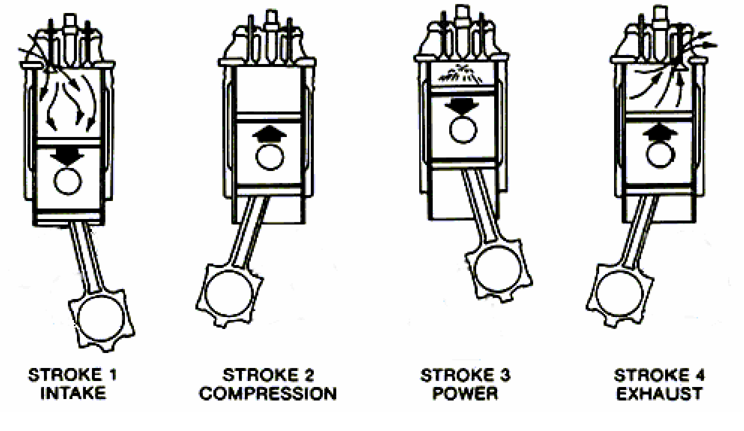


**Figure 1**
**THE FOUR STROKE DIESEL**

In order to turn the ship's propellers, the up and down motion of the piston must be converted into rotational motion of a shaft. Accordingly, a rod – called the connecting rod – is attached to the piston at its upper end and to the rotating shaft at its lower end. A visual summary of the discussion to this point is provided by Figure 1.

## The Connecting Rod And The Crankshaft

The up and down motion of the piston - or, more generally, any opposed in and out motion - is referred to as reciprocating motion.  The connecting rod converts the reciprocating motion into rotary motion.  It is important to note, however, that in order to get a turning motion the connection to the shaft must be offset from the shaft's center. This is accomplished by attaching the bottom of the connecting rod to a crank.  You can think of the crank functioning as a handle attached to the edge of  a wheel.  The attachment of the connecting rod at its top is by means of a pin, the gudgeon pin; at its bottom by the wrist, or crank, pin.  See Figures 2 & 3.

**Figure 2**
**CONNECTING ROD**

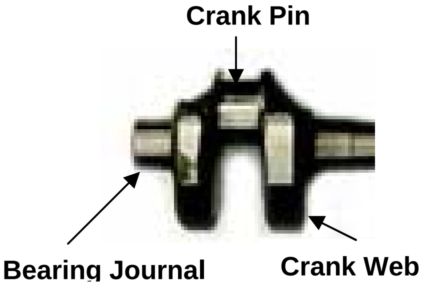


**Figure 3**
**CRANK**

As noted, it is only during the power stroke that energy is created to do the useful work of the engine, with the connecting rod transmitting the energy to the rotating crankshaft.  Some of the energy, therefore, must be stored and then released gradually to provide the power for the other strokes of the engine.  That is, the connecting rod is always an energy transmitting component of the engine, but sometimes from the rotating shaft to the piston.  The energy storing device of the engine is the flywheel, a wheel with a rim of high mass, located just aft of the cylinders.

It should be noted that two complete rotations of the crankshaft corresponds to the complete 4 stroke cycle.

Each cylinder has its own connecting rod and crank so that the power from each cylinder is applied to the crankshaft at the appropriate point in its rotation. This means that the power is being transmitted in a sucession of bursts of energy. However, the high inertia of the flywheel, together with that of the crank webs – the counterweights of the crankshaft - minimizes irregularity in the motion of the shaft by absorbing and releasing energy smoothly with little variation in turning speed.

Diesel engines such as the Winton 159 – 6 or the Enterprise DMG - 26  that are installed in ships such as the Potomac where, in effect, the propeller shafts are just extensions of the crankshaft – that is, the propeller shaft is turning at the same speed as the crankshaft - the flywheel does not have to be as massive as would otherwise be the case since the inertia of the turning propellers contributes to that of the flywheel and counterweights.

## The Arrangement Of The Cranks

For the stability of the crankshaft and the smoothness of the crankshaft's rotation, the position of the several cranks on the crankshaft of a six cylinder engine are displaced from one another by 120 degrees. That is, looking at the crankshaft from the flywheel, say, you would see the shaft with two of the cranks positioned at top dead center, two at 120 degrees past top dead center and two at 120 degrees before top dead center. See Figure 4.

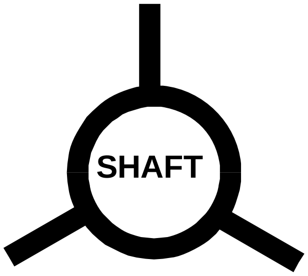


**Figure 4**
**ARRANGEMENT OF CRANKS**
**6 Cylinder Engine**

Up to this point no distinction has been made between the starbord and portside engines. The first difference we note is in the positional arrangement of the cranks for the different cylinders. The Enterprise engine numbers the cylinders with number 1 in the forewardmost position and number 6 the closest to the flywheel The numbering scheme is arbitrary. Some engines reverse the numbering, cylinder 1 then being closest to the flywheel. With this numbering the arrangement is as shown in Table 1.

TABLE 1

| CYLINDER NUMBER | POSITION OF CRANK* | |
|---|---|---|
| | PORT ENGINE | STARBOARD ENGINE |
| 1 | 0º | 0º |
| 2 | 240º | 120º |
| 3 | 120º | 240º |
| 4 | 120º | 240º |
| 5 | 240º | 120º |
| 6 | 0º | 0º |

* In degrees with respect to top dead center

Figure 5 is a schematic of the arrangement viewed from the side.

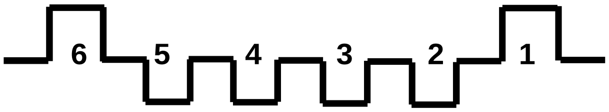


**Figure 5**
**ARRANGEMENT OF CRANKS**

Firing Order

The arrangement of the cranks is very closely related to the order in which the cylinders fire. Again, consideration has to be given to a firing order that will give as uniform and evenly spaced turning impulses as possible, while at the same time minimizing those forces that would cause the engine to get out of balance or produce torsional vibrations.

With both set to ahead, the firing order for the Winton and Enterprise engines are as shown in Table 2:

Table 2

| MODEL | ENGINE | FIRING ORDER |
|---|---|---|
| Winton 158 - 6 | Port | 1,5,3,6,2,4 |
| | Starbord | 1,2,4,6,5,3 |
| Enterprise DMG - 26 | Port | 1,2,4,6,5,3 |
| | Starbord | 1,5,3,6,2,4 |

Valve Timing

In describing the various events taking place in the cylinder we did not indicate specific times for their start or end. By giving the four strokes the names intake, compression, power and exhaust, it might seem that each of these several actions start or end either at the beginning or the end of the stroke, that is, when the piston is either at the very top or very bottom of its motion. In fact, none of the events do so. Since the various events are controlled by the opening and closing of the valves, a more complete description requires specifying when the valves open and close.

Conceptually, describing when the valves open and close could be done by referring to the appropriate stroke and position of the piston. An entirely equivalent approach, and the one normally employed, is to use the position (angle) of the crank with respect to top or bottom dead center of the crankshaft.

To illustrate and fix the ideas involved, we will use the portside Winton engine set to ahead.

The six events we have to specify are the opening and closing of the air intake valve, the opening and closing of the fuel injection valve and the opening and closing of the exhaust valve. The crank angles shown in Table 3 are appropriate for the Winton 158 – 6 at cruising speed. Although timing will vary with different speeds and with different makes and models of engine, the general picture remains the same. In looking at Table 3, recall that two complete rotations of the crankshaft make up a cycle, as do the 4 strokes of the piston.

Table 3

| Event | Crank Angle | Corresponding Piston Stroke |
|---|---|---|
| Air inlet valve opens | 20 degrees before top dead center | Exhaust |
| Air inlet valve closes | 35 degrees past bottom dead center | Compression |
| Injection valve opens | 10 degrees before top dead center | Compression |
| Injection valve closes | 20 degrees past top dead center | Power |
| Exhaust valve opens | 35 degrees before bottom dead center | Power |
| Exhaust valve closes | 20 degrees past top dead center | Intake |

It will be easier to understand what is happening in the cylinder if we look at the processes occurring, rather than the timing of the opening and closing of the valves. For these purposes, we can identify four processes, defined by the interval between valve openings and closings:

| Process | Interval Definition |
|---|---|
| Air Intake | From Opening Of Air Inlet Valve Until It Closes |
| Compression | From Closing Of Air Inlet Valve Until Injection Valve Opens |
| Expansion (Injection,Combustion& Expansion) | From Opening Of Injection Valve Until Opening Of Exhaust Valve |
| Exhaust | From Opening Of Exhaust Valve Until It Closes |

The duration of each of these processes is shown in Table 4:

Table 4

| Process | Duration (in degrees) |
|---|---|
| Air Intake | 235 |
| Compression | 155 |
| Expansion | 155 |
| Exhaust | 235 |

Two points can be seen immediately from Table 4:

- Durations are not equal.
- There must be overlap. For each pair the durations add up to 390 degrees, while a rotation is only 360 degrees.

As an example of this overlap, recall from Table 3 that the air inlet valve opens at 20 degrees before top dead center while the exhaust period does not end until the exhaust valve closes at 20 degrees past top dead center. So both valves are open during 40 degrees of rotation. The reason for this is that as the crank approaches top dead center the piston has very little movement and the cylinder volume above the piston decreases very slightly, even with considerable travel of crank. The exhaust gases flowing rapidly out of the cylinder, as a result of the push given to them by the piston before reached the vicinity of top dead center, have some inertia which maintains their velocity and tends to create a partial vacuum in the cylinder. If the air inlet valve is opened at this time, this vacuum tends to draw air into the cylinder, so that the inward flow of air is actually started before the piston begins to move downward on its intake stroke. This gets more air into the cylinder and consequently makes more air available for burning the fuel.

For another interesting aspect of valve timing, note from Table 3 that the fuel injection valve opens at 10 degrees before top dead center while the piston is still travelling upward in the compression stroke. The reason for this is that combustion is not instantaneous and there is an appreciable length of time between the ignition of the first particles of fuel and spreading of combustion throughout the whole charge. The time interval between sucessive positions of the piston is very short and fuel injection must start before top dead center in order that combustion may be well started by the time the piston starts on its downward stroke. The higher the engine speed, the faster the piston travels and the earlier injection must be started.

The reader may be interested in seeing how the the timing information for the Winton portside engine appeared in its 1931 manual. The timing diagram included here as Figure 6 (on page 8) is the usual way of presenting timing information. The diagram also refers to the starting air valve - ignore it for now.

Figure 7 (also on page 8) is a summary schematic that illustrates several of the concepts discussed above. Accordingly, no specific crank angles are shown. The suction stroke, of course, is the same as the intake stroke.

## Cams And The Camshaft

In order for the engine to operate properly, the rotating crankshaft must continuously “communicate” its position to the valves so that they can open and close in the correct order at the correct time. The valves are actuated by cams that are located on a rotating shaft, the camshaft.The connection between the crankshaft and the camshaft has to take two factors into account: (1) The crankshaft and camshaft are physically separated. (2) The crankshaft makes two rotations per cycle.

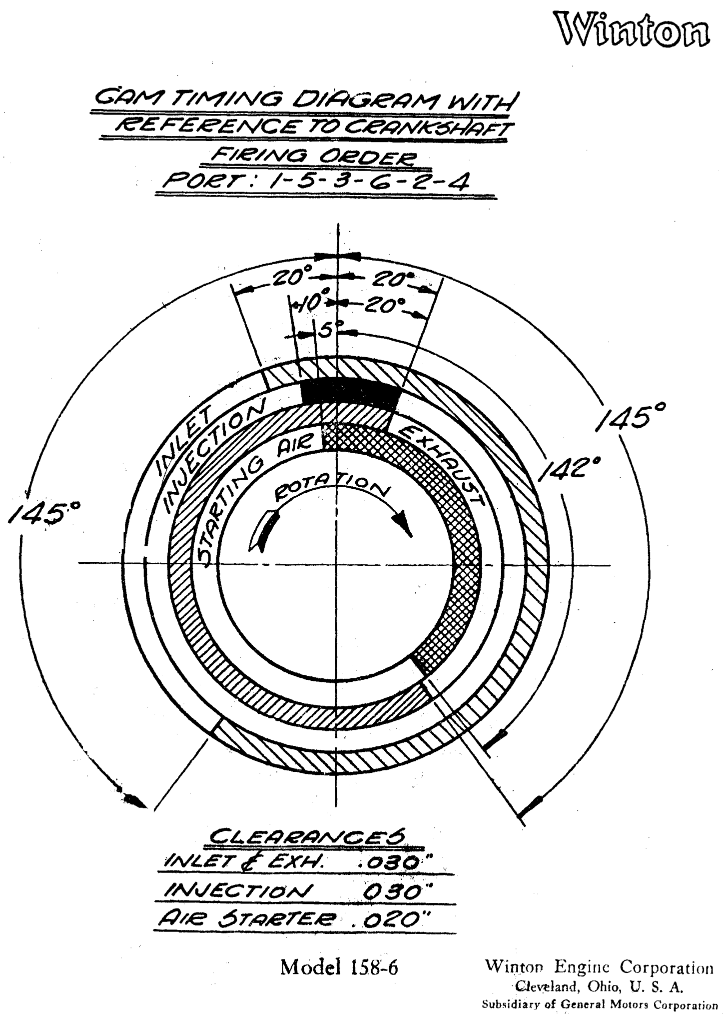


**Figure 6**

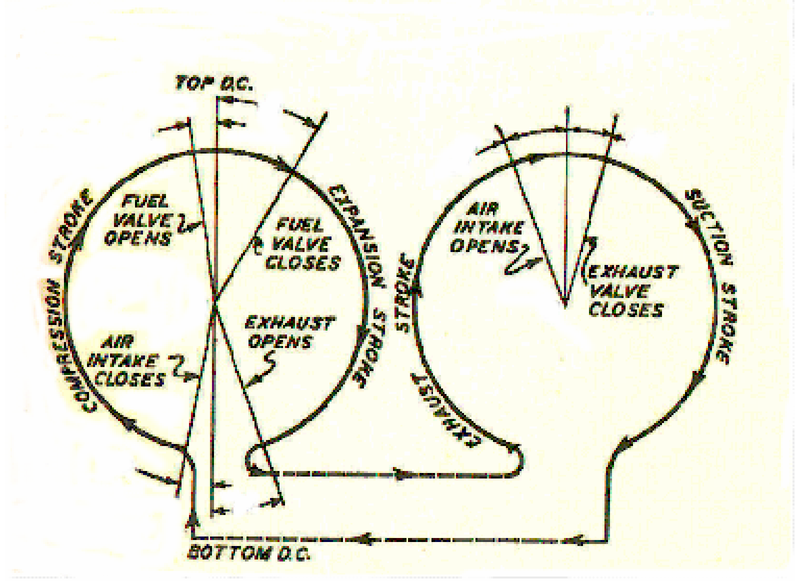


**Figure 7**

A gearing mechanism provides the necessary solution. Details of the valve gear differ among different engines, with some using just gears, others using chain drives and some both gears and chains. Both the Winton 158 – 6 and the Enterprise DMG - 26 use gearing only.

The vertical reciprocating motion that opens and closes each valve is imparted by a rocker arm - a valve lever that rocks on a fixed fulcrum with one end of the lever pressing against the valve stem and the other resting on a roller which is in contact with the cam. Figure 8. shows a cross – sectional picture of a typical cam. As can be seen, the cam is a circle with a ”toe” extending out for some portion of the circle. A valve is activated when the roller comes in contact with the toe. The valve is held open as the roller goes up, over and down the toe. Then, when the roller is once again on the circumference of the base circle, the valve will be closed.

The position of the toe on the base circle determines the valve timing. The height and shape determines the length of time the valve is held open. Thus the inlet and exhaust cams have a much longer toe than the fuel injection cam.

Although the length of time the different valves are held open are the same whether the engine is set to ahead or astern, the timing is different. Accordingly there are separate ahead and astern cams for each valve, separately for each cylinder.

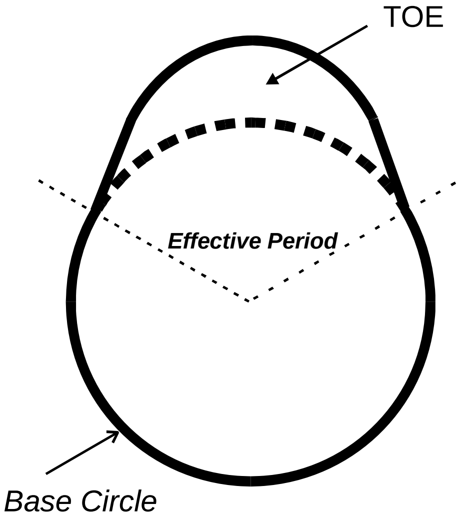
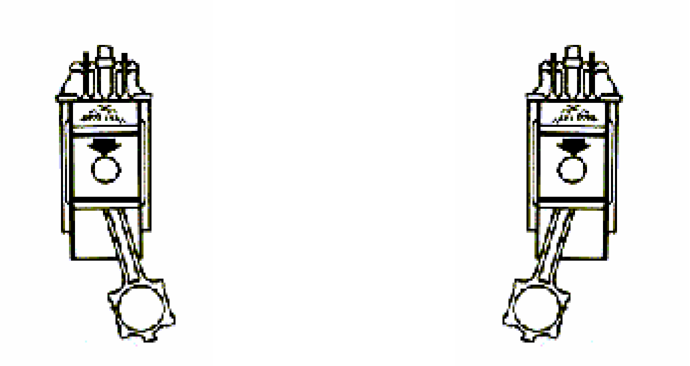


**Figure 8**
**A TYPICAL CAM**

<u>Right And Left Handedness</u>

Looking forward, the crankshaft of a marine diesel engine set to ahead can rotate in either a clockwise or counterclockwise direction. If the rotation is clockwise the engine is referred to as being right handed; if counterclockwise, as being left handed. Whether right or left handed, the engine is operating in the same way. That is, all the strokes of the diesel engine cycle occur and occur in the same order. Similarly, the length of time the various valves remain open remains the same. The difference comes about because of a difference in timing and, in particular, the timing of the power stroke.

The basic idea involved is demonstrated in Figure 9. Remember that it is the power stroke that provides the energy for the rotation of the crankshaft. Figure 9(a) reproduces the power stroke of Figure 1. Because the connecting rod is coming down on the right, the crankshaft is being given a clockwise rotational impulse. That is, Figure 9(a) is a diagram of the power stroke of a right handed engine. However, if the timing is changed so that the connecting rod comes down on the left in the power stroke, we have the situation shown in Figure 9(b), a diagram of the power stroke of a left handed engine.



**(a)**
**right handed engine**

**(b)**
**left handed engine**

**Figure 9**
**POWER STROKE**

Simply summarized, Figure 9(b) is the mirror image of Figure 9(a). The other strokes of a left handed engine are then also mirror images of their counterparts in a right handed engine. Mirror symmetry is also the key to understanding the dfference of the timing diagrams of right and left handed engines. For example, the the fuel injection valve of the portside Winton 158 – 6 opens at 10 degrees before top dead center and closes at 20 degrees after top dead center. See Figure 6. This engine is a right handed engine, as is also noted on the diagram. For the starbord side engine, a left handed engine, the fuel injection valve opens at 10 degrees after top dead center and closes at 20 degrees before top dead center.

On ships which have twin diesels, such as the Potomac, either engine can be a right handed engine. For hydrodynamic stability, the other engine will then be a left handed one. As we have seen, the Winton had the right handed engine to port and the left handed one to starbord. The Enterprise engines now on the Potomac have the right handed engine to starbord and the left handed one to port.

## Reversing The Engine

When direct reversing marine diesel engines such as the Winton 158 – 6 or the Enterprise DMG - 26 are set to astern they operate as their mirror images do. Since the mirror image operation of the portside engine is the starbord engine, the appropriate timing diagram for the portside engine set to astern is the same as that for the starbord engine set to ahead and vice versa. Thus, for example, the diagram in Figure 6 could have been labeled more completely as: “port ahead/ starbord astern”.

To put an engine into reverse, the engine is stopped and the whole camshaft is moved axially so that the astern cams come into the correct position. Clearly, to allow this to happen the gear on the camshaft and the one with which it meshes in the driving train must have straight teeth and the camshaft gear must be wide enough to keep it in mesh in either the ahead or astern position.

It is interesting to note that in the 1931 trial runs of the Thetis, her engines were reversed at full speed in 30 sconds.

## The Starting Air Valve

The starting air valve was mentioned, but ignored, because unlike the inlet, fuel injection and exhaust valves, the starting air valve operates only when the engine is being maneuvered. That is, either at the initial starting up of the engine, or when changes which involve stopping and then starting up again occur, like changing speed or reversing . As with the other valves, the starting air valve is activated by a cam on the camshaft and has its opening and closing events described on the timing diagram. Although on the camshaft, the cam is not in contact with the roller of the starting air rocker arm until the operation of a hand lever brings the cam and roller together. At the same time, the action of this hand lever causes the fuel rocker to be pulled away from its cam.

Starting air – air under pressure – when introduced into the cylinder acts in the same way as do the expanding gases of combustion and will drive the piston down. In other words, we again have a power stroke. A return to the normal underway operation of the engine follows once the engine starts turning.

## Other Diesels On The Potomac

In addition to the two main engines there are 4 other diesel engines on the Potomac: two 6 cylinder generators, driven by John Deere diesel engines; a 2 cylinder Lister-Petter diesel driven pump for pumping sea water to the Potomac’s fire stations in an emergency and the 3 cylinder emergency generator (also a Lister-Petters) located just aft of the pilot house.

## What’s In, What’s Out

This note has tried to include the components and concepts that will provide a good understanding of the Potomac’s engines, while ignoring many facets that are vital to the actual running of the engines but were felt to be too much on the engineering side. Thus there has been no discussion of such topics as how the engine is cooled or how the moving parts are lubricated. Whether or not to talk about piston rings provides a good example of a topic right on the edge. (Piston rings are the technical answer to how the cylinder’s “plug” can be loose enough to allow up and down motion, yet tight enough to act as an effective seal.)

The fact that the Potomac is operating, and operating well, with engines that are over a half century old, taken together with the fact that there are sister ships of the Potomac still operating with their original engines, is a real tribute to their manufacturers and to those who operate and maintain them.

# The 6 Diesel Engines Aboard the Potomac*

2 main engines:

440hp Enterprise Diesels, water cooled
600+ were built in the 1940's by Enterprise Engine Company in SF
6, 12" diameter cylinders, 4 stroke, 400 rpm, reversing
Engines started by compressed air
Engines weigh over 16 tons each
Potomac's Engines built in 1943; are from a WWII tug; were donated by Crowley Marine
[The original 2 main engines were 670hp Winton Diesels, each weighing 26 tons. They were junked sometime after the ship was raised on 3/18/81. As a result of replacing the engines there was a loss of approximately 20 tons of ballast.]

2 60kw Lugger engine/generator sets:

John Deere Diesels equipped with Northern Lights generators
[Assembled by Alaska Diesel Electric Co. in Seattle]
6 cylinder, 1800 rpm, water cooled – produces 120v 208v AC electricity

1 Engine/pump for fire emergency:

2 cylinder "Lister-Peeter" brand Diesel. Made in Dursley, England
12 hp, 3,000 rpm, air cooled
Pumps sea water to 7 fire stations aboard the Potomac

112kw emergency engine/generator set:

3 cylinder "Lister-Peeter" brand Diesel, located aft of pilot house
20hp, 1800rpm, air cooled

Major equipment operated by electric motors:

2 compressors to charge 4 compressed air storage tanks
2 main pumps
1 elevator operated by 1hp 200v electric motor
17hp windlass operated by a Westinghouse 1500rpm electric motor for anchors and bow hawser
1 windlass on starbord boat deck for hoisting boats
Steering gear; quadrant type with arms operating 2 rudders, powered by 1 main electric motor and equiped with 1 auxiliary.

Fuel;

Non taxable #2 Diesel. Fuel contains red dye. Looks pink when mixed.
Total capacity 7,500 gal.; port and starboard tanks each of 3,750 gal. capacity
Burns approximately 50 gals. per hour; approximately 150 running hours (=7500/50)

Propellers:

3 blades, 62" diameter, 53" pitch

Engine is cooled by pumping fresh water through "radiator" type tubes below water line; known as heat exchangers or keel coolers.
Carries 800 gallons of fresh water.
Sewerage is contained in tank for pumping to shore facilities
Originally had a small steam boiler for radiator heating
2 anchors, 450 feet of anchor chain (5 "shots" at 90 feet each)

Outside Engine Room:

Note red $CO_2$ engine room fire suppression tanks
12" diameter main engine piston on display in radio room

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*Engine room summary compiled by Howard Murray