Restoration Plan

For the Tugboat *Arthur Foss*'s 1934
Washington Iron Works Diesel Engine

and

Proposal for a Restoration Workshop Series
to Implement the Restoration Plan

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Executive Summary

The *Arthur Foss* is a historic wooden tugboat built in 1889 and converted to diesel power in 1934. It was retired in 1970, donated to the non-profit institution Northwest Seaport the same year and designated a National Historic Landmark in 1989. It cruised Puget Sound as a heritage vessel with a volunteer crew until 2001. At this time, a combination of rising insurance costs, a damaged throw-out bearing, and difficulty in retaining experienced professionals halted its cruising operation.

A condition report performed by diesel mechanic Adrian Lipp in October 2004 determined that restoring the *Arthur Foss*'s engine would be feasible for Northwest Seaport through planned repairs, service, and maintenance. Many of these activities are also essential to preserving the engine as an artifact, as unchecked corrosion could destroy the engine from the inside out. The condition report also determined that the engine should not be operated until certain repairs were made, to prevent further damage.

This condition survey informed a list of recommended repairs for restoring and preserving the engine. First, the valves and valve cages should be inspected, serviced, and repaired, and extensively corroded cages rebuilt or replaced. Then, the fuel injectors and throw-out bearing should be serviced and rebuilt. The engine bearings should also be serviced and assessed for damage. After these repairs and actions, Northwest Seaport should turn to overhauling each of the engine's six cylinders, starting with a detailed inspection of prior repairs and known issues, then servicing the rings, pistons and liners.

While these actions will return the engine to stable, operable condition, a long-term restoration plan must have two other components. First, an ongoing maintenance and "exercise" plan should be developed and implemented as soon as possible. Second, spare parts should be collected and cared for to ensure the viability of future repairs.

These recommended repairs presented Northwest Seaport an opportunity to develop an innovative public program following a successful restoration workshop model used by other maritime heritage groups. A ten-year Diesel Engine Theory and Practice workshop would break the recommended repairs into segments and invite members of the public to help accomplish specific repairs and maintenance every year.

This proposed workshop series would start by servicing the valves and valve cages in 2005, the fuel injectors in 2006 and the shaft and engine bearings in 2007. After these components are serviced, the workshop would overhaul one cylinder per year for six years, ending in 2013. During the final year, the workshop would service all the components restored during the workshop series and perform a new condition survey to identify the next restoration priorities.

In addition to returning the antique engine to operating condition, holding a restoration workshop series is an excellent opportunity for participants to experience traditional maritime engineering and learn about diesel engine construction and repair. Heavy duty diesels like the *Arthur Foss*'s engine are excellent illustrations of engine construction and repair, as their parts are easily visible and designed to be taken apart with basic tools.

Although the initial condition survey and planning was performed in 2004 and Diesel Engine Theory workshops were held in 2005, 2006, and 2007, this report was finalized in January 2008.

Contents

Introduction 1
- The *Arthur Foss* and its Historic Engine 1
- Condition Survey 2
- Preservation Standards 2

Recommended Repairs 4
- Valves 4
- Fuel Injectors 6
- Major Propeller Shaft Bearings 7
- Engine Bearings 8
- Cylinders 10
- Maintenance Plan 11
- Spare Parts Collection 12

Proposed Workshop Series 14
- Workshop Model for Restoration Projects 14
- Workshop Design: Diesel Engine Theory & Practice 15
- Yearly Objectives 15
  - 2005 – Valves 16
  - 2006 – Fuel Injectors 16
  - 2007 – Bearings 17
  - Bollard Pull Test 18
  - 2008 – Cylinder Four 18
  - 2009 – Cylinder One 18
  - 2010 – Cylinder Five 19
  - 2011 – Cylinder Two 19
  - 2012 – Cylinder Six 19
  - 2013 – Cylinder Three 19
  - 2014 – Service & Re-Evaluation 19
  - Beyond 20
- Anticipated Results 20
- Sample Workshop Curriculum 21
- Sample Workshop Schedule 21

Additional Recommendations 23

Glossary 24

Introduction

Northwest Seaport's historic tugboat *Arthur Foss* holds the status of National Historic Landmark for its significant contributions to regional, national and international events and trade, and for its representation of traditional construction and configuration methods used for coastal tugboats. A vital portion of the tug's significance as a landmark and as a historic ship is its antique diesel engine, installed in 1934 when many industries converted from steam to internal combustion power.

A 2004 condition survey focused on the *Arthur Foss*'s engine, with the intention of assessing its current condition and how to restore it to operational condition. The data from this condition survey was used to create an ordered list of recommended preservation and rehabilitation tasks designed to preserve and rehabilitate this highly significant artifact.

The *Arthur Foss* and its Historic Engine

Northwest Seaport's historic tugboat *Arthur Foss* is powered by a six-cylinder heavy-duty diesel engine manufactured in 1934 by Washington Iron Works. In addition to being an essential part of the *Arthur Foss*, this engine is a significant artifact with connections to regional and national industry.

Washington Iron Works, a Seattle foundry that operated from 1892 to 1986, manufactured steam boilers and logging equipment before launching its diesel engine line in 1921. Adrian Estep, a mechanical engineer at the San Francisco-based Atlas-Imperial Engine Company, partnered with Washington Iron Works to produce a reliable, easily-serviced diesel engine. Between 1921 and 1951, the company manufactured approximately 634 diesel engines that powered tugboats, fishing boats and stationary power plants at logging camps through Washington State and the Pacific Coast. Even after ceasing to manufacture engines, made commercially obsolete by post-WWII technological innovations and changes in labor regulations, the company continued to produce logging cranes and other heavy equipment until closing its plant in 1986.

Today, only fifteen to twenty Washington Iron Works engines remain in existence and of those only eight are still mounted in vessels. The *Arthur*'s engine, number 347 of WIW's diesel line, is the third-largest diesel engine the company ever produced and the largest surviving engine. With an 18" bore, a 24" stroke and a maximum RPM of 200, the engine produced 700 to 900 horsepower. It uses compressed air to start and is direct-reversing, meaning that to turn the propeller in reverse the engine itself is stopped and re-started in reverse. The engine does have a clutch that allows engineers to disengage the propeller, but its speed and direction are telegraph controlled by an engineer rather than from the bridge.

The *Arthur Foss* last cruised on its own power in 2001. At this time, a combination of rising insurance costs and difficulty in retaining both volunteer crew and experienced professional consultants led to a halt of its cruising mission. Additionally, volunteer engine crew observed that the tug's clutch was in poor condition and in need of professional service. While the tug stayed at the dock, restoration activity turned to repairing the bulwarks and the decks through a Save America's Treasures grant. The engine remained un-inspected, raising fears that it had seized and become inoperable. This potential damage made staff and volunteer crew reluctant to work on the engine, which in turn likely increased the engine's deterioration as lubricants degrade and parts can seize or corrode if not operated and serviced regularly.

Condition Survey

On September 14, 2004, professional diesel mechanic Adrian Lipp donated his time to inspect the engine and make a recommended work list. As a former Northwest Seaport volunteer, Lipp had served as chief engineer and caretaker of the tugboat during the 1990s and had extensive experience both operating and maintaining its engine and systems. Now a professional specializing in the large-bore, heavy-duty diesels, he used both professional knowledge and familiarity with the *Arthur Foss* to perform a preliminary condition survey.

The survey's main goal was to determine whether or not the engine had seized. To test this, Lipp oiled all of the engine's moving part, both to prepare it for motion and as an essential maintenance and preservation activity. He then pushed each intake, exhaust and air start valve down manually using a pry bar to lift the valve rockers, which in turn pushed the valves down. Only a small movement was needed to determine that the valves were not stuck. He also performed a brief visual inspection of the cylinder heads.

After finding no apparent damage during this initial inspection, Lipp then turned the engine over by hand for two full revolutions, using a long lever to "bar" it forward. The engine turned over smoothly (though slowly, as is typical for engines of its size), showing that it had not seized. With this evidence, Lipp concluded that the engine could be restored to operational condition with planned repairs and maintenance.

Lipp used the condition survey, previous experience with the *Arthur Foss* and professional knowledge as a mechanic to create a prioritized list of repairs and preservation activities to both restore the engine to operational condition and keep it preserved into the future.

Preservation Standards

As the *Arthur Foss* is both owned by an organization dedicated to historic preservation and recognized as a National Historic Landmark, Northwest Seaport must adhere to certain standards of preservation and documentation to ensure that the vessel's significance and authenticity is not compromised. The government publication *the Secretary of the Interior's Standards for Historic Vessel Preservation Projects* provides general guidelines for preservation and restoration activities, including recommendations specific to machinery and equipment. These include:

- Lubricating bearings, etc, of motors and generators. Rotating, if possible
- Repairing rather than replacing deteriorated material whenever possible
- Cleaning dirt, loose paint, corrosion, etc from machinery using the least caustic/abrasive effective means

- Disassembling and thoroughly cleaning interiors and moving parts of machinery, lubricating parts with clean lubricant.
- Ensuring that operable machinery is not permitted to deteriorate through lack of maintenance or protection
- Establishing and adhering to a regular schedule of inspection, lubrication, and rotation of operable machinery
- Retaining and preserving existing machinery that are important in determining the overall historic character of the vessel

The *Standards* also include recommendations for documentation of historic preservation projects, including:

- Thoroughly recording all work performed on the vessel in the course of treatment, with notations of method and materials used in the work, original fabric affected by the work, and the reasoning or justification for the work.
- Keeping records of regular maintenance and cleaning of the vessel
- Thoroughly recording damage to the vessel from external causes, as well as changes over time in the form or condition of the vessel

In addition to the *Standards*, there is another important resource available to guide the restoration of the *Arthur Foss*'s engine without compromising its authenticity: the original Washington Iron Works diesel engine operation and repair manuals. Old Tacoma Marine Inc has generously provided Northwest Seaport with copies of these manuals, which will be used to determine optimal engine settings and other adjustments.

With these guidelines and resources, any restoration activities on the *Arthur Foss*'s antique engine should:

- Adhere to the guidelines given by the Secretary of the Interior's Standards for Historic Vessel Preservation Projects
- Use the original factory settings and recommendations given by Washington Iron Works in its original manuals
- Be documented through photography, recording specific restoration and maintenance activities, and noting the cleaners, solvents, paints, and other products used on it. This information should be presented in reports to be kept in Northwest Seaport's Arthur Foss archives and to be distributed as requested to stakeholders and community members

These steps will ensure that the *Arthur Foss*'s engine is preserved and restored without sacrificing its significance or authenticity.

Recommended Repairs

The 2004 condition survey informed seven main recommendations for preserving and rehabilitating the engine. First, Northwest Seaport should service the valves and valve cages, and remove those that are extensively damaged and at risk of damaging the cylinder heads. Then, the fuel injectors and throw-out bearing should be serviced and rebuilt. The shaft bearings should also be serviced and assessed for damage. After these repairs and actions, Northwest Seaport should turn to overhauling each of the engine's six cylinders, starting with a detailed inspection of prior repairs and known issues, then to servicing the rings, pistons and liners.

These actions will return the engine to stable, operable condition. To keep it in this condition, Northwest Seaport should create an ongoing maintenance and "exercise" plan for the engine, starting as soon as is feasible. Finally, the organization should accumulate and care for a spare parts collection to ensure future repairs.

Valves

The highest priority for preserving and rehabilitating the engine is to service the intake, exhaust and air start valves. As a six-cylinder engine, the *Arthur Foss*'s engine has six exhaust valves, six intake valves, twelve air start valves (six in the cylinder heads and six over the camshaft) and six snifter valves. These valves are separate pieces inserted into the engine and are meant to be easily removed, serviced or replaced with minimal tools.

Valves are an essential part of the engine, as they regulate the flow of air through the combustion chamber and starting systems. Without operational valves, the engine could experience catastrophic failure. A common scenario for damage due to malfunctioning valves involves a stuck valve protruding into the cylinder's combustion chamber, causing the piston to push against the valve during operation. The valve could either bend or break, causing extensive damage to the cylinder head and possibly cracking it. Cracks in the cylinder head put the engine at risk for spilling coolant water into the combustion chamber and causing even more extensive damage to the engine through hydraulic force on the piston. As such, servicing the valves and ensuring their smooth operation is an essential part of preserving and restoring the *Arthur Foss*'s engine.

Intake and Exhaust Valves – the intake and exhaust valves are mounted in the cylinder head and control the flow of air into and out of the combustion chambers. Each valve is a plunger-shaped piece of metal mounted in a round cast iron "cage" and controlled by springs. The exhaust valves, subject to high temperatures from expelled hot air, are cooled by pumping water into chambers called "water jackets" in the valve cage; the intake valves are cooled by the fresh air they suck into the chamber. Exhaust and intake valve cages are identical, but those in better condition are typically used for exhaust to withstand the high temperatures of gas expelled from the combustion chamber.

During engine work in 1997, volunteer engineers determined that about half of the intake and exhaust valve cages were stuck in the cylinder heads and could not be removed for service. These valves and several others were still stuck during the 2004 condition survey. This stickiness is caused by corrosion in the valve cage water jackets. If not regularly serviced, the corrosion builds up, fills the chamber, and begins to press outwards against the cylinder head. This problem is particularly bad in engines that used a salt-water cooling system at any time, as salt exacerbates corrosion and cannot be flushed out of the cast iron.

As the *Arthur Foss* used a salt water cooling system until 1999 (when a fresh-water system with an external heat exchanger was installed by volunteer crew), the valve cages are almost certainly stuck in the cylinder heads due to this corrosion process. If left alone, the intake and exhaust valve cages will continue to corrode from within, pushing out against the cylinder heads with enough force to crack them.

Air Start Valves – the air start valves control the compressed air that floods the cylinders to start the engine. There are two sets of air start valves on each cylinder, one mounted in the cylinder head and one above the cam shaft.

The condition survey found that many of the air start valves were corroded and sticking. Although these valves are not water-cooled and therefore not subject to the extensive salt-induced corrosion affecting the intake and exhaust valves, the compressed air used to start the engine carries a high volume of water which condenses and leads to corrosion.

The air start valves located in the cylinder head are all stuck in the same way that many of the intake and exhaust valves are stuck, swelling outwards. However, as the corrosion is not salt-induced, these valves will not corrode and swell to the extent that they damage the cylinder head. The air start valves located above the cam shaft are also corroded, causing them to push against the valve guide.

Both sets of air start valves should be removed and serviced similarly to the intake and exhaust valves, but they are not as high a priority as the intake and exhaust valves as they are not at risk of cracking the cylinder heads.

Snifter Valves – the snifter valves are used to relieve excess pressure in the cylinders. The 2004 condition survey found these in good condition. They should be serviced as part of a routine maintenance plan, but are not in need of specific repairs.

Recommendations – Due to the potential damage to the cylinder heads from unchecked corrosion, servicing the intake and exhaust valves and valve cages are the top priority for preserving and restoring the *Arthur Foss*'s engine. The air start valves should also be serviced, though this is not as pressing a priority as the intake and exhaust valves. Servicing these valve sets will involve removing them from the cylinder head, using powerful, specialized tools to extract those that are stuck, machining and cleaning the valves and cages, testing them for fit and condition, and replacing them in the cylinder heads.

Removing the intake, exhaust, and air start valve cages may severely damage or destroy those in the worst condition. Despite this risk, removing them is essential to the long-term preservation of the engine. If left un-serviced, the intake and exhaust valve cages will continue to expand outward, ultimately cracking the cylinder heads from within. As the *Arthur* has several spare valve cages but no spare cylinder heads, damaging or destroying a valve cage may be a necessary action to preserve the engine as a whole.

Fuel Injectors

The next priority for preserving and rehabilitating the engine is to service the fuel injectors. The fuel injectors are installed in each cylinder head and deliver sprays of fuel into the pressurized combustion chambers. They are finely adjusted to spray just the amount of fuel needed for optimal combustion.

When operating the *Arthur Foss* in 1996, the volunteer crew experienced a runaway engine, caused by misadjustments to the engine's fuel injectors. While the runaway problem was resolved later that year, the fuel injectors were never returned to their optimized settings. The 2004 condition survey also determined that a collection of parts for spare fuel injectors had been improperly stored and were in need of maintenance and repairs.

Though the 2004 condition survey did not find evidence of additional damage to the fuel injectors, they are still a high priority for service. According to the original Washington Iron Works diesel engine manual, dirty, leaky or misadjusted fuel injectors can cause excessively smoky exhaust by releasing the wrong amount of fuel into the combustion chamber. This in turn causes an excessive buildup of carbon, which gums up the piston rings and valves. Carbon buildup can cause slow burning and overheating. Misadjusted fuel injectors can also cause "knocking" due to early fuel spray, difficulty starting the engine, cylinders "missing" the combustion stroke or a runaway problem like that in 1996.

Recommendations – After addressing the immediate threat to the engine posed by corroded valve cages, the fuel injectors should be serviced to correct mis-adjustments and ensure that they are clean and functional. Servicing the fuel injectors will involve removing each one from the engine, then disassembling them down their major parts (the housing, spring, stem, nozzle, lever and other pieces), cleaning these parts, performing necessary repairs and then reassembling them.

The fuel injectors should then be tested and the fuel valve setting adjusted according to factory specifications. The original Washington Iron Works diesel engine manual describes the adjustment process:

> "Mount the fuel valve in the test bracket on the side of the engine and connect it to the high pressure fuel systems by means of the pipe provided for that purpose. Pump up the fuel pressure with the hand priming pump to 4000 lbs and set the spring nut on the fuel valve so the stem is just held tight on the seat without leaking at that pressure. Then turn the spring nut down *two turns more* to get the additional spring tension necessary for proper operation of the fuel valve. If the engine smokes with the fuel valve set this way, it may be necessary to set up another half or three-quarter turn on the fuel valve spring nut while the engine is running."

Seattle-area mechanics specializing in heavy duty diesel engines perform this test using a modern torque wrench to precisely measure the amount of pressure needed to open the spray valves. After adjusting the injectors to these original specifications, the resulting pressure measurements are averaged together. After disassembling, cleaning and rebuilding each injector, it is set to this average pressure, resulting in an optimized pressure setting.

As at the time of the 2004 condition survey the engine's built-in test stand was missing, these adjustments may need to be performed in a machine shop with a specialized test stand. While adjusting the fuel valve setting, the injector nozzles should also be checked for unimpeded fuel spray from all five holes in the tips.

After reassembling the fuel injectors and reinstalling them, the engine's timing should be re-set. The original Washington Iron Works diesel engine manual describes how to time the fuel injectors to open at the proper time:

> "Close all the fuel valve shut-off valves on the fuel manifold and open the compression relief valve on each cylinder. Bar the engine over by hand in the same direction it turns while running until the pointer is exactly at the correct opening point as marked on the flywheel. Shorten the fuel valve pushrod and leave it loose
>
> "Open the fuel stop valve for the cylinder which is being timed, set the governor lever in full speed position and pump up the fuel pressure by hand to 4,000 lbs. Then lengthen the fuel valve push rod, watching the fuel pressure gauge, until the pressure drops to 2,000 lbs. then tighten up on the jam nut on the push rod.
>
> "To check this setting, back the engine a few degrees, pump up the fuel pressure again, and in turning the engine in the ahead direction the fuel pressure should drop to almost zero at the correct time of opening the fuel valve. The engine will not idle properly unless this is carefully done. After the fuel valves are properly adjusted, *it is very important* to remove the excess fuel oil from the cylinders by shutting off the fuel stop valves, opening the compression relief valves and turning the engine over on air a few times. The engine should idle well with a fuel pressure of about 1,200 to 1,500 lbs."

The *Arthur Foss*'s engine has marks on its flywheel indicating the proper position for each cylinder during this timing process, while the manual also contains a table that gives relevant measurements for common flywheel sizes.

The spare fuel injector parts should also be serviced, reassembled and tested in the same way as the main fuel injectors, then stored as discussed in a later section of this report.

Major Propeller Shaft Bearings

The two major propeller shaft bearings are babbitted bearings that transfer and control the forces exerted by the engine and the propeller. The throw-out bearing is the part of the clutch that engages and disengages the propeller. The thrust bearing is aft of the clutch and contains surfaces that the propeller shaft pushes against to transfer the thrust from the propeller to the hull. Both of these bearings are babbitted collars that surround the propeller shaft and can be easily damaged by overheating or friction. Babbitt is a soft alloy of tin and other metals that serves as a low-friction contact surface when properly lubricated. It is poured into moulds set onto bearing surfaces, giving babbitted bearings the alternate term "poured bearings."

Throw-Out Bearing – the throw-out bearing is the connection between the clutch control wheel and the clutch itself that allows the propeller shaft to be engaged or disengaged. It the bearing that remains stationary with the clutch controls and a collar that turns with the propeller shaft when engaged. When the control wheel, located near the engineer's station, is turned, it moves the throw-out bearing forward, which compresses a set of metal arms coupled to the clutch wheel. This action pushes the clutch against the flywheel, which engages the propeller shaft.

The *Arthur Foss*'s throw-out bearing was reportedly damaged in 2001 when the clutch was incorrectly engaged and applied excessive force to one side of the bearing. The friction from this force created heat, which damaged the bearing's babbitted surface. The 2004 condition survey confirmed this damage through observing the smeared babbitt visible on the edges of the bearings. This damage can be repaired by removing the throw-out bearing and sending it to a specialized machine shop to remove and re-pour the babbitt, and machine it to the correct specifications.

Thrust Bearing – the thrust bearing is a thick collar around the propeller shaft that contains the contact surfaces that push the propeller against the boat, in turn creating forward or reverse movement. It consists of two halves lined with thickly-poured babbitt, bolted around the propeller shaft and connected to the engine bed.

Though the 2004 condition survey did not examine the thrust bearing, it is assumed to be in good condition as it has no record of malfunction. The original Washington Iron Works operation manual notes that the company's thrust bearings are "extra large and will never give any trouble if properly oiled." While oiling the thrust bearing is part of the extended operation procedures for the Arthur Foss, records of maintenance and lubrication are not archived or accessible. Additionally, the friction generated from the force of the propeller shaft is cooled through a water-jacket system similar to those in the valve cages. As the thrust bearing is cooled with salt water, it is also be at risk of the salt-induced corrosion described in the *Valves* subsection and should be inspected in the future.

Recommendations – After servicing the fuel injectors, the throw-out bearing should be repaired by removing it and re-pouring the babbitted surfaces. This is costly work that can only be performed by a specialized machine shop, but it is absolutely necessary for the long-term preservation of the engine. It is also necessary to complete this repair before engaging the propeller again, as this could further damage the clutch.

Less urgently, the thrust bearing should be serviced by taking it apart and examining the babbitted surfaces for potential wear caused by improper oiling. It should also have inspection holes drilled through the water cooling system to assess corrosion; the results of this inspection may be used to create a repair plan if necessary. However, the lack of actual damage makes this service a low priority compared to the more urgent actions recommended in this report.

Engine Bearings

The engine bearings are used to balance and suspend the engine's pistons, connecting rods and crankshaft within the cylinders and crank pit. There are three sets of engine bearings, the wrist pin bearings, rod bearings and main bearings. The rod bearings and main bearings use poured babbitt surfaces similar to the throw-out and thrust bearings.

These bearings balance the enormous pressures exerted by the engine and should be regularly checked as part of routine maintenance. A damaged bearing can cause extensive damage to the engine, as the contact surfaces between moving parts wear out and bind.

Rod Bearings – the rod bearings are located at the joint between the crankshaft and connecting rod. They are poured bearings shaped like two half-circles set into rectangles and are bolted together over the crankshaft's journal. The flat exterior of the rod bearing is bolted to the flat end of the connecting rod. These should be inspected yearly and serviced when necessary.

There are two main tests to assess the condition of the rod bearings. First, a "bump" test measures the clearance between the bearing and the crankshaft journal by lifting each bearing with a hydraulic jack and using a dial indicator to measure the gap to the thousandth of an inch. The original Washington Iron Works operation manual specifies that the rod bearings should fit to 0.00075 per inch of diameter.

Second, the rod bearings should be tested to make sure that they have the proper clearance on the journal between the two crank throws. This can be assessed by using a pry bar to push the rod bearing to one side and evaluating the noise it makes. If the bearing slides smoothly and makes a sharp "kertok" sound, then the bearing clearance is acceptable. If the sound is dull, absent or "squishy", then the bearing clearance is unacceptable and should be adjusted.

Main Bearings – the main bearings are located on the dividers in the crank pit and hold the crankshaft level. They are poured bearings shaped like two half-circles of metal with babbitted interior surfaces that fit together around the crankshaft in the dividers. These two "shells" can be removed and re-babbitted without disturbing the crankshaft.

The Washington Iron Works manual describes the "strain test" used to check the main bearing alignment:

> "To check the alignment of the main bearings, a strain gauge can be used to a very good advantage. This can be done without disturbing anything on the engine, except to remove the cover plates to get at the shaft of the engine. A strain gauge is simply a dial indicator with an extra heavy spring. The dial rod is pointed instead of flat and there is an adjustable pointed rod on the opposite side of the dial.
>
> "Bar the engine over so the crank bearing is at the bottom of the stroke. Insert the strain gauge between the crank throws as shown in Figure 17. Then bar the engine over, taking readings at each quarter turn. This can be done with the connecting rod in place. The maximum difference in any reading should not exceed 0.006" for 24" stroke engines."

The strain test indicates how much the crank throws flex through one revolution of the crankshaft, in turn indicating how much the crankshaft is flexing. If a main bearing is worn out, the crankshaft will flex more and create measurable strain between the crank throws.

Wrist Pin Bearings – the wrist pin bearings are located at the joint between the piston and the connecting rod. They are visible as thick metal bars of metal on either side of the connecting rod. These should be checked visually to make sure that the connecting rod rides evenly on the bearing. If roughly the same amount of bearing on either side of the connecting rod is visible, then the rod is not bent or flexed at an incorrect angle. They can also be "bumped" like the rod bearings, but this is more difficult due to the position of the wrist pin bearings.

Recommendations – after the immediate threats and damage to the engine have been resolved, the engine bearings should be checked in the ways described above. The results of these tests should then be used to create a maintenance plan and any necessary repairs. In addition to these tests, the floor of the crank pit should be periodically drained of oil and checked for flakes of babbitt, indication of damage to a main or rod bearing.

Cylinders

After these specific repairs are made to the entire engine, the cylinders should each be overhauled. The cylinders are individual units that contain the combustion chambers in which the pistons move up and down. The *Arthur Foss*'s engine has six cylinders, made of cast iron parts that fit tightly together.

Each cylinder should be serviced by disassembling the systems contained within the cylinder, performing a detailed inspection, cleaning and lubricating each system or part, repairing any obvious damage, and putting it back together. This will allow Northwest Seaport to create a complete condition report of each cylinder and to fix specific issues occurring in only one cylinder.

Cylinder One – The 2004 condition survey found Cylinder One in generally good condition. There was some evidence of water leaking from the bottom of the liner, which should be addressed during the inspection and servicing.

Additionally, the head on Cylinder One is of an old style, different from the engine's other heads. It has threads for a different style of valve collar using one big nut rather than two smaller nuts, but has been modified to use the same valve collars as the rest of the cylinders. According to experts in the antique engine community, the engine's cylinder heads were all of this old style, but then were replaced with the newer ones. These experts think that there were subsequent problems with cylinder number one that led to using the old head once again.

Cylinder Two – the 2004 condition survey found Cylinder Two in generally good condition, with no notable damage or issues.

Cylinder Three – the 2004 condition survey found Cylinder Three in generally good condition, with no notable damage or issues.

Cylinder Four – the 2004 condition survey found evidence of damage and repairs to Cylinder Four. There are several metal patches on the exterior, made from lead and attached with small screws. There is also a thick steel band tightened and bolted around where the head meets the cylinder, and a crack in the forward side of the cylinder head. Finally, the water jacket between the cylinder wall and the liner is leaking, indicating a crack inside the cylinder as well.

This damage and repair should be inspected and documented, then disassembled and further inspected. Beyond these first steps, it is difficult to predict what the next steps will be, as they will depend on what mechanics find during the disassembly. The metal patches on the exterior should also be thoroughly inspected to determine whether they are still strong. Depending on the results, they may require repair or possibly replacement.

Cylinder Five – The 2004 condition survey found Cylinder Five in generally good condition, with no notable damage or issues.

Cylinder Six – The 2004 condition survey found Cylinder Six in generally good condition, with no notable damage or issues.

Recommendations – Each cylinder should be individually serviced, starting with removing the rockers, intake, exhaust and air start valves and cages, and fuel injectors from the cylinder heads. These components should already have been cleaned, serviced and rebuilt, but this is an opportunity to quickly clean and service them again.

After removing these parts, the coolant and exhaust system should be disconnected and the cylinder head removed, using the overhead crane in the engine room. The cylinder head should be thoroughly inspected and documented, then cleaned and repaired if needed. Then the piston and connecting rod should be disconnected from the rod bearing and removed from the cylinder through the head, then further disassembled. Once these are out, the rod bearing should be disassembled into its two halves, which should be removed individually due to their weight and the necessity of lifting them out of the crank pit with ropes. Finally, the liner, the metal lining between the cylinder walls and the piston, should be removed from the cylinder, using four hydraulic jacks placed in the crank pit to push up against the liner. If the liner is difficult to remove, it can be heated and paraffin applied to its seals, which should loosen it enough for removal.

Once the cylinder is disassembled in this way, a variety of inspections and repairs should be undertaken. The liner should be inspected for wear above the piston rings, which can develop a ridge from wear. Any ridges present on the liners should be honed off with either a hand tool or by a professional machine shop. The removable, cast iron piston rings should be replaced and new rubber gaskets should be installed on the top of the cylinder where it contacts the cylinder head. The rod bearings should be inspected and serviced if necessary. Finally, the copper head gaskets should be annealed or replaced.

This major disassembly of each cylinder is also a chance to clean and lubricate the individual pieces of the cylinder—especially those components not already serviced—and to fix any additional problems encountered. The bearings should also be checked again during this process, and spare parts should be rotated through the engine. The role of spare parts is discussed later in this section.

Servicing each cylinder is also an excellent opportunity for detailed documentation of the current condition of each cylinder, including past repairs. A new condition report and list of further recommended restoration activities can then be compiled using this information.

Maintenance Plan

In addition to these specific repairs, the *Arthur Foss*'s antique diesel engine should be subject to a routine maintenance plan. These activities, which includes cleaning, lubricating, and exercising the engine and its related machinery and systems, preserves the engine through controlling corrosion and dirt buildup, ensures that any damage will be noticed before it becomes extensive, and keeps the engine and engine room looking authentically cleaned and cared for. Performing these activities will also ensure that the recommended repairs discussed in this report are effective, as the main agents of deterioration will be controlled.

Recommendations – A maintenance plan that is both thorough and feasible should be developed and implemented. Maintenance work should be performed on a set schedule, using a checklist that serves as both a reminder and a record of the work performed, as per the Standards for Historic Vessel Preservation Projects. This should include regular cleaning, lubricating, exercising, and inspecting the engine and its systems, with repairs and painting whenever necessary.

Northwest Seaport may also wish to use these maintenance activities as opportunities for engine-room programming, including short classes, public demonstrations and volunteer involvement.

Spare Parts Collection

The final recommendation from the 2004 condition survey is to care for and expand the collection of spare parts for the *Arthur Foss*'s engine. Maintaining a thorough collection of spare parts is essential to the engine's long-term maintenance and preservation. It is the nature of engines and metal to degrade over time and it is necessary to replace worn or damage parts to preserve the engine as a whole. It also is part of the vessel's authenticity, as tugboats and other working boats would have carried extensive spare part collections to perform in-the-field repairs. Engines manufactured by Washington Iron Works were widely known for their serviceability, with marine engineers able to quickly replace many parts of an engine while underway.

It is also important to have a collection of spare parts if the *Arthur Foss* returns to cruising condition, as engine trouble while underway must be resolved as quickly as possible. Simply operating the engine and the vessel guarantees that pieces will wear, and some may be damaged or destroyed. This is part of the vessel's authenticity and should be planned for, especially as not operating the engine increases the risk of damage to its components.

Recommendations – any existing spare parts should be rehabilitated and properly stored. The 2004 condition survey identified valve cages, fuel injector components, head gaskets, a piston and a rod bearing stored on the tug and in Northwest Seaport's workshop spaces. These are valuable both as spare parts and as original pieces of the vessel. They should be cleaned and serviced, then rotated through the engine to both ensure that they are functional and to wear them evenly.

Any parts not installed in the *Arthur Foss*'s engine should be professionally managed as part of Northwest Seaport's maritime heritage collection. They should be cleaned, inventoried, and stored in a dedicated, climate-controlled space away from other collections to ensure that the off-gassing of materials and lubricants will not damage artifacts.

The organization may wish to create a separate collection for these spare parts to ensure that they are properly cared for but still used in the engine. Any parts too damaged or worn to be used in the engine should be transferred to Northwest Seaport's permanent collection for preservation or its educational collection for public viewing.

The spare parts collection should be actively expanded whenever possible. Washington Iron Works stopped producing its diesel engine line in 1951, but continued to manufacture spare parts on request until about 1980. Since then, new spare parts have been available only through custom machine work and the company itself closed in 1986. As such, many members of the antique diesel community collect parts from Washington Iron Works and other engine brands that can be refurbished and used to keep remaining engines functional. It may be possible to purchase spare parts from these collectors.

However, the *Arthur Foss*'s engine is of the largest specification that Washington Iron Works offered. Only four engines using an 18 by 24 inch cylinder were produced, including the eight-cylinder engine in the former Washington State ferry *Vashon* that was lost in Southeast Alaska in the 1990s. As such, many spare parts for the *Arthur Foss* may be impossible to purchase from collectors or mechanics.

Due to these difficulties, it will likely be necessary to create entirely new spare parts for the *Arthur Foss*'s engine. While many of the original patterns for correctly-sized parts were also lost with the ferry *Vashon*, professional machinists can create new patterns to cast new parts from. Creating these new patterns will be expensive, but once made unlimited spare parts can be cast from them. This process is essential to the long-term preservation of the *Arthur Foss*'s engine.

Proposed Workshop Series

The repairs recommended by the 2004 condition survey and described in this document present opportunities to create programs that use the *Arthur Foss*'s antique engine to educate members of the public about Pacific Northwest maritime heritage. The least of these programming opportunities is resuming the demonstrations and engine room tours that Northwest Seaport provided during the 1980s and 1990s, which exercise the engine as recommended in the maintenance plan. The greatest opportunity is to create a restoration workshop program, following the successful model used by other maritime preservation groups such as the Center for Wooden Boats.

By creating a workshop program that invites members of the public into the Arthur Foss's engine to help perform recommended repairs, Northwest Seaport addresses the three main focuses of its mission: preserving, interpreting, and developing educational opportunities regarding Puget Sound and Northwest Coast maritime heritage. A workshop program would also create opportunities for partnerships within the Seattle maritime heritage community, with organizations such as the Center for Wooden Boats and the Youth Maritime Training Academy interested in expanding their own programs. Finally, creating a workshop program that invites members of the public into a working engine room and educates them about marine repair is a powerful way to recruit and begin training new volunteers to help maintain the *Arthur Foss* and its engine.

Workshop Model for Restoration Projects

The history of maritime restoration workshops in Seattle begins with the Center for Wooden Boats, a non-profit organization dedicated to preserving and interpreting Northwest Coast small craft. Since its origins in the 1970s, the Center identified teaching woodworking and other relevant skills as a high priority for maintaining its vessels. Over the years, teaching became an increasingly important focus for the Center. In 2004, it greatly expanded its workshop programs, offering knot-tying, watercolor painting and other activities beside the traditional woodworking and sail-making. Workshops combine traditional teaching methods such as lectures and demonstrations with hands-on projects that allow students to experience as well as learn.

This model is well-suited for restoring the *Arthur Foss*'s antique diesel engine. Heavy-duty diesel engines like it were designed to be easily serviced “in the field” with few specialized tools. They were built with numerous access panels and exposed systems, and typically carried a variety of spare parts so that damaged pieces could be quickly swapped out without affecting performance. Old-time marine engineers maintained and repaired their machinery themselves. Using a workshop model, Northwest Seaport can provide course participants with an authentic experience without the years of training and apprenticeship.

In addition, the sheer size and design of the *Arthur Foss*'s engine makes it excellent for teaching workshop participants about how diesels and internal combustion engines in general work. It contains nearly all of the same parts as modern truck or marine engines, but many are exposed on the outside or visible through the access doors.

Workshop Design: Diesel Engine Theory & Practice

The recommended repairs from the 2004 condition survey can be broken into discrete tasks that fit into a ten-year restoration workshop series following the model described above. The first nine years would each accomplish a specific repair or set of repairs and supporting tasks that include cleaning, painting, testing, and documenting different engine components. The final year would reassess and service the engine, perform any additional needed repairs discovered and not addressed during the first nine years, and create a new restoration plan. At the same time, the workshop series could teach participants principles of how diesel engines work and how to repair them. Such a workshop series should be named Diesel Engine Theory and Practice, to illustrate its focus of both restoring the *Arthur Foss*'s engine and educating participants about it.

Workshop courses should be open to a maximum of eight participants, since the engine room is of a limited size, and limited to ages fourteen and up. The workshop will involve moving machinery, heavy and fragile tools, and activities that require personal responsibility and long attention spans.

Workshop courses should also include group lunches and a final dinner. In addition to saving time otherwise wasted on finding a prompt and cost-effective meal in the South Lake Union neighborhood, mealtimes are excellent opportunities to informally discuss ideas and problems encountered during course time. Meals in the galley also reflect the authentic experience of working aboard a Puget Sound tugboat, as most tugs carried a full-time cook until the 1960s. The final dinner would allow participants to relax, congratulate themselves and each other, and reflect on the work performed—and be an excellent opportunity to involve board members and to invite family members and guests to view the workshop results.

This proposal is prepared with Historic Ships Wharf at Lake Union Park in mind as a facility, as it is the *Arthur Foss*'s permanent moorage. However, the course should ultimately be able to be hosted anywhere. While the tug currently does not cruise and rarely leaves its moorage, it will return to cruising Puget Sound in the future. Engine room workshops and other programming could ultimately be held even while underway, so as to enhance the authenticity of the experience provided.

Yearly Objectives

The 2004 condition survey identified four specific areas on the engine that should be addressed, the valves, fuel injectors, bearings, and service to the individual cylinders. A schedule of yearly objectives for the proposed Diesel Engine Theory workshop series was created following these nine projects, with the final year focusing on servicing the restored systems and performing a new condition survey. Each yearly session focuses on a different project and includes both major restoration work and routine maintenance.

These yearly objectives should remain flexible, as the results of one session may affect the projects planned for the next. For example, some components due for servicing may be difficult to remove without extensive disassembly beyond the scope of a particular year's course, and should instead be removed while disassembling the entire cylinder.

2005 – Valves

The first year of the Diesel Engine Theory workshop series should address the engine's intake and exhaust valves and valve cages by:

- Removing the engine's six exhaust and six intake valve sets
- Disassembling, cleaning, machining, replacing springs and performing other needed repairs on these twelve valve sets and any spare valve sets
- Reassembling and reinstalling six intake and six exhaust sets; storing spare valve sets

In addition to disassembling, repairing and reinstalling the valves, this process includes additional educational opportunities such as:

- Illustrations of how valves function in an internal combustion engine
- Illustrations of the effects of salt-induced corrosion on cast iron
- Introduction to using machine shop tools and facilities
- Demonstrations of the valve grinding process

At the conclusion of the first workshop session, the *Arthur Foss*'s intake, exhaust, and spare valve sets should be serviced, repaired and re-installed in the engine. Valve cages damaged beyond repair should be replaced with available spares. This step will allow engineers to safely start the engine for the first time since 2001.

2006 – Fuel Injectors

The second year of the Diesel Engine Theory workshop series should address the engine's fuel injectors by:

- Removing the engine's six fuel injectors
- Disassembling, cleaning, machining, and performing other needed repairs on these six injectors and any spare injectors
- Reassembling and testing the fuel injectors, then re-setting them to Washington Iron Works factory specifications
- Reinstalling six rebuilt injectors; storing any spare injectors

Since the rocker assemblies on each cylinder head must be removed prior to removing the fuel injectors, this workshop session should also:

- Remove the engine's rocker assemblies from each cylinder
- Remove the engine's push rods from each cylinder
- Remove the engine's six air-start valves in the cylinder heads
- Disassemble, clean, strip and re-paint the rockers assemblies
- Disassemble, clean, service and repair the air-start valves
- Inspect the push-rods and machine straight if necessary
- Clean and paint each cylinder head
- Reassemble and reinstall the air start valves and the rocker assemblies

In addition to disassembling, repairing and reinstalling the injectors, rocker assemblies and air start valves, this process includes additional educational opportunities such as:

- Illustrations of how fuel injectors function in an internal combustion engine
- Introduction to using machine shop tools and facilities

At the conclusion of the second workshop session, the *Arthur Foss*'s fuel injectors and air start valves should be serviced, repaired, re-set and reinstalled in the engine, and the rocker assemblies and cylinder heads repainted. This step will rectify the mis-adjustments made to the fuel injector timing prior to the 1996 runaway engine.

2007 – Bearings

The third year of the Diesel Engine Theory workshop series should address the engine's bearings by:

- Removing the engine's throw-out bearing from the clutch and bringing it to a professional machine shop for inspection and re-babbitting
- Inspecting and testing the engine's connecting rod, main, and wrist-pin bearings
- Visually inspecting the engine's thrust bearing
- Reinstalling the engine's throw-out bearing

Since the large access panels on the engine's base must be removed to inspect and test its main, rod, and wrist-pin bearings, this workshop session should also:

- Clean the crank pit and oil pump intake
- Strip and re-paint the access panels
- Visually inspect each crank pit bay for babbitt flakes

In addition to repairing the throw-out bearing and testing the connecting rod, main and wrist-pin bearings, this process includes additional educational opportunities such as:

- Illustrations of how each bearing helps conduct force through the engine
- Illustrations of how the pistons connect to the crankshaft and create rotating force
- Tours of an industrial machine shop with the capacity to re-babbitt bearings and perform other specialized work

At the conclusion of the third workshop session, the *Arthur Foss*'s throw-out bearing should be repaired and reinstalled, its main, connecting rod, and wrist-pin bearings inspected and tested, and any problems noted for future repair. This step will allow engineers to safely engage the propeller for the first time since the 2001 damage to the throw-out bearing.

Bollard Pull Test

Between the third and fourth sessions of the Diesel Engine Theory workshop, Northwest Seaport should perform a Bollard Pull test of the *Arthur Foss*'s engine's current power. In this test, a vessel is connected to a stationary dock or other object with a large scale. The vessel then pulls forward while the scale measures the force exerted by the vessel, in turn testing the power of the engine. The test should be replicated at the end of the workshop series, to test improvements made in the engine's efficiency after servicing each cylinder.

2008 – Cylinder Four

The fourth year of the Diesel Engine Theory workshop series should address the engine's fourth cylinder, which shows evidence of extensive past repairs, by:

- Removing the rocker assemblies, intake, exhaust, and air start valve sets, fuel injector and push rods; all previously serviced by the Diesel Engine Theory workshop series
- Inspecting and removing, then cleaning and servicing the cylinder head
- Removing the piston and connecting rod, then disassembling, inspecting, and cleaning each
- Removing and inspecting the cylinder liner, honing out ridges if necessary
- Replacing the piston rings and cylinder gaskets
- Documenting, inspecting, and repairing the existing patches and repairs made to the cylinder in previous years
- Reassembling and reinstalling these component parts, in reverse order of removal

In addition to these activities, this process includes additional educational opportunities, such as:

- Illustrations of how the many components of a cylinder work together within an internal combustion engine
- Illustrations of traditional repair methods for heavy-duty engines, such as pinned lead patches and exterior bands

At the conclusion of the fourth workshop session, the systems in the *Arthur Foss*'s fourth cylinder should be inspected, serviced and repaired. Additionally, the past repairs made to the engine should be documented, with informed speculation on the original causes of damage included in the final report.

2009 – Cylinder One

The fifth year of the Diesel Engine Theory workshop series should address the engine's first cylinder by following the disassembly, inspection, and repair pattern established by working on its fourth cylinder. The order of moving from cylinder four to cylinder one is chosen to balance the engine's firing order.

In addition to the process outlined for cylinder four, the fifth year should investigate the possible water leak in cylinder one and perform repairs if necessary.

2010 – Cylinder Five

The sixth year of the Diesel Engine Theory workshop series should address the engine’s fifth cylinder by following the pattern established by working on previous cylinders.

2011 – Cylinder Two

The seventh year of the Diesel Engine Theory workshop series should address the engine’s second cylinder by following the pattern established by working on previous cylinders.

2012 – Cylinder Six

The eighth year of the Diesel Engine Theory workshop series should address the engine’s sixth cylinder by following the pattern established by working on previous cylinders.

2013 – Cylinder Three

The ninth year of the Diesel Engine Theory workshop series should address the engine’s third cylinder by following the pattern established by working on previous cylinders.

The ninth year should also include creating the patterns to cast new valves and valve cages for the engine’s spare parts collection.

2014 – Service & Re-Evaluation

The tenth and final year of the Diesel Engine Theory workshop series should conclude the ten-year restoration process by:

- Re-servicing the engine’s component systems, such as valve sets, fuel injector and bearings
- Cast new sets of valves and valve cages to expand the spare parts collection and replace any valves that have extensively corroded since the 2005 workshop session
- Conduct a new condition survey, with emphasis on the changes in condition and future work that should be accomplished

In addition to these activities, this process includes additional educational opportunities, such as:

- Illustrations of how the many components of a cylinder work together within an internal combustion engine
- Illustrations of changes in engine components and systems over time
- Demonstration of methods used to survey engines and prepare condition reports

At the conclusion of the tenth workshop session, the *Arthur Foss*’s engine should be stabilized and restored to operating condition. The information gained from the new condition survey should then be used to create a new ten-year plan for restoration activities and a long-term plan for maintaining the systems and components necessary for keeping the engine operational for future decades.

Beyond

After the proposed ten-year span of the Diesel Engine Theory workshop series, the program should be evaluated for continuing it beyond the initial restoration process. Possible new focuses for the course include:

- Routine yearly service and maintenance of engine and components
- Creating new parts and components
- Repair and maintenance of fuel, oil and cooling systems
- Systems outside the engine room that are also the responsibilities of engineers, such as the steering system, compressed air, and plumbing

Northwest Seaport may also wish to further expand its diesel engine programming, by creating programs such as:

- Marine engineer training and practice
- Day-long “engineer for a day” experiences
- “Exchange engineers” from other institutions with a maritime heritage or industry focus

Anticipated Results

If the recommended repairs are made and the Diesel Engine Theory workshop series implemented, Northwest Seaport will:

- Stabilize the engine’s deterioration and restore it to operating condition
- Address damage and agents of deterioration on a system-by-system basis
- Help recruit and train new engine room volunteers
- Create a new plan for long-term maintenance and preservation, focusing on new priorities
- Fulfill Northwest Seaport’s mission of preserving and interpreting maritime heritage through educational programs

The Diesel Engine Theory workshop series as proposed does not address the issues inherent to cruising or operating the engine for long periods of time. Northwest Seaport may need to undertake additional engine repairs or service if the *Arthur Foss* returns to cruising.

Sample Workshop Curriculum

The Diesel Engine Theory Workshop series should use a variety of strategies to educate participants about the operation, repair, and maintenance of an antique diesel engine, including:

- an introduction to the *Arthur Foss*'s history and a tour of the tug, emphasizing the engine's importance to the vessel
- a lecture on Diesel Engine Theory and Function given by Dan Grinstead, a local expert on antique engines and machinery, illustrated with his collection of engine parts cut apart to show the interior chambers
- daily discussions of work to be performed and justification for the work
- demonstrations of complex work, such as valve grinding and bearing machining
- directed and supervised performance of repair and maintenance tasks, such as lubrication, grinding, and disassembly, both on the *Arthur Foss* and at off-site facilities
- relevant field trips to illustrate portions of engine repair not possible on the vessel

The majority of the workshop series will be spent in directed, supervised, hands-on activities to enable participants to learn by applying lecture and demonstration to their own experience.

Sample Workshop Schedule

Each Diesel Engine Theory Workshop session should be laid out over five days and follow a general pattern of introduction, disassembly, repair and cleaning, reassembly, and operation. These day-long classes would be best scheduled on Saturdays to both maximize the number of people who can take them and to allow mechanics to completed needed work between sessions. Due to the nature of the work, a full week may be needed between sessions to complete any work not accomplished and perform repairs too time-consuming for workshop participants.

A sample schedule illustrating an individual workshop follows.

Day One

09:00	Greeting and introductions
09:30	Diesel Engine Theory lecture
10:30	Tour of the *Arthur Foss* and introduction to project
11:30	Start engine, record settings
12:00	Lunch break
13:00	Disassemble engine through demonstrations and supervised participation
16:45	Debrief and cleanup
17:00	Session adjourned

Day Two

09:00	Review of previous session's work, introduction to day's work
09:30	Complete disassembly if necessary; clean and service relevant parts
12:00	Lunch break
13:00	Continue cleaning and servicing
16:45	Debrief and cleanup
17:00	Session adjourned

Day Three

09:00	Review of previous session's work, introduction to day's work
09:30	Clean and service relevant parts
12:00	Lunch break
13:00	Continue cleaning and servicing
16:45	Debrief and cleanup
17:00	Session adjourned

Day Four

09:00	Review of previous session's work, introduction to day's work
09:30	Rebuild and test relevant parts
12:00	Lunch break
13:00	Continue rebuilding and testing, begin reassembly of engine
16:45	Debrief and cleanup
17:00	Session adjourned

Day Five

09:00	Review of previous session's work, introduction to day's work
09:30	Complete reassembly of engine, prepare for operation
11:00	Snack break
11:30	Operate engine, record settings, learn bell signals
14:30	Debrief and cleanup, fill out course evaluations

15:00 Celebratory dinner
17:00 Course adjourned

Additional Recommendations

The recommended repairs and Diesel Engine Theory workshop address the immediate restoration needs for the engine itself. However, there are several tasks that Northwest Seaport should consider undertaking that fall outside this scope.

Oil Cooler – the *Arthur Foss*'s oil cooler is broken and currently disconnected. This should be replaced with a new oil cooler of a similar type (which are readily available for purchase) and hooked up to the engine's oil system.

Air Compressor – the *Arthur Foss*'s main air compressor, located aft of the engine beside the modern generator, should be overhauled and serviced as part of a routine maintenance plan for the engine room.

Battery Banks – the current battery bank in the *Arthur Foss*, located behind a plywood frame, contains batteries that reportedly came from a diesel-electric submarine. Regardless of actual origin, they are quite old and should be replaced with new or newer batteries if feasible.

Keel Cooler – the *Arthur Foss*'s engine was originally seawater-cooled, with coolant water piped directly to the engine from a through-hull fitting. In 2000, Northwest Seaport volunteer engineers converted the engine to use fresh water coolant and installed a heat exchanger on the port side of the engine. While this reduces the corrosion damage from the original seawater-cooling system (it is impossible to eliminate corrosion from an engine that has been saltwater-cooled, as discussed in the *Valves* portion of the recommended repairs), the heat exchanger used to cool the fresh water poses several problems.

First, it takes up significant space on the port side of the engine room and its supports are located in front of the access panels for cylinders number one and three. Second, it may be too small for the *Arthur Foss'*s engine, as some volunteer engineers reported signs of overheating during the brief window between installing the heat exchanger and the halt of cruising. Third, it detracts from the authentic appearance of the engine room, as both the heat exchanger and its additional plumbing and pumps were absent prior to 2000.

Instead of the heat exchanger, Northwest Seaport should consider installing a "keel cooler," a network of pipes that run outside of the hull to cool the freshwater in the coolant system. This would eliminate the need for the heat exchanger and its associated plumbing, both making access to the engine easier and restoring the authentic look of the engine room. It would also eliminate overheating problems, as a keel cooler can address a much higher volume of fresh water coolant.

Glossary

As with many fields, marine engineering and repair contain many specific terms indecipherable to the average lay person. This glossary attempts to clarify a portion of the "engineer speak" used in this document.

Babbitt – an alloy of tin and other metals that creates a low-friction contact surface within engine bearings

Bearing – a low-friction contact between engine parts that move, such as the connecting rod and the crankshaft

Connecting rod – metal rods that connect the piston to the crankshaft

Crankshaft – the horizontal metal bar that transfers the cylinder's up-and-down motion into the round-and-round motion that drives a propeller or other device

Camshaft – the horizontal metal bar that uses metal lobes to push up the push rods; it is connected to the crankshaft with gears

Fuel Injector – an assembly mounted in the cylinder head that connects the fuel system to the combustion chambers and regulates the spray of fuel provided during the power stroke

Journal – the portions of the crank shaft that rest between the protruding throws. The journals form the contact for the rod bearings

Push Rod – the vertical bars installed between an engine's camshaft and its rockers, used to transfer mechanical signals to the engine's valves and fuel injectors

Propeller Shaft – the long cylindrical shaft connected to the engine's fly wheel and crankshaft through a clutch or other system, which rotates the propeller using the force of the engine

Rockers – the metal "arms" mounted on the tops of the cylinder heads that transfer movement from the push rods to the intake valves, exhaust valves, and fuel injectors

Throw – the paired portions of the crank shaft that protrudes at a right angle from its center line. Two crank throws produce the crank "forks" that support the journals

Timing – the sequence and duration of an engine's valves, fuel injectors, or other component performing its specific action during the four-stroke combustion cycle

Valve – a controlled intake or outlet in an engine system, which can be opened and closed to regulate the passage of air, fuel, or other matter into or out of an enclosed space. The term "valve" can also refer to the plunger-shaped pieces of metal that actually seal the space

Valve Cage – a cylindrical cast iron jacket that contains springs, the plunger-shaped valve, and the shaped "seat" that forms the valve seal; some valve cages also contain inlets and outlets for a water cooling system

Washington Iron Works – a Seattle foundry opened in 1882 that manufactured heavy equipment for industry and transportation. It produced diesel engines between 1921 and 1951, and logging equipment until closing in 1986