TECHNICAL REPORT

OGV CLEAN FUEL REGULATION INVESTIGATION OF OPERATIONAL ISSUES PRELIMINARY FINDINGS

ARB CONTRACT NO. 09-410

PREPARED FOR

Air Resources Board
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EXECUTIVE SUMMARY

The California Maritime Academy (CMA) was asked to evaluate issues associated with the implementation of the California Air Resources Board (ARB) ship fuel regulation, which began on July 1, 2009. This recently adopted regulation requires the use of low sulfur marine distillate fuels (distillate fuels) by oceangoing vessels (OGV) within twenty-four (24) nautical miles of the California coastline. While most vessel operators are successfully complying with the regulation without incident, some operators have reported operational difficulties that may be related to fuel switching from heavy fuel oil to distillate fuel. Shipboard issues that are potentially related to the use of distillate fuel under the ARB ship fuel regulation include: 1) vessel stalling, 2) variable engine speed at low loads, 3) difficulty starting, and 4) inability to operate at full cruise speed. ARB requested that the CMA perform the following tasks:

- Task 1: Investigate the root causes of operational difficulties or incidents that could be related to the use of low sulfur distillate fuel
- Task 2: Identify strategies or lessons learned that have been used to address or avoid operational issues found in Task 1
- Task 3: Prepare a technical report that summarizes the findings reported from Tasks 1 and 2, and that recommends solutions to avoid operational issues

This report satisfies Task 3 by summarizing the work that the CMA performed to evaluate the operational incidents related to implementation of the ship fuel regulation and providing recommendations for ship operators.

Based on the available information, CMA Technical Staff believes that heating of the distillate fuel resulting in viscosity below the recommended minimum level, often combined with other factors, was the cause of most operational difficulties associated with the usage of low sulfur distillate fuel. The other factors include: (1) worn fuel system equipment, such as fuel pumps or seals; (2) engine adjustments not optimized for the use of distillate fuels such as rack or governor settings; and (3) operational procedures not optimized for the use of distillate fuel.

The use of a low viscosity distillate fuel combined with worn high-pressure fuel pumps resulted in inadequate fuel injection pressures. Loss of propulsion can result under these circumstances, due to excessive leakage of fuel within the high-pressure fuel pumps. Excessively worn or leaking pumps can result in low fuel injection pressures and incomplete combustion. Therefore, it is critical that shipboard crew maintain the fuel injection pumps within manufacturer’s specifications, and ensure that fuel viscosity is maintained above 2 centistokes (cSt) at the high-pressure fuel pump inlet. Recommendations for improved practices stemming from this review include:

- Perform a Fuel Switching Test Prior to Visiting California
- Determine Condition of High-Pressure Fuel Pumps Using the Fuel Pump Index
- Document Fuel Switching Procedures for the Crew
- Adjust Preventative Maintenance Schedule of Fuel System Components as Determined by Operational Experience
- Specify and Verify Distillate Fuel Viscosity
- Maintain Fuel Systems to Prevent External Leakage
- Check Governor Pre-set Speed Setting or Binding of the Fuel Rack
- Transfer Control from the Bridge to Engine Control Room if the Engine is Difficult to Start
- Evaluate Cylinder Lubrication

1 INTRODUCTION

1.1 Background

In July, 2008, the California Air Resources Board (ARB) adopted a regulation to reduce the public's exposure to air pollutants from ocean-going vessels. The regulation required ocean-going vessel operators to use cleaner-burning low sulfur distillate fuels within twenty-four (24) nautical miles of the California coastline in their main engines, auxiliary engines, and auxiliary boilers, starting in July, 2009 [1]. Ocean-going vessel operators normally use heavy fuel oil (HFO or residual fuel), which is more viscous, and higher in sulfur content and other components that increase exhaust emissions.

Most vessel operators are successfully complying with the ARB regulation without incident. However, some operators have reported operational difficulties that may be related to the use of the distillate fuel.

Observed shipboard issues that are potentially related to the ARB ship fuel regulation include: 1) vessel stalling, 2) variable engine speed at low loads, 3) difficulty starting, and 4) inability to operate at full cruise speed.

The ARB requested that the CMA evaluate the issues associated with implementation of the ship fuel regulation. Specifically, the CMA was asked to perform the following:

- Task 1: Investigate the root causes of operational difficulties or incidents that could be related to the use of low sulfur distillate fuel

- Task 2: Identify strategies or lessons learned that have been used to address or avoid operational issues found in Task 1

- Task 3: Prepare a technical report that summarizes the findings reported from Tasks 1 and 2, and recommends solutions to avoid operational issues.

1.2 Report Scope

The data discussed here and the conclusions reached are based on preliminary data. This report summarizes the work that CMA performed to evaluate the operational incidents related to implementation of the ship fuel regulation from December 2009 through September 2010.

2 INFORMATION AND APPROACH

2.1 Sources of Information and Data Analysis

The CMA, in most cases, did not have access to the involved vessels or crew. Root cause could not be investigated at the source of the incident. All results and conclusions are based upon documents and communications as described below.

The California Maritime Academy reviewed a range of information to support this effort. A variety of documents and information were considered in our evaluation. Relevant documents were United States Coast Guard (USCG) Loss Of Propulsion (LOP)[1] incident reports [2], San Francisco Pilots incident log [3], Long Beach Pilot incident log [4], industry responses to an ARB fleet survey of vessel operator experience with the low sulfur fuel [5], ARB "Overview of Data Gathering on Ocean-Going Ship Operational Experiences" [6], engine manufacturer technical reports from MAN "*Operation on Low-Sulphur Fuels*" [7], "*Wartsila, Distillate Fuel Use, Technical Information to all Owners / Operators of Wartsila RTA and RT-Flex Engines*" [8], MAN, "*Guidelines on Operation on Distillate Fuels, Low-viscosity Fuels*" [9], Hyundai Heavy Industries, "*Operation on MAN B&W engines on the low sulphur fuels*" [10], and service manuals, MAN Diesel, "*46-108 MC Engines [11 &12]",* MAN Diesel, "*50-108 ME Engines*" [13 & 14], Wartsila, "*RTA84C"* [15 & 16], Wartsila, RT-Flex96C [17 & 18]. The CMA also reviewed information from shipping lines, USCG staff who conducted vessel casualty investigations, licensed marine engineers, marine surveyors [19] and other technical data sources [20].

The information described above was analyzed to identify the reported symptom, stated cause, successful remedy, subsequent analysis, and potential root cause. The CMA technical staff also researched the technical documents associated with the use of low sulfur distillate fuels and discussed the information with the appropriate individuals. Phone conferences were held with fleet managers, engine manufacturers' representatives, and marine surveyors. The CMA technical staff also visited vessels to discuss operational problems and methods used for fuel switching with ship-board personnel. In the following sections, CMA Technical Staff provides a brief summary of the data collected on the 3 key sources of information regarding operational experiences: the ARB Survey, USCG LOP Reports and the Pilot Incident Data.

[1] A reportable marine casualty, in accordance with 46 CFR 4.05-1(a)(3), includes a loss of main propulsion, primary steering, or any associated component or control system that reduces the maneuverability of the vessel.

2.2 ARB Ocean-Going Vessel Operational Experience Survey

In fall 2009, the ARB requested any ship owner or operators (shipping lines, tanker operators, cruise lines, etc.) that operate in California to complete the Oceangoing Ship Survey (Survey). The Survey requested information only for oceangoing ships (both domestic and foreign-flagged) that visited a California port in 2009.

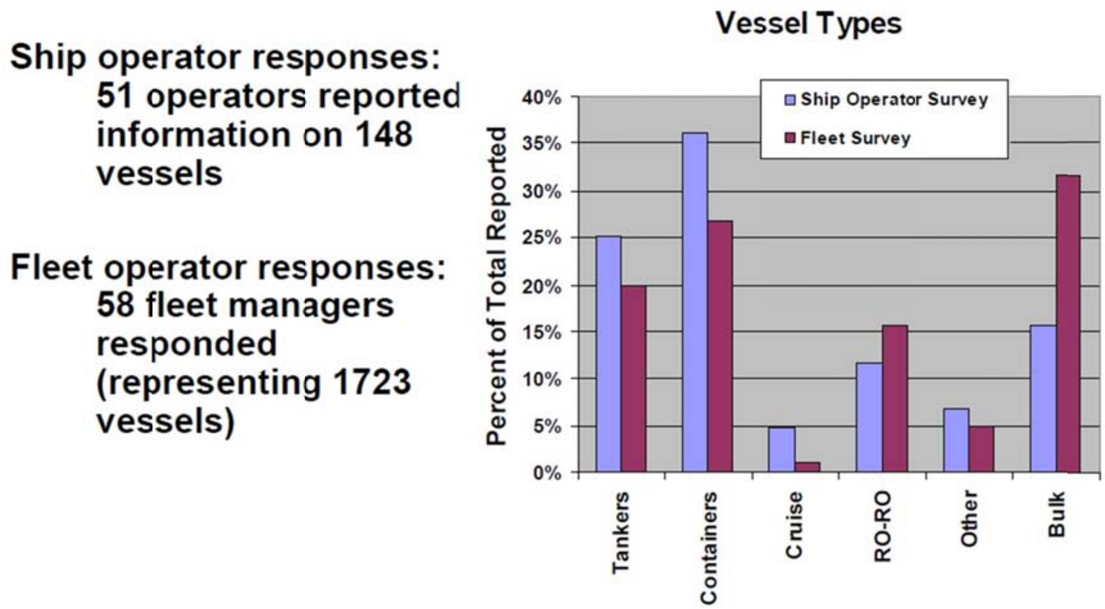
The primary goal of the Survey was to

- Collect information on operational experiences from available sources (vessel owners or operators).
- Compile a central list of information and recommendations.
- Provide information to maritime industry.
- Identify primary areas of concern to aid in implementation.

The Survey consisted of two parts, Part I requested contact information on owner/operator of the vessel/s. Part II requested information on the vessel's engines (such as model, year, horsepower, typical loads and fuels used) and ability to operate on low sulfur distillate fuel.

The survey was sent to the ARB listserve which is comprised of 2400 members. A total of 58 fleet managers responded to the survey, providing information on the fleets that they manage and 51 individual vessel operators responded. Figure 2.2-1 gives an overview of the survey responses and the vessel types which were included in the survey. Additional information on the survey and survey results can be found at:
http://www.arb.ca.gov/ports/marinevess/meetings/042810/ARB_OGV_Data_Gathering.pdf

Figure 2.2-1: Number of OGV Survey Participants and Vessel Types



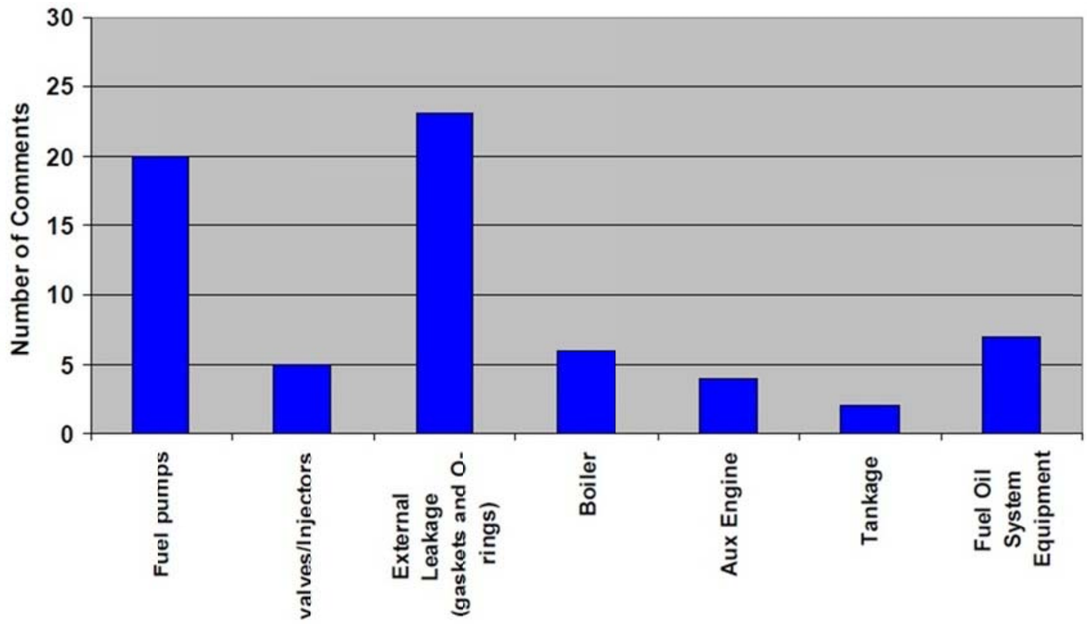
Source: ARB [Reference 5]

The problems reported to ARB in the Survey were very similar in context to the USCG LOP incident reports which will be discussed later in this chapter. As a whole, these two sources of information overlapped though the Fleet Survey revealed problems which did not impact the maneuvering capability of the vessel.

Operational Problems Reported in the ARB Survey

The fuel switching operational problems reported in the ARB Survey were primarily noted as occurring after switching from heavy fuel oil to distillate (see Figure 2.2-2 below) and a higher number of problems were noted during maneuvering as compared to transiting. Equipment problems were noted across a variety of equipment with the highest number of problems focusing on equipment leaks and with fuel pumps as shown in Figure 2.2-2.

Figure 2.2-2: OGV Survey Reported Equipment Problems



***This information was compiled by categorizing the survey comment fields**

Source: ARB [Reference 5]

Excessive fuel leakage due to the low viscosity of distillate fuel can be a significant problem that can affect vessel operation (Figure 2.2-2). Excessive fuel leakage from fuel system gaskets and seals, circulating pump shaft seals, high-pressure fuel pumps, and fuel valves has been reported. Internal leakage through high-pressure fuel pumps and fuel valves can result in an excessive amount of fuel returning back to the fuel drain tank.

When operating on distillate fuel a decrease in fuel oil system pressure due to internal wear of the fuel circulating pumps or hysteresis/sluggish operation of the fuel system back-pressure regulating valve is also a related factor. Low system pressure will retard the timing of fuel delivery to the combustion chamber and will amplify any internal leakage within the high pressure fuel pump. This can be expected to negatively affect peak firing pressures and can result in incomplete fuel combustion.

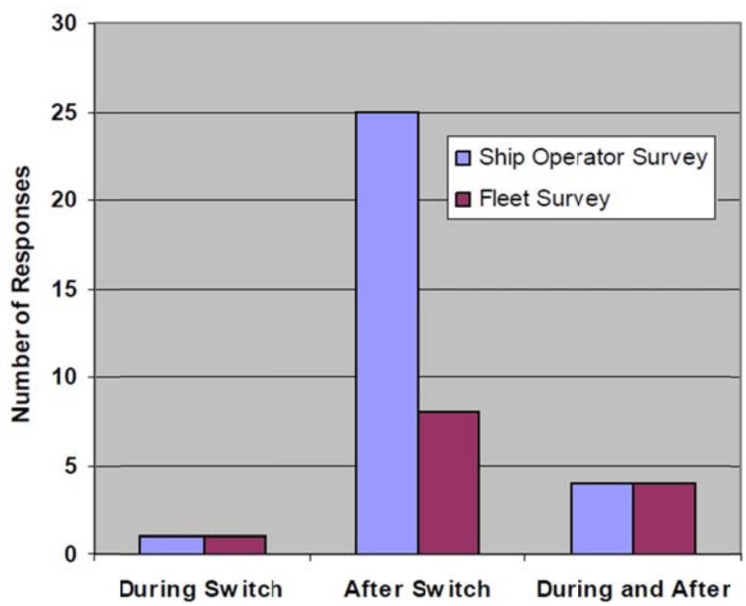
Excessive wear and scuffing on the high-pressure pump was reported. In two Survey reports the condition was sufficiently severe to cause seizure of the fuel pump plunger within the barrel. It is not known if the pump seizures were caused by improper fuel switching procedures or were due to low lubricity of the fuel. It is also not known if the pumps were operated with the fuel viscosity below the manufacturer's minimum limit of 2 cSt.

Some vessels reported that they had difficulty running at their full cruising speed when operating on distillate fuel. Since distillate fuels are less dense than heavy fuel oil, they contain less heat energy per unit of volume. When running on distillate fuel the high-pressure fuel pumps will be required to inject a slightly increased volume of fuel into the combustion chamber to maintain the same power output. This problem was discussed with technical representatives with two of the largest marine propulsion diesel engine manufacturers. The representatives from both companies believed that the high-pressure fuel pumps for these engines are designed to supply sufficient volume and that a reduction in speed should not occur if the engine is operated under normal parameters.

Figure 2.2-3 illustrates the responses to an OGV Survey question "If you had problems, did the problems occur during fuel switching, after fuel switching or both?" Vessel operators reported that more difficulties occurred after fuel switching then the time period during which the fuel switching was taking place.

While the industry has not routinely switched from HFO to distillate fuels when transiting into a port for a number of years, common problems associated with this process, fuel incompatibility and thermal shock, are well understood. It may be this heightened awareness as to the critical factors associated with the fuel switching process which has resulted in the positive outcome. Indeed very few instances of fuel incompatibility or fuel pump seizure due to thermal shock were reported in the survey. This data is an indicator that in the majority of cases these procedures are adequate to protect the engine injection equipment.

Figure 2.2-3: OGV Survey Timing of Problems Due to Fuel Switching



Source: ARB [Reference 5]

2.3 USCG Loss of Propulsion Incident Reports

The USCG routinely tracks loss of propulsion (LOP) incidents. Beginning in early 2009, USGS added a “Fuel Switching Related” designation to LOPs that they believe to be primarily related to fuel switching. A summary of the LOP incidents recorded by the USCG District 11 for ocean-going vessels transiting to and from California ports between January 2009 and July 2010 is provided in Table 2.3-1 and graphically depicted in Figure 2.3-1. As can be seen, during this time there was an increase in total LOP when the California regulation began implementation in July 2009 and then a steady decline for the twelve month period from July 2009 to July 2010 during which the CMA Technical Staff reviewed the USCG reports.

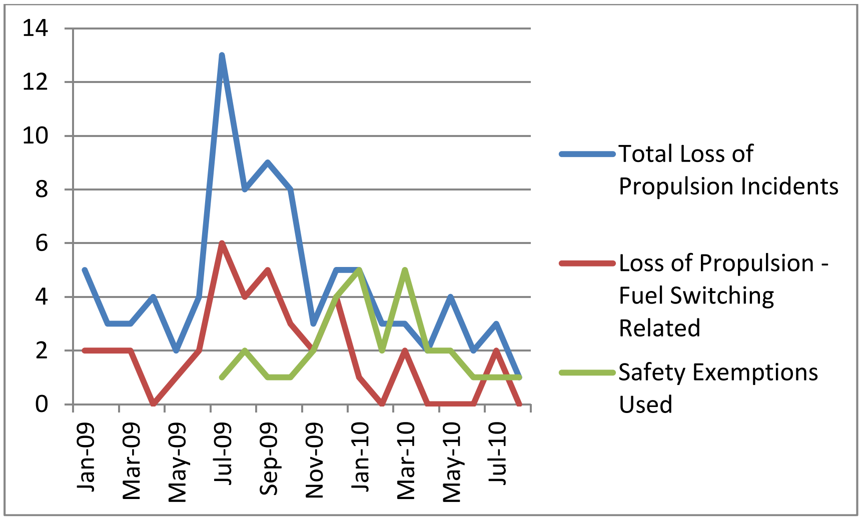
Table 2.3-1 and Figure 2.3-1 also provides data on the frequency that which ocean-going vessel operators used the Safety Exemption. The California ARB ship fuel regulation contains a Safety Exemption, which allows the vessel master to use HFO if that person determines that compliance would endanger the safety of the vessel, its crew, its cargo, or its passengers because of severe weather conditions, equipment failure, fuel contamination, or other extraordinary reasons beyond the master’s reasonable control. A number of vessel masters have utilized this provision to allow the engineering staff time to make necessary repairs to the main engine or fuel system.

Table 2.3-1: Summary of Loss of Propulsion Incidents.

LOSS OF PROPULSION INCIDENTS *Monthly Totals in 2009 - 2010*	Total Loss of Propulsion Incidents	Loss of Propulsion - Fuel Switching Related	Safety Exemptions Used	Problems Reported by Pilots
Jan-09	5	2		
Feb-09	3	2		
Mar-09	3	2		
Apr-09	4	0		
May-09	2	1		
Jun-09	4	2		
Jul-09	13	6	1	33
Aug-09	8	4	2	25
Sep-09	9	5	1	14
Oct-09	8	3	1	14
Nov-09	3	2	2	4
Dec-09	5	4	4	6
Jan-10	5	1	5	
Feb-10	3	0	2	
Mar-10	3	2	5	
Apr-10	2	0	2	
May-10	4	0	2	
Jun-10	2	0	1	
Jul-10	3	2	0	
Totals	*89*	*38*	*28*	*96*

Source: USCG [Reference 1]

Figure 2.3-1: Comparison of Various Loss of Propulsion Incident Types



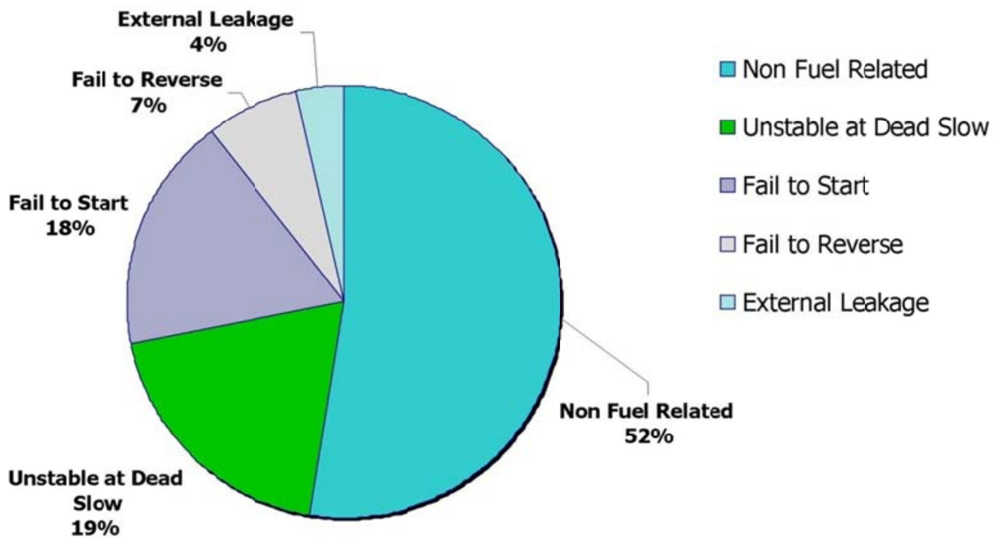
Source: USCG [Reference 1]

It should be noted that over half of all the reported LOP incidents were not listed as fuel switching related, as seen in Figure 2.3-2 below. While there have been some vessels which have had difficulty operating on distillate fuel, LOP incidents are currently at pre-regulation levels. With about 10,000 vessel visits between July 1, 2009 and July 31, 2010 the vast majority are successfully operating on distillate fuel. However, continued operational difficulties remain a concern and this report provides an initial evaluation of the root causes of LOP incidents.

<u>Operational Problems Noted in the LOP Incident Reports</u>

CMA Technical Staff reviewed the LOP incident reports that were denoted by the USCG as being fuel switching related and identified the primary operational issue that resulted in the LOP. As shown in Figure 2.3-2, the primary operational issues noted were: the main propulsion engine was unstable at low loads, the main engine failed to start, excessive fuel leakage, and failure to reverse. It is the opinion of CMA Technical Staff that the LOP incidents are primarily related to: 1) fuel viscosity management, 2) maintenance procedures, 3) crew training, and 4) fuel system equipment condition. Below, CMA Technical Staff discuss the four operational issues most commonly reported in the LOP Fuel Switching Related reports reviewed as part of this investigation.

Figure 2.3-2: Breakdown of LOP Incidents.



(Data obtained from information contained within USCG Incident Reports)
Source: USCG [Reference 1]

FAIL TO START

The main engine will not start on distillate fuel. In many cases, this was preceded by unstable operation at Dead Slow. The specific cause in each case varied but included excessively worn high-pressure fuel pump plunger/barrel wear, misadjusted or inoperative variable injection timing, low pressure within the fuel system, sticking high-pressure pump suction valve push rods, and excessively low fuel viscosity.

UNSTABLE AT DEAD SLOW

The main engine speed varies or the engine stalls when running at Dead Slow. The engine will run reliably at higher speeds. In many cases, this problem was resolved by simply increasing the engine governor setting so as to raise the Dead Slow speed by 2 or 3 RPM. In other cases, engine control was transferred from the Bridge to Engine Control Room because this allows a finer control of engine speed.

FAIL TO REVERSE

The main engine can run at low loads and will start normally; however, it cannot start when the engine attempts to reverse while the vessel is proceeding through the water above a certain speed. In that condition, there can be considerable negative torque created by the propeller “wind milling”. An engine that can start in the ahead direction may have trouble in this scenario due to the extra load imposed by the “wind milling” effect of the propeller.

EXTERNAL LEAKAGE

There are leaking O-rings on fuel valves (fuel injectors) causing excessive fuel leakage and leakage on high-pressure manifold. Loss of propulsion was due to a voluntary shut-down of the main engine to repair leakage before vessel proceeded to its destination.

Types of Vessels and Engines Involved in LOP Incidents

To date all of the vessels reporting a loss of propulsion have utilized the 2-stroke cycle slow-speed crosshead type diesel engine for propulsion. Figure 2.3-3 illustrates the different types of vessels which encountered Fuel Switching Related LOP incidents.

Figure 2.3-3: Vessel Types Involved in Fuel Switching Related LOP Incidents from 7/1/09 through 9/2/10

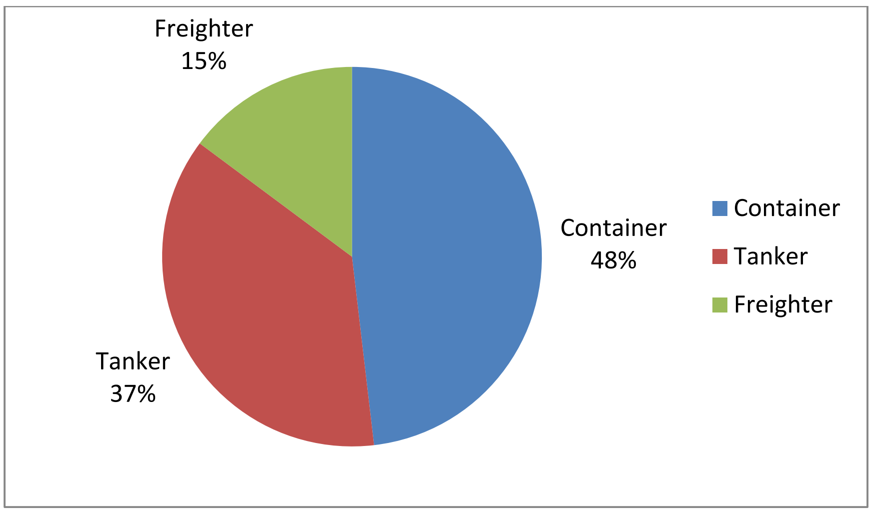


Figure 2.3-4 is a breakdown of all LOP incidents regardless of cause. A comparison of the engine bore size for fuel switching related LOP incidents is given in Figure 2.3-5. While engines with bore sizes between 600 & 700 mm have the highest percentage of incidents, this may be due to the popularity of this engine size.

Figure 2.3-4: Vessel types Involved in LOP Incidents from 1/1/09 through 9/2/10

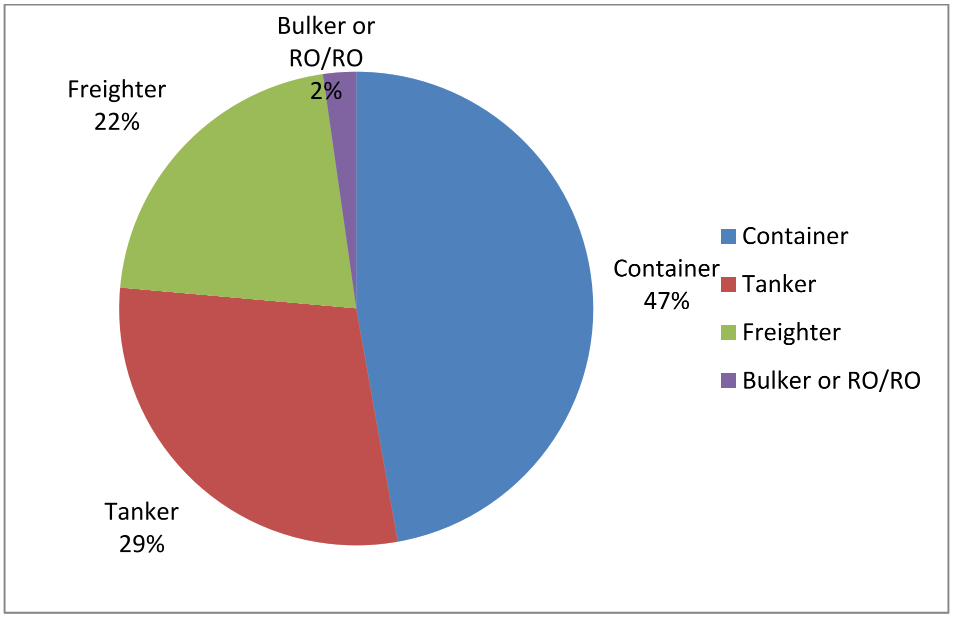
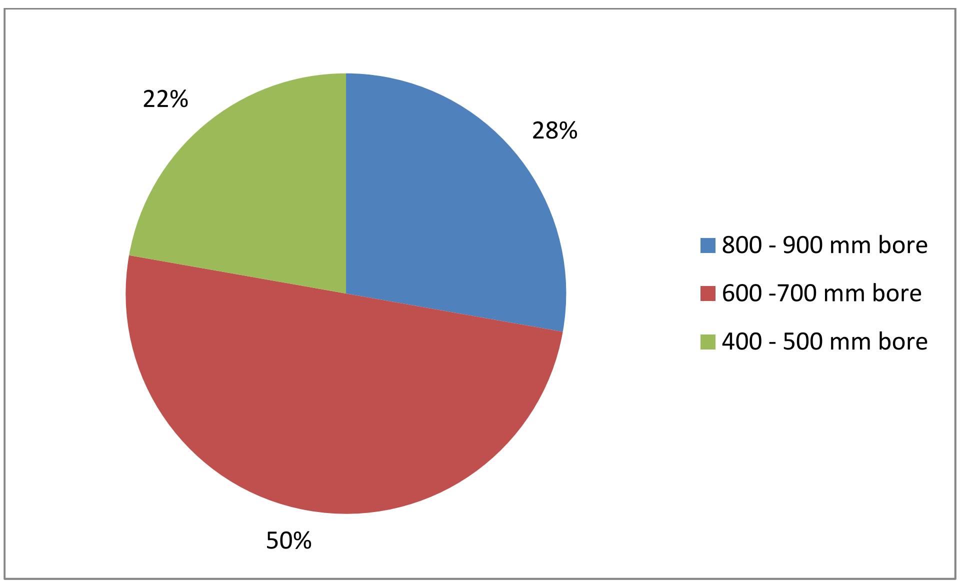


Figure 2.3-5: Fuel Switching Related LOPs Referenced by Cylinder Bore Size



The fact that engines with fewer than seven cylinders have the largest percentage of fuel switching related LOP's as shown in Figure 2.3-6 may be more than purely statistical. The more cylinders that an engine has the less it would be affected by poor combustion in one of those cylinders.

Figure 2.3-6: Fuel Switching Related LOPs Referenced by Number of Engine Cylinders

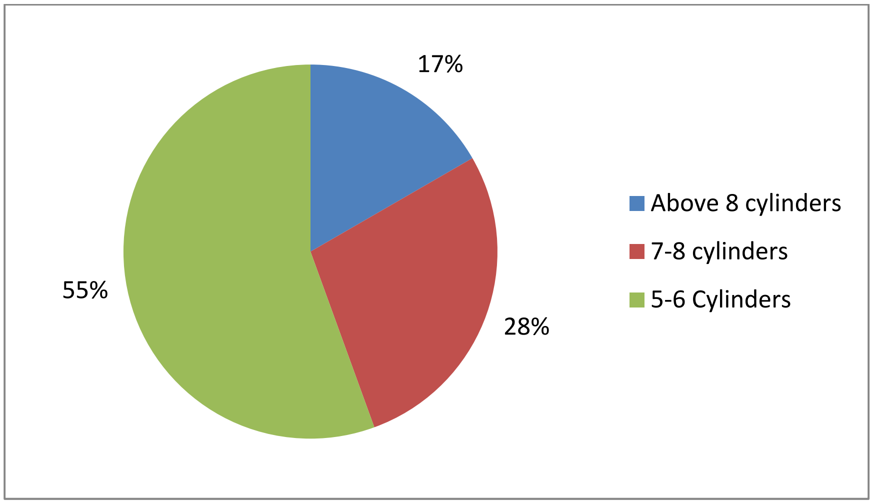
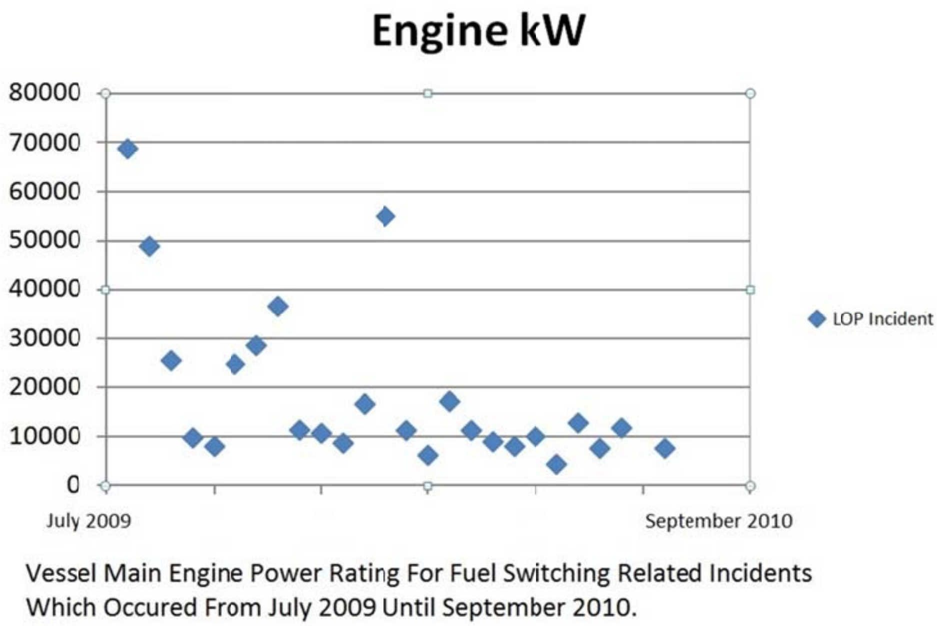


Figure 2.3-7 lists the propulsion power of those vessels which experienced fuel switching related LOP incidents. After carefully considering all the data provided concerning the different 2-stroke cycle diesel engines which experienced fuel switching related LOP incidents, we did not have sufficient information on vessel population to determine if there is a trend or if the data simply reflects the percentage of engines in the fleet visiting California.

Figure 2.3-7: Fuel Switching Related LOPs Referenced by Propulsion Power Output

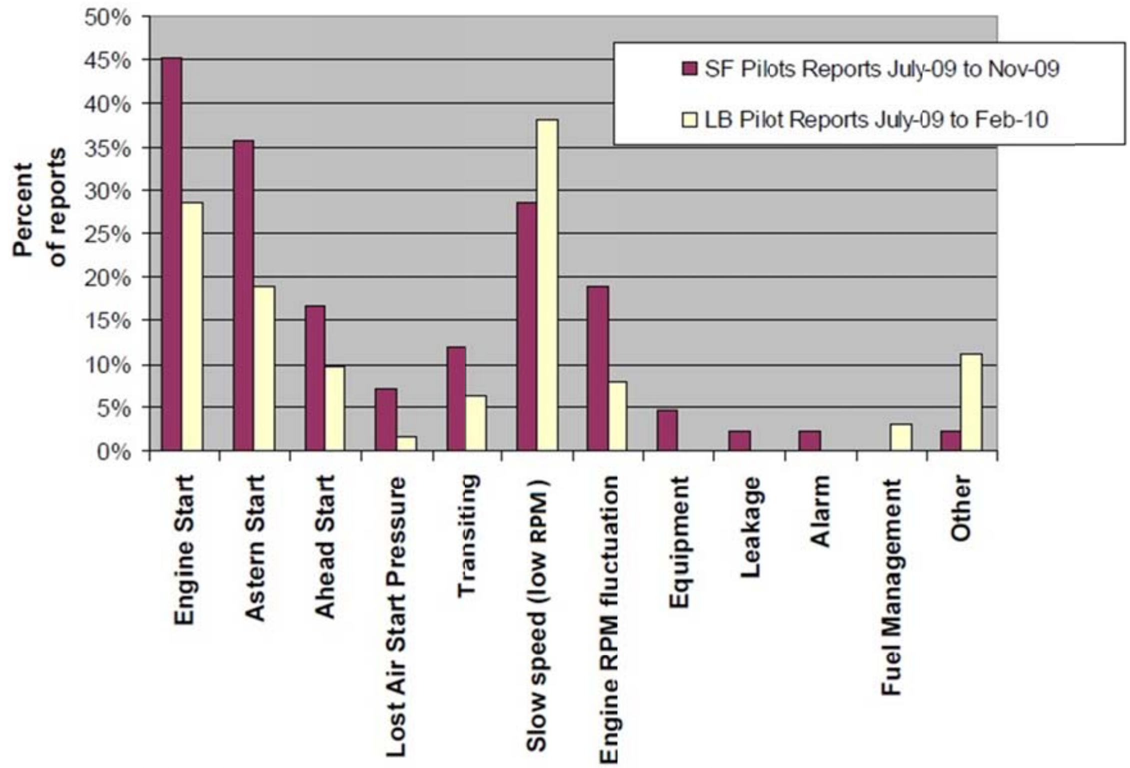


Source: USCG [Reference 1]

2.4 Bar Pilot Incident Logs

From July 2009 through December 2009, the San Francisco Bar Pilots and the Long Beach Bar Pilots maintained logs of any operational issues that they noted while piloting a vessel. The types of operational issues were grouped into 12 categories as shown in Figure 2.4-1 below. The operational problems reported show similar patterns to the USCG LOP incident reports. However, problems noted in the pilot logs did not always lead to an LOP incident.

Figure 2.4-1: Breakdown of OGV Incidents Reported by SF Bar & LB Pilots



***Based on 42 SF Bar Pilot reports and 63 LB Pilot reports**

As is shown, the vast majority of the operational incidents reported instability of the engine at low RPM (Dead Slow) or failure to start while running on distillate fuel. In addition, some vessels have reported difficulty starting the main engine in the astern direction while the vessel is moving through the water above a certain speed. The CMA Technical Staff believes the root cause for all three of these problems was poor combustion at low loads caused by low injection pressures and/or improper injection timing.

3 RESULTS AND DISCUSSION

In this section, CMA Technical Staff provide a general overview of fuel types followed by the range of possible root causes considered as part of this preliminary evaluation.

3.1 Marine Fuel Types

Marine distillate fuel characteristics and specifications are described by the International Maritime Organization (ISO) 8217 fuel standard. Marine distillate fuels are listed in this standard as DMX, DMA (MGO), and DMB (MDO). DMX is not normally carried aboard merchant vessels as it has a lower flashpoint and additional storage requirements. DMA and DMB are the most common distillate fuels and they have guaranteed good combustion characteristics due to the specified cetane index (see Table 3.1).

Distillate fuels, as compared to heavy fuel oil, have far fewer handling requirements, burn cleaner, and contain considerably less ash or carbon residue. Engine manufacturers have indicated that viscosities for DMA and DMB distillate fuels have no adverse effect on the operation of fuel injection components as long as the 2 cSt minimum viscosity is maintained. Low sulfur distillate fuels typically have a viscosity in the lower part of the allowable range which can cause problems if the fuel is heated excessively within the fuel system. The temperature-viscosity diagram Table 3.2 graphically shows the effects of temperature on the viscosity of marine distillate fuels.

Distillate fuels have considerably lower densities than residual fuel which results in a net reduction in the calorific values by volume. As high pressure fuel pumps are volume controlled, the fuel pump index will typically increase to maintain the same engine load.

Marine Residual Fuels (RMX, HFO or residual fuel) are categorized by their viscosity at 50° C. As the name implies, these fuels are the residual left behind in the crude oil cracking process. They contains a concentration of unwanted impurities like vanadium, sodium, and up to 5% m/m sulfur and are unsuitable as fuels for most other land and marine-based equipment because of their high emissions.

The ability to burn heavy fuel oil in the slow-speed crosshead diesel engine began in the mid-1950's. Considerable research and development was required to overcome the inherent problems in burning HFO. The initial breakthrough came with the availability of cylinder lubricating oils which could neutralize the formation of acids which formed as a result of the combustion of high-sulfur fuel oils.

Vessels operating in either the International Maritime Organization (IMO) Emission Control Areas (ECA) or under the ARB Fuel Regulation mandate will be required to burn fuels with a sulfur content considerably lower than the upper sulfur limit of DMA as specified in the ISO 8217 fuel standard.

Table 3.1: ISO 8217 Fuel Standard

DNV MANAGING RISK

ISO 8217 Fuel Standard, Fourth Edition 2010

For marine distillate fuels and for marine residual fuels.

MARINE DISTILLATE FUELS

Parameter	Unit	Limit	DMX	DMA	DMZ	DMB
Viscosity at 40°C	mm^2/s	Max	5.500	6.000	6.000	11.00
Viscosity at 40°C	mm^2/s	Min	1.400	2.000	3.000	2.000
Micro Carbon Residue at 10% Residue	% m/m	Max	0.30	0.30	0.30	-
Density at 15°C	kg/m^3	Max	-	890.0	890.0	900.0
Micro Carbon Residue	% m/m	Max	-	-	-	0.30
Sulphur [a]	% m/m	Max	1.00	1.50	1.50	2.00
Water	% V/V	Max	-	-	-	0.30 [b]
Total sediment by hot filtration	% m/m	Max	-	-	-	0.10 [b]
Ash	% m/m	Max	0.010	0.010	0.010	0.010
Flash point	0°C	Min	43.0	60.0	60.0	60.0
Pour point, Summer	0°C	Max	0	0	0	6
Pour point, Winter	°C	Max	-6	-6	-6	0
Cloud point	°C	Max	-16	-	-	-
Calculated Cetane Index		Min	45	40	40	35
Acid Number	mgK0H/g	Max	0.5	0.5	0.5	0.5
Oxidation stability	g/m^3	Max	25	25	25	25 [c]
Lubricity, corrected wear scar diameter (wsd 1.4 at 60°C [d]	um	Max	520	520	520	520 [c]
Hydrogen sulphide [e]	mg/kg	Max	2.00	2.00	2.00	2.00
Appearance			Clear & Bright [f]			[b, c]
a	A sulphur limit of 1.00% m/m applies in the Emission Control Areas designated by the International Maritime Organization. As there may be local variations, the purchaser shall define the maximum sulphur content according to the relevant statutory requirements, notwithstanding the limits given in this table.					
b	If the sample is not clear and bright, total sediment by hot filtration and water test shall be required.					
c	Oxidation stability and lubricity tests are not applicable if the sample is not clear and bright.					
d	Applicable if sulphur is less than 0.050% m/m.					
e	Effective only from 1 July 2012.					
f	If the sample is dyed and not transparent, water test shall be required. The water content shall not exceed 200 mg/kg (0.02% m/m).					

MARINE RESIDUAL FUELS

Parameter	Unit	Limit	RMA [a]	RMB	RMD	RME	RMG				RMK		
			10	30	80	180	180	380	500	700	380	500	700
Viscosity at 50°C	mm^2/s	Max	10.00	30.00	80.00	180.0	180.0	380.0	500.0	700.0	380.0	500.0	700.0
Density at 15°C	kg/m^3	Max	920.0	960.0	975.0	991.0	991.0				1010.0		
Micro Carbon Residue	% m/m	Max	2.50	10.00	14.00	15.00	18.00				20.00		
Aluminium + Silicon	mg/kg	Max	25	40		50	60						
Sodium	mg/kg	Max	50	100		50	100						
Ash	% m/m	Max	0.040	0.070			0.100				0.150		
Vanadium	mg/kg	Max	50	150			350				450		
CCAI	-	Max	850	860			870						
Water	% V/V	Max	0.30	0.50									
Pour point (upper) [b], Summer	°C	Max	6		30								
Pour point (upper) [b], Winter	°C	Max	0		30								
Flash point	°C	Min	60.0										
Sulphur [c]	% m/m	Max	Statutory requirements										
Total Sediment, aged	% m/m	Max	0.10										
Acid Number [e]	mgKOH/g	Max	2.5										
Used lubricating oils (ULO): Calcium and Zinc; or Calcium and Phosphorus	mg/kg	-	The fuel shall be free from ULO, and shall be considered to contain ULO when either one of the following conditions is met: Calcium > 30 and zinc >15; or Calcium > 30 and phosphorus > 15.										
Hydrogen sulphide [d]	mg/kg	Max	2.00										
a	This residual marine fuel grade is formerly DMC distillate under ISO 8217:2005.												
b	Purchasers shall ensure that this pour point is suitable for the equipment on board, especially in cold climates.												
c	The purchaser shall define the maximum sulphur content according to the relevant statutory requirements.												
d	Effective only from 1 July 2012												
e	Strong acids are not acceptable, even at levels not detectable by the standard test methods for SAN. As acid numbers below the values stated in the table do not guarantee that the fuels are free from problems associated with the presence of acidic compounds, it is the responsibility of the supplier and the purchaser to agree upon an acceptable acid number.												

Source: ISO 8217 Fourth Edition 2010 -06-15

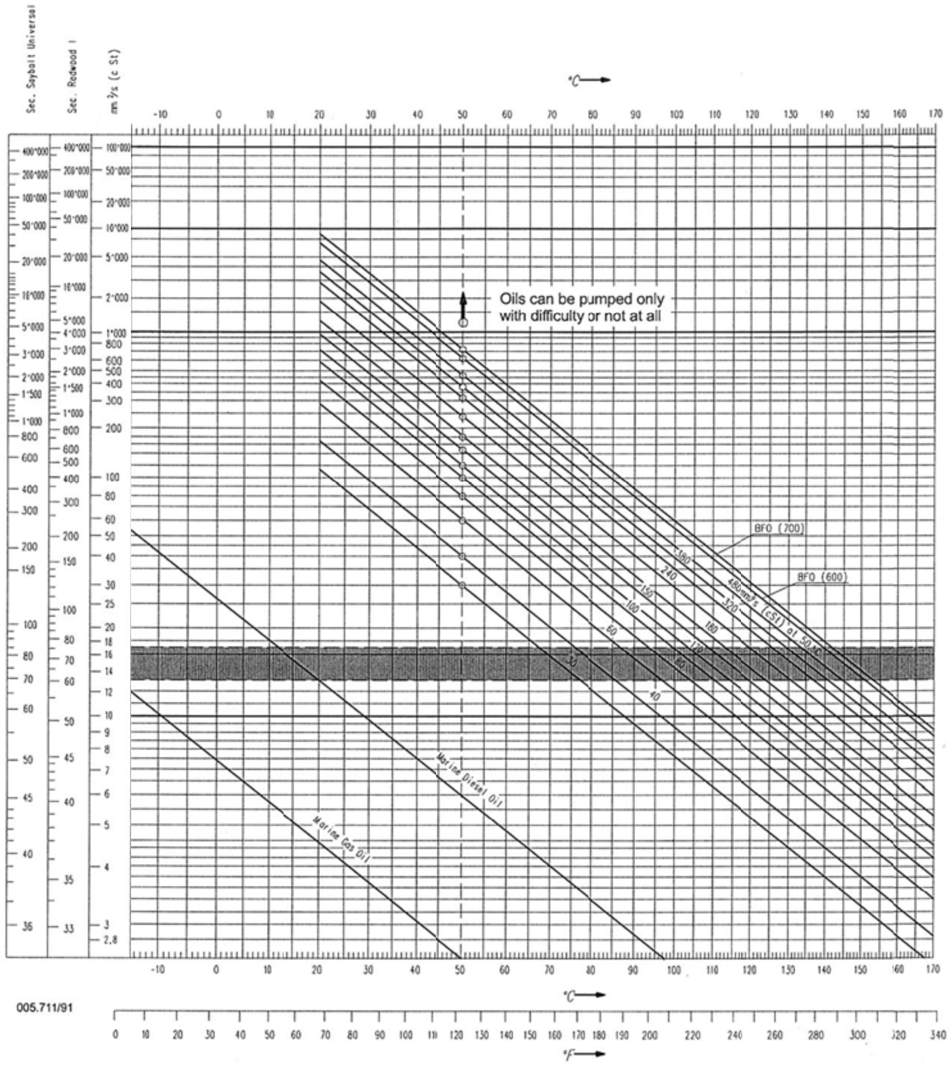
Source: Det Norske Veritas [Reference 21]

Table 3.2: Temperature-Viscosity Diagram

SULZER **RT-flex96C** Operation **0270–2/A1**

Viscosity - Temperature Diagram

Typical Values of Petroleum Fuel Oils



Recommended viscosity before fuel pumps

Example:

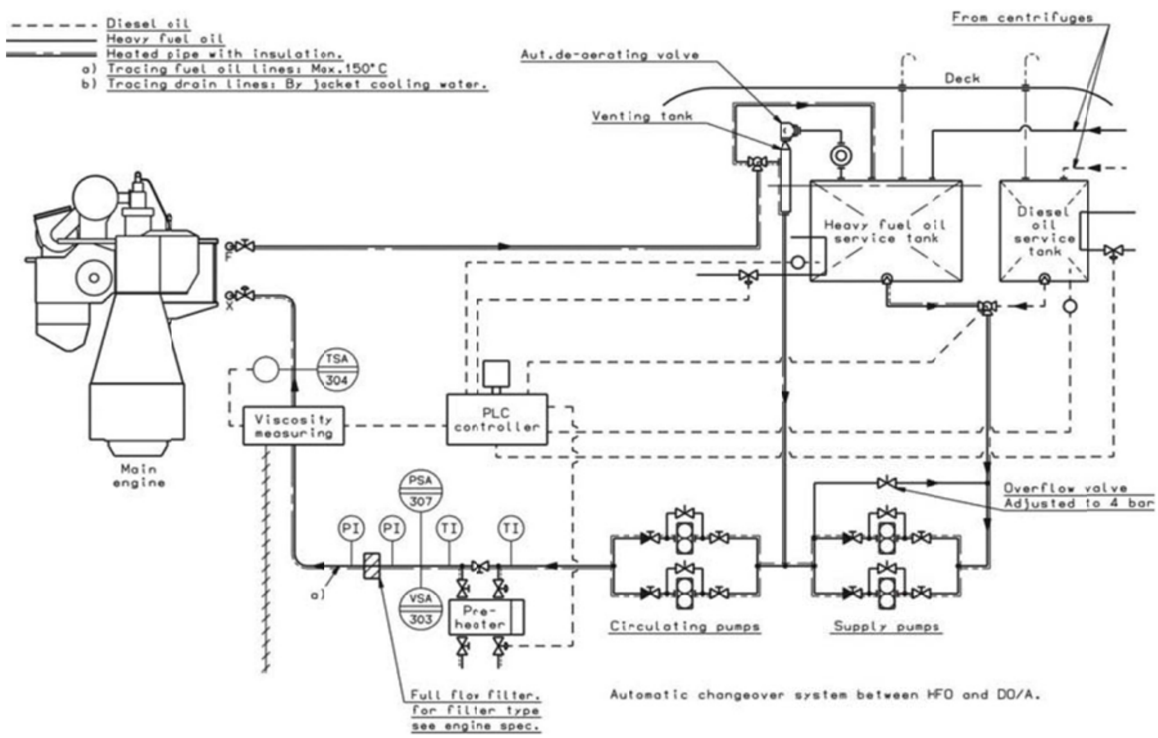
To obtain the recommended viscosity before fuel pumps a fuel oil of 150 mm²/s (cSt) at 50 °C must be heated to 108–120 °C.

Source: Sulzer Diesel

3.2 Fuel Viscosity Management Issues

Fuel viscosity can vary considerably depending on the fuel type and operating temperature. The fuel system for a modern diesel engine operating on heavy fuel oil has standard features to insure reliable engine operation. To accurately maintain the viscosity within a narrow range the fuel is continually being circulated (Figure 3.2-1). Modern systems are designed to handle fuel with viscosities as high as 700 centistokes (cSt) at 50° C.

Figure 3.2-1: Example of Engine Fuel Flow Schematic Drawing.



Source: MAN Diesel [Reference 22]

A circulation system is necessary to insure proper operation of the diesel engine at all load conditions when burning HFO. Fuel viscosity must be maintained throughout the entire fuel injection system even when the main engine is stopped. Because HFO is very viscous, the fuel must be heated to about 100 to 120 degrees Celsius within the system fuel tanks and fuel lines to reduce the fuel's viscosity. The viscosity of heavy fuel oil is generally maintained between 13 and 17 cSt (see Table 3.2). If the heavy fuel oil becomes too viscous, the fuel may not pump properly.

To prevent the formation of vapor in the circulating system, a fuel supply pump increases the pressure of the fuel entering the circulating system to a typical pressure of 4 bar. An undesired effect of the circulating system is that when operating on distillate fuel, the distillate may be heated as it circulates near the hot engine components. The temperature of some of the fuel system components will be close to the temperature of the engine jacket cooling water (80° C). The result is an undesirable drop in the viscosity of the distillate fuel even with all the system heating sources shut off.

The properties of distillate fuel are considerably different than HFO and accordingly it has different parameters that must be maintained. Distillate fuel has stricter specifications assuring fuel quality and improved combustion characteristics within the combustion chamber are to be expected. Distillate fuels have lower densities than HFO, which results in a net reduction in the calorific values by volume. Distillate fuels typically have a viscosity in the lower part of the allowable range (1.5 - 6 cSt at 40°C). We believe that many operational problems are occurring because the fuel viscosity can become excessively low due to overheating within the fuel system. The proper control of fuel viscosity during engine operation is a key constraint for operation on distillate fuels.

There are two principal reasons for the specification of a minimum fuel viscosity:
1) A change in fuel pump timing due to increased leakage between the plunger helix and spill port. Fuel leakage requires the pump plunger to raise higher within the barrel before fuel pressure becomes high enough to open the fuel valve and start the injection process. Retardation of fuel timing and lower peak firing pressures in the combustion chamber occurs as a direct result, and
2) The requirement for the fuel to lubricate the fuel pump barrel and plunger during operation. If the fuel viscosity drops below specified values the oil film may not be sufficient to prevent metal to metal contact between the pump barrel and plunger. Excessive plunger and barrel wear, or in extreme cases plunger seizure, can be a direct result of this reduction in lubricity. Though the minimum values for distillate fuel and HFO are different, the requirement to maintain fuel viscosity above a given limit to prevent damage to the injection equipment is the same principle.

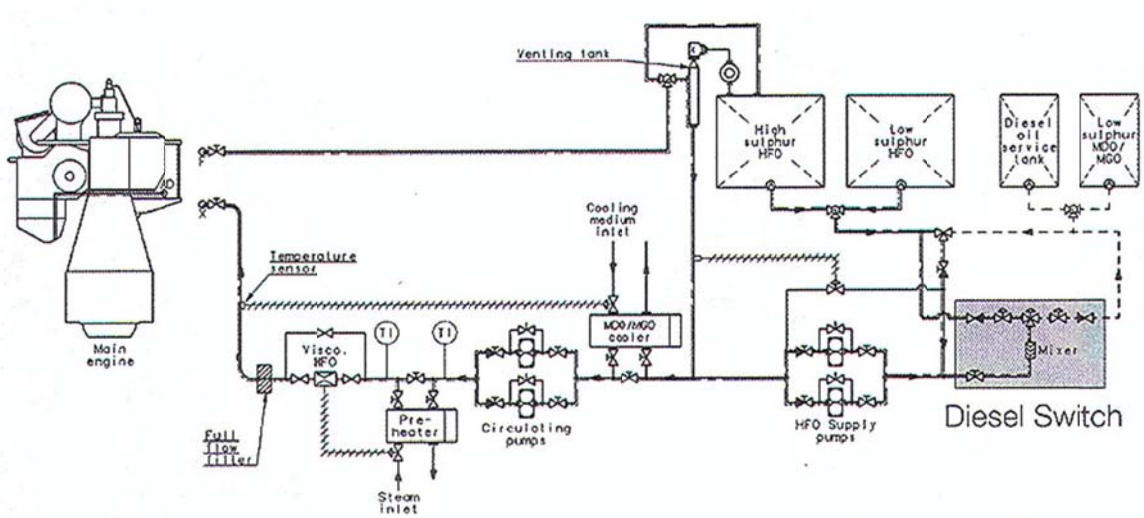
At low engine loads, the circulation of distillate through the high-pressure pumps may also heat the circulating fuel and cause its viscosity to drop below specified minimums. At low loads or when the engine is stopped, the fuel continues to be circulated through the fuel system. Since the fuel pumps and fuel valve are mounted to the main engines, they are heated indirectly by the engine through thermal conduction in the metallic components. Even with all of the system steam tracing turned off, circulation through the high-pressure pumps and fuel valves can increase distillate fuel temperature above minimum required values. On those vessels which are have difficulty maintaining distillate fuel above 2 cSt the installation of a fuel cooler/chiller into the fuel system is highly recommended.

While we believe that viscosity management has been the principle cause for many of the operational problems investigated as part of this study, it is by no means the only concern when switching from distillate fuel to heavy fuel oil or vice versa. The other concerns are 1) fuel incompatibility and 2) thermal shock to the engine fuel injection equipment. Because of the low number of reports or incidents associated with these concerns, we believe that these issues are well understood and are not significant. It may be this heightened awareness as to the critical factors associated with the fuel switching process which has resulted in the positive outcome. Concerns of fuel incompatibility arise from the fact that distillate fuel with low aromatic hydrocarbon content and heavy fuel oil will be mixed together within the fuel circulation system for an extended period of time during the fuel switching process. The asphaltenes contained within the heavy fuel oil has the potential to precipitate as heavy sludge. This sludge has the potential to clog fuel filters which in turn can starve the engine of fuel. This concern can be minimized by testing of vessel bunkers, prior to loading, to insure compatibility of the two fuels. While this issue is a genuine concern it has not been significant factor as reported. In addition, fuel switching takes place well offshore and must be completed by the time the vessel enters the 24 nm regulatory zone.

Thermal shock to fuel injection equipment can occur due to sudden fuel temperature changes. A sudden change in fuel temperature flowing through the injection equipment can result in an unequal expansion of the moving parts resulting in seizure. This phenomenon can occur within the high pressure fuel pump (plunger/barrel) or fuel valve (needle valve) if the temperature of fuel at the engine is allowed to vary too quickly during the fuel switching process. The allowable rate of change for temperature can vary significantly between engine models and the manufacturer's recommendations should always be followed.

During the switching process, a mixture of fuels with significantly different properties is circulated within the fuel system. For example, if the system was charged with distillate fuel and changing over to HFO was desired, the fuel temperature would be increased at a steady rate while HFO was slowly introduced into the fuel circulating system through a mixing valve. Throughout the process the appropriate fuel viscosity must be maintained while raising the fuel temperature at the prescribed rate. Automation is available which can simplify the switching process for the engineering crew and avoid rapid temperature deviations. One example would be the "Diesel Switch" sold by MAN B&W and is illustrated in Figure 3.2-2.

Figure 3.2-2: Modern Fuel System with A Distillate Fuel Cooler and Diesel Switch Modifications



Source: MAN Diesel [Reference 23]

3.3 High Pressure Fuel Pump Leakage

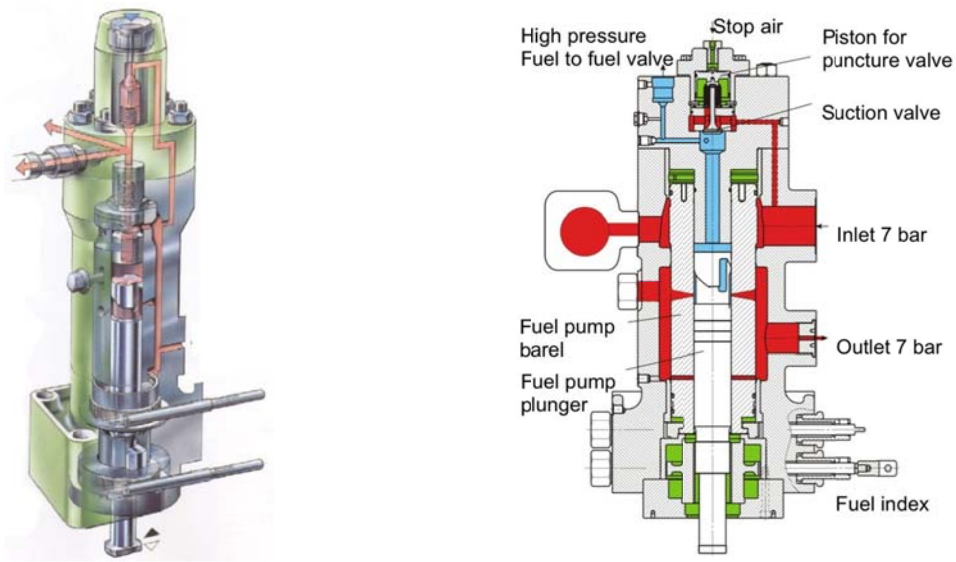
The high pressure fuel pump system for a typical main engine is shown schematically in Figure 3.3-1 and as an assembly drawing is shown in Figure 3.3-2. This component has been associated with issues concerning leakage past the suction valve and internal O-rings. High pressure fuel pump leakage can occur due to, 1) worn barrel and plunger (piece 556 & 532), 2) leaking puncture valve slide (piece 723) or valve housing “O-ring” seals (piece 711), or 3) Leaking suction valve slide (piece 448) or seal (piece 473.)

The barrel and plunger are manufactured to very precise tolerances to minimize fuel leakage. A small amount of leakage is required as the fuel is utilized to lubricate these moving metallic parts. Over time, as the pump plunger and barrel become worn fluid leakage will increase. Using fuel with lower viscosity will increase the leakage volume even further. If the leakage becomes excessive, it will reduce the pump discharge pressure resulting in a reduced volume of fuel going to the engine.

The puncture valve (pv) is a safety feature that is designed to shut-down pump delivery if a pneumatic signal from the main engine control system is activated. The pneumatic signal acts upon the air piston (piece 664) which in turn presses down on the puncture valve slide lifting it off the sealing surface. Once the pv slide opens, high-pressure fuel can exit the barrel cavity and drain to the pump suction gallery.

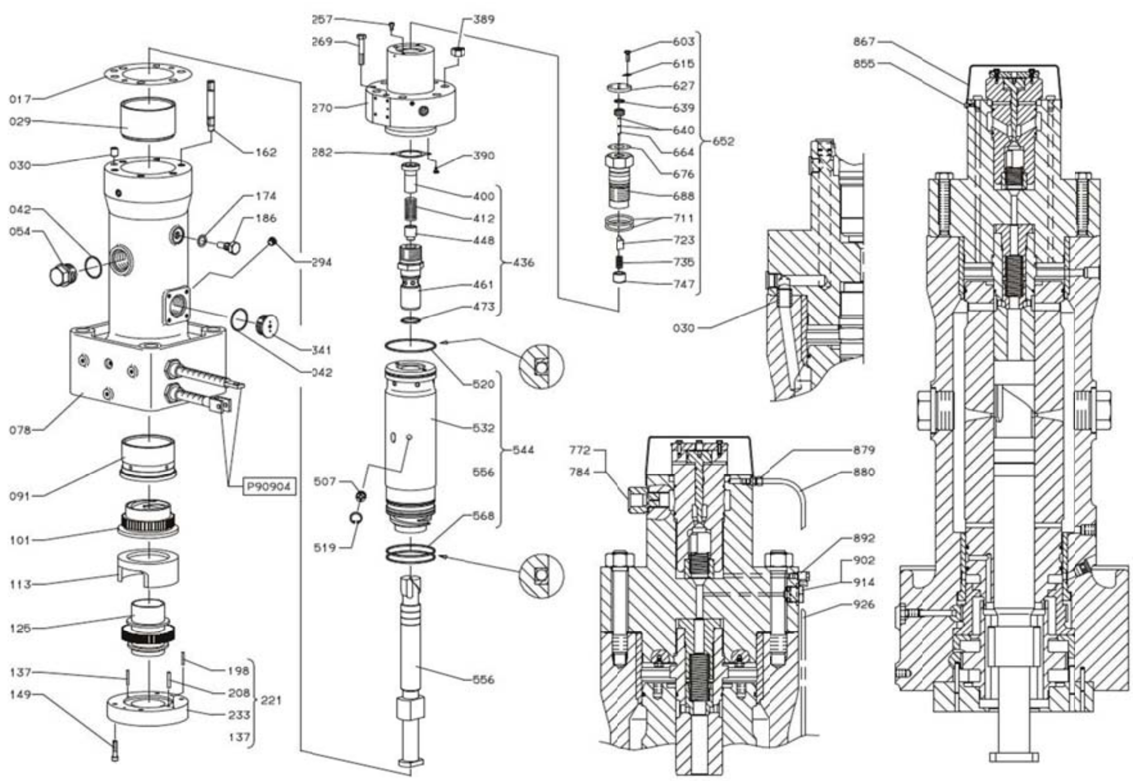
The suction valve slide automatically lifts off its sealing surface allowing fluid from the pump suction gallery to enter the pump barrel on the downward stroke of the pump plunger. Any leakage of the housing seals or slide will lower the developed pressure on the upward plunger stoke and decrease fuel delivery volume. The decrease in fuel volume may decrease the fuel injection pressure.

Figure 3.3-1: High Pressure Fuel Pump Overview Drawings



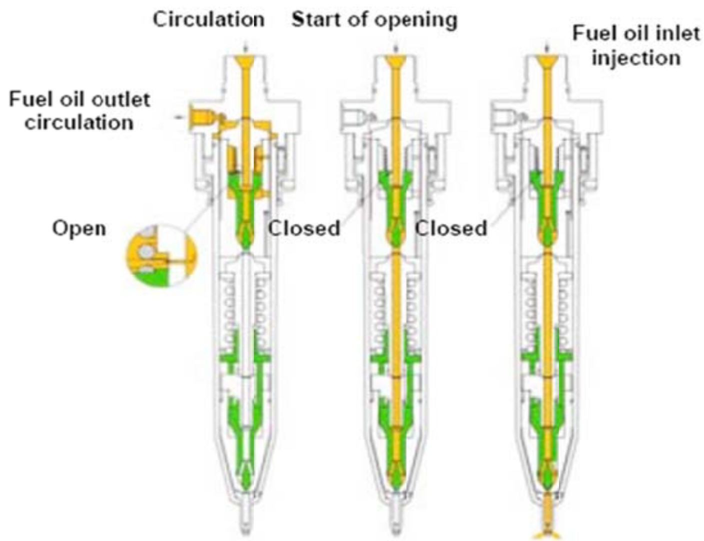
Source: MAN Diesel

Figure 3.3-2: High Pressure Fuel Pump Assembly Drawings



Source: MAN Diesel

Figure 3.3-3: Example of Fuel Injector Circulation Diagram



Source: MAN Diesel

Problems with the fuel pump have been correlated with excessive internal leakage between the high-pressure pump plunger and barrel. This problem was identified as a likely root cause for some of the LOP incidents. For fuels with lower viscosity, more leakage will occur thereby decreasing fuel injection pressures.

An engine with worn high-pressure fuel pumps may run at higher speeds but will have difficulty starting or running at dead slow. Fuel injection pressure of mechanically actuated fuel pumps tends to be lower at low engine revolutions due to decreased plunger velocities. Leaking seals for the puncture valve may be observed by the external leakage or by the increased flow rate into the fuel catch tank. A leaking O-ring seal in the suction valve may reduce injection pressures which would be indicated by a drop in exhaust temperature.

The fuel pump index is dependent on the amount of pump wear and the viscosity of the fuel oil. Worn fuel pumps and leaking suction valves will show up as an increased fuel index and results in lower fuel injection pressures. The manufacturer recommends overhauling the pumps when the index has increased 10% above the fuel index for a new pump.

Low fuel viscosity will increase leakage in the fuel pump, and thereby necessitate higher indexes for injecting the same volume. The energy content per unit volume and the specific gravity of the distillate fuel can therefore also influence index. All parameters that affect the fuel oil consumption (ambient conditions, pmax, etc.) should be monitored during the fuel switch over process.

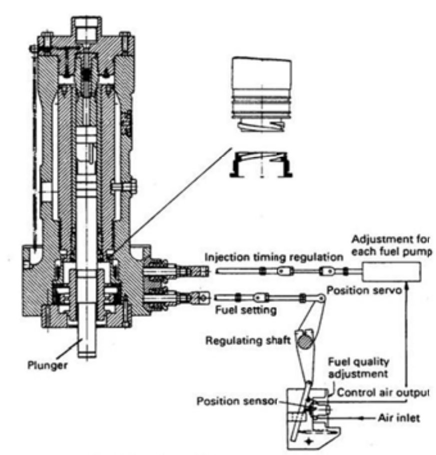
3.4 High Pressure Fuel Pump Variable Injection Timing

On those engines fitted with Variable Injection Timing (VIT), the engine control system will significantly advance the injection of fuel into the cylinder to increase peak firing pressures and improve combustion during engine start-up. It is important that the VIT injection control system is working properly when operating on low-viscosity distillate fuels. The lower viscosity increases leakage past the fuel pump plunger lowering injection pressures and retarding fuel injection into the combustion chamber. A properly working VIT control will mediate this problem and improve combustion during the initial engine starting process.

Figure 3.4-1 depicts a common control arrangement used by MAN B&W on the slow-speed diesel engines. In this arrangement the pump barrel can be mechanically raised or lowered to advance or retard injection timing. The pump barrel has a threaded lower end which fits into the internal threads of the timing guide. The timing guide has a gear rim which meshes with a toothed rack that is linked to a servo-air cylinder. The position of the upper toothed rack determines the vertical position of the barrel relative to the plunger.

The VIT system must be checked regularly to insure that the system is moving freely and is operating in the manner prescribed by the engine manufacturer.

Figure 3.4-1: Super VIT System



Source: MAN Diesel

3.5 External Fuel System Leakage

The distillate fuel can act as a solvent removing hardened deposits left by heavy fuel oil. The viscosity of the distillate fuel is much lower, allowing for a larger quantity of fuel to leak past. Sealing O-rings can lose their elasticity and ability to seal properly due to the high temperatures to which they are exposed. Changing fuel temperatures cause expansion & contraction of fuel system components. O-rings which have degraded due to exposure to heat over a long period of time may not able to conform to the changes and leakage occurs.

4 CONCLUSIONS AND RECOMMENDATIONS

4.1 Fuel Viscosity Management is Critical

Based on the available information, CMA Technical Staff believes that heating of the distillate fuel resulting in viscosity below the recommended minimum level, often combined with other factors, was the cause of most operational difficulties associated with the usage of low sulfur distillate fuel. The other factors include: (1) worn fuel system equipment, such as fuel pumps or seals; (2) engine adjustments not optimized for the use of distillate fuel such as rack or governor settings; and (3) operational procedures not optimized for the use of distillate fuel. The use of a low viscosity distillate fuel combined with worn high-pressure fuel pumps resulted in inadequate fuel injection pressures. Loss of propulsion can result under these circumstances, due to excessive leakage of fuel within the high-pressure fuel pumps. Excessively worn or leaking pumps can result in low fuel injection pressures and incomplete combustion. Therefore, it is critical that shipboard crew maintain the fuel injection pumps within manufacturer's specifications, and ensure that fuel viscosity is maintained above 2 centistokes (cSt) at the high-pressure fuel pump inlet. Recommendations for improved practices stemming from this review include:

- Perform a Fuel Switching Test Prior to Visiting California
- Determine Condition of High-Pressure Fuel Pumps Using the Fuel Pump Index
- Document Fuel Switching Procedures for the Crew
- Adjust Preventative Maintenance Schedule of Fuel System Components as Determined by Operational Experience
- Specify and Verify Distillate Fuel Viscosity
- Maintain Fuel Systems to Prevent External Leakage
- Check Governor Pre-set Speed Setting or Binding of the Fuel Rack
- Transfer Control from the Bridge to Engine Control Room if the Engine is Difficult to Start
- Evaluate Cylinder Lubrication

4.2 Recommendations

4.2.1 Perform Fuel Switching Pre-Testing

Performing a test-run on distillate fuel prior to the vessel entering a maneuvering situation is absolutely vital. The test run should be performed in a safe area prior to entering maneuvering situations such as ports. Testing should be done periodically since fuel equipment wears over the life of the vessel. Test-runs should include trials under slow speed maneuvering conditions, such as changing direction from ahead to astern. Test runs provide invaluable training to the vessel's crew and an opportunity to repair any problems that are revealed as a result. During this pre-test, the response to the astern bell should be assessed and the condition of the high-pressure fuel pumps should be checked to determine that the internal leakage will not be excessive on the less viscous distillate fuel.

4.2.2 Determine Condition of High-Pressure Fuel Pumps Using the Fuel Pump Index

The fuel pump index is dependent on the amount of pump wear and the viscosity of the fuel oil. Worn fuel pumps and leaking suction valves will show up as an increased fuel index. The manufacturer recommends overhauling the pumps when the index has increased 10% above the fuel index for a new pump.

4.2.3 Document Fuel Switching Procedures

It is essential that the vessel is supplied with written fuel switching procedures that follow engine manufacturer's guidelines. These guidelines should be specific to the actual shipboard systems if they deviate from the standard recommended fuel system. The engineering crew must fully understand the procedures and know the locations of all pertinent system valves and equipment.

When shifting from heavy fuel oil to distillate fuel, all fuel line steam tracing should be turned off prior to switching. Fuel viscosity must be maintained within manufacturer's recommendations throughout the switching process.

With low viscosity fuels, the diesel oil day tank used to store the distillate fuel should be maintained at as low a temperature as possible. As an option, the engine manufacturers can provide equipment which has been designed to automate the switching process. Modern fuel systems react very quickly to any change and this option would greatly assist the crew in maintaining fuel viscosity and temperature during this transition period.

4.2.4 Adjust Preventative Maintenance Schedule of Fuel System Components as Determined by Operational Experience

The maintenance schedule for fuel injection equipment will need to be adjusted to insure that excessive internal leakage does not occur. Since distillate fuel exhibits a lower viscosity, the volume of leakage past any gap will be greater. The allowable wear for fuel pump and fuel valve (injector) components will be correspondingly reduced as a result of the lower viscosity of the distillate. The manufacturers' guidelines should be used as a starting point and adjusted over time as experience is gained with engine operation on distillate fuel.

4.2.5 Specify and Verify Fuel Viscosity

When ordering bunkers, the vessel operator should specify low-sulfur distillate with as high a viscosity as possible. Distillate fuel should never be heated within the fuel system to the point that its viscosity drops below 2 cSt. If the viscosity of the fuel cannot be maintained above 2 cSt due to the absorption of heat within the fuel circulating system, the addition of a heat exchanger to cool the fuel would alleviate the problem.

4.2.6 Maintain Fuel Systems to Prevent External Leakage

Any system leakage should be repaired prior to burning distillate fuel as the less viscous fuel tends to remove heavy fuel deposits thereby increasing the volume of the leak. Engineering staff should check the general condition of fuel system sealing O-rings for loss of elasticity or cracking. They should also check that the fuel rack moves easily without binding and the pre-set governor speed setting is correct.

Before operating on distillate fuel for the first time, it may be beneficial to sample the condition of fuel pump O-ring seals by removing a seal from the oldest pump to determine if the elasticity of the seal is adequate. If the sample seal is cracked, hardened, or otherwise not in good condition, it may be advisable to replace all seals prior to running on distillate fuel.

4.2.7 Check Governor Pre-set Speed Setting or Binding of the Fuel Rack

Engine failure to start may be associated with initial governor setting being insufficient and limiting fuel delivery. It is important that engine crew check that the pre-set governor speed setting pressure is not set too low or for too short a time period. They should also assure that there is no binding in the fuel pumps, rod connections, or bearings. If the engine fails to start on Bridge control, switching to the Engine Room Console may allow the engine to start in some instances.

4.2.8 Transfer Engine Control

Additional care must be used until the starting characteristics of the engine on distillate are proven. It is recommended that engines that have not recently operated on distillate fuel transfer control to the engine control room when reversing the main engine while under way. This will allow the engineers to increase the starting fuel setting if the engine does not start on the first attempt. Vessel engineers should be experienced in controlling the engine from both the engine control room and from the engine side.

4.2.9 Evaluate Cylinder Lubrication

When operating on low sulfur fuel the cylinder oil feed rate and the usage of a cylinder lubricating oil with a base number (BN) of 40 should be evaluated carefully. When a cylinder lubricating oil formulated for high sulfur fuel ~70BN is used for long periods of time the un-neutralized calcium carbonate can form a hard deposit on the upper land of the piston crown and interfere with proper cylinder/piston ring lubrication. Reducing the cylinder oil feed rate is normally sufficient for operation on low sulfur fuels for short periods of time. It is not expected that vessels will need to switch to the lower BN oil for compliance with the California ARB Fuel Regulation. Cylinder lubricating oil feed rates can vary considerably between engine makes and models and it is extremely important that the engine manufacturer's instructions be consulted and closely followed.

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