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3600 Marine Engine Application and Installation Guide

- **Distillate Fuel**
- **Heavy Fuel**

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Engine Systems - Distillate Fuel Oil

Engine Fuel System Description

Refer to Figures 1, 2, and 3 on pages 24, 25 and 26 for schematics of the engine fuel system.

The standard primary fuel system components include an engine driven fuel transfer pump, duplex media type filters (secondary), unit fuel injectors and a fuel pressure regulator. Optional Caterpillar supplied fuel system components include flexible hoses, a manual fuel priming pump, and a duplex primary fuel strainer.

If used, the primary duplex fuel strainer is installed remote from the engine in the transfer pump suction line. The strainer has 178 micron (0.007 in.) cleanable elements. The manual priming pump is installed on the engine in parallel to the engine driven pump. The manual pump helps to bleed air from the fuel piping before initial engine operation and following engine maintenance (filter element changes, injector replacement, etc.). It has a suction lift of 2.6 m (8.5 ft) and a flow of 38 L (10 gal) per 115 revolutions. The manual priming pump has a lift of 7.8 m (25.5 ft) if the fuel lines between the fuel tank and the pump are full, as after a filter element change.

To avoid air suction into the fuel transfer pump at low suction pressures and seal leakage at high suction pressures, the fuel pressure at the engine driven transfer pump at rated speed must be greater than -39 kPa (-5.7 psi) or less than 100 kPa (14.5 psi). If the manual priming pump is used the suction pressure must be less than 50 kPa (7.25 psi). The engine driven transfer pump may be used for fuel with a viscosity up to 40 cSt at 50°C. Higher viscosity fuels require a fuel booster module to circulate and heat the fuel prior to engine operation (see the *Heavy Fuel Oil* section of this guide).

The engine driven transfer pump delivers fuel to the unit injectors via the secondary fuel filters. The 5 micron (0.0002 in.) duplex filters are usually both in service for normal operation, although one housing may be isolated at a time during operation for filter replacement if required. The recommended fuel delivery pressure to the injectors is 414-690 kPa (60-100 psi) at rated speed.

The unit injector combines the functions of pumping, metering and injecting into a single unit. It is mounted in the cylinder head at the centerline of each cylinder. External manifolds supply fuel from the transfer pump to the drilled passages in the cylinder head, eliminating the need for high pressure fuel lines. A 100 micron (0.004 in.) edge type filter within each injector prevents contaminants from entering the injector during maintenance. Fuel circulates through the injectors and the portion that is not used for combustion cools the injectors and is returned to the fuel tank via the pressure regulating valve. For heavy fuel oil applications a special cooling circuit is designed in the unit injector to supply and circulate the coolant through the injector tip (see the *Heavy Fuel Oil* section of this guide).

The fuel delivery pressure to the injectors is controlled by adjusting the pressure regulating valve on site. The valve is a spring loaded variable orifice type mounted on the front right side of the engine, and it maintains adequate injector supply pressure for all engine speed and load ranges. The pressure regulator must be adjusted at the installation site. To provide 414-690 kPa (60-100 psi) fuel to the injectors, the fuel return line restriction must not exceed 350 kPa (51 psi) at rated engine speed.

Engine Fuel Flow Rates

Refer to the table on page 6 for 3600 engine fuel flow rates and heat rejections at various engine speeds.

Bulk Storage and Delivery Systems

Shipboard fuel systems must insure a continuous supply of clean fuel to the engines. Bulk fuel is usually stored in a large tank(s) and transferred to a smaller tank(s) (day or service tank) near the engine room by one of three methods:

- Fuel flows by gravity from the ship's main tank(s) to the service tanks. The engine driven transfer pump takes fuel directly from the service tank. Fuel is normally returned from the engine through a deaeration tank back to the transfer pump inlet or directly back to the service tank.
- An electric driven transfer pump delivers fuel from the ship's main tank to a settling tank. After allowing time for settling of water and solids the fuel is transferred to the service tank.
- A fuel oil separator may be used to transfer fuel from the ship's main or settling tank to the service tank.

Install vents on each tank to relieve air pressure created by filling and to prevent vacuum formation as fuel is consumed. Water and sediment should be periodically drained from each fuel tank.

Seal piping and fittings to prevent air or dirt contamination. Air in the system causes hard starting, erratic engine operation, and can also erode injectors.

Fuel lines can be black iron pipe, steel pipe or copper tubing. Galvanized, aluminum, or zinc-bearing alloy pipe must not be used.

3600 Engine Fuel Flow

	Rated Speed rpm	Fuel Flow-L/min (gal/min)		Fuel Heat Rejection Without Injector Tip Cooling, kW (Btu/min)
		to Engine	from Engine	
3606	1000	41.5 (11.0)	32.4 (8.6)	12.5 (712)
	900	38.0 (10.0)	30.0 (7.9)	11.0 (626)
	750	31.5 (8.3)	24.5 (6.5)	10.5 (598)
	720	30.0 (7.9)	23.6 (6.2)	10.0 (567)
3608	1000	41.5 (11.0)	30.0 (7.9)	16.7 (951)
	900	38.0 (10.0)	27.6 (7.3)	14.6 (831)
	750	31.5 (8.3)	22.6 (6.0)	14.0 (797)
	720	30.0 (7.9)	21.4 (5.6)	13.3 (757)
3612	1000	78.5 (20.7)	60.1 (15.9)	25.0 (1423)
	900	72.0 (19.0)	55.4 (14.6)	22.0 (1252)
	750	61.2 (16.2)	47.3 (12.5)	20.2 (1150)
	720	58.1 (15.3)	45.2 (11.9)	19.1 (1087)
3616	1000	78.5 (20.7)	55.2 (14.6)	33.3 (1895)
	900	72.0 (19.0)	51.1 (13.5)	29.3 (1668)
	750	61.2 (16.2)	43.2 (11.4)	26.9 (1531)
	720	58.1 (15.3)	41.2 (10.9)	25.4 (1446)

Maximum inlet restriction on pump = -39 kPa (-5.7 psi).
Maximum return line restriction = 350 kPa (51 psi) at rated speed.

Day Tank (Distillate Fuel Service Tank)

Day tanks are used in almost all marine applications. The installation design must consider engine mounted transfer pump limitations. *Total suction head must not exceed 2.6 m (8.5 ft).*

Locate tanks to avoid fuel levels higher than the engine fuel injectors to prevent fuel leakage into the cylinders due to static head when the engine is shut down. If overhead mounting is unavoidable, include an open/close solenoid valve in the supply line and a 3.45 kPa (0.5 psi) check valve in the return line.

The delivery line carrying fuel to the fuel transfer pump and the return line carrying excess fuel to the service tank should be no smaller than the engine fittings. Larger fuel supply and return lines ensure adequate flow if the fuel tank feeds multiple engines over 9.14 m (30 ft) from the tank or temperatures are low. *The maximum inlet flow restriction is -39 kPa (-5.7 psi) at rated speed.* Caterpillar fuel pumps prime up to 2.6 m (8.5 ft) of suction lift, but pipe size, bends, and cold ambients modify this capability. Position fuel suction lines to remove fuel about 76 mm (3 in.) above the tank bottom and near the tank end opposite the return line. Do not use joint cement affected by fuel or gasketed connections. *Flexible fuel lines must be installed at the engine fuel inlet and outlet to accommodate engine motion.*

The return line should enter the top of the tank without shutoff valves. Avoid dips so air passes freely and prevents vacuum in the fuel system. All return fuel from the engine must be allowed to deaerate before being returned to the engine. The maximum return flow restriction is 350 kPa (51 psi) at rated speed.

All engines add heat to the fuel as the engine operates. The day tank can be sized to dissipate the added heat. If this is not possible fuel coolers may be required (see the section on *Fuel Temperature*).

Figure 4 on page 27 shows a typical delivery system from the day tank to a main propulsion engine.

See Figure 5 for a recommended tank design. The rules and regulations for fuel tanks of the applicable marine society must be observed.

Typical Arrangement of Service Tank

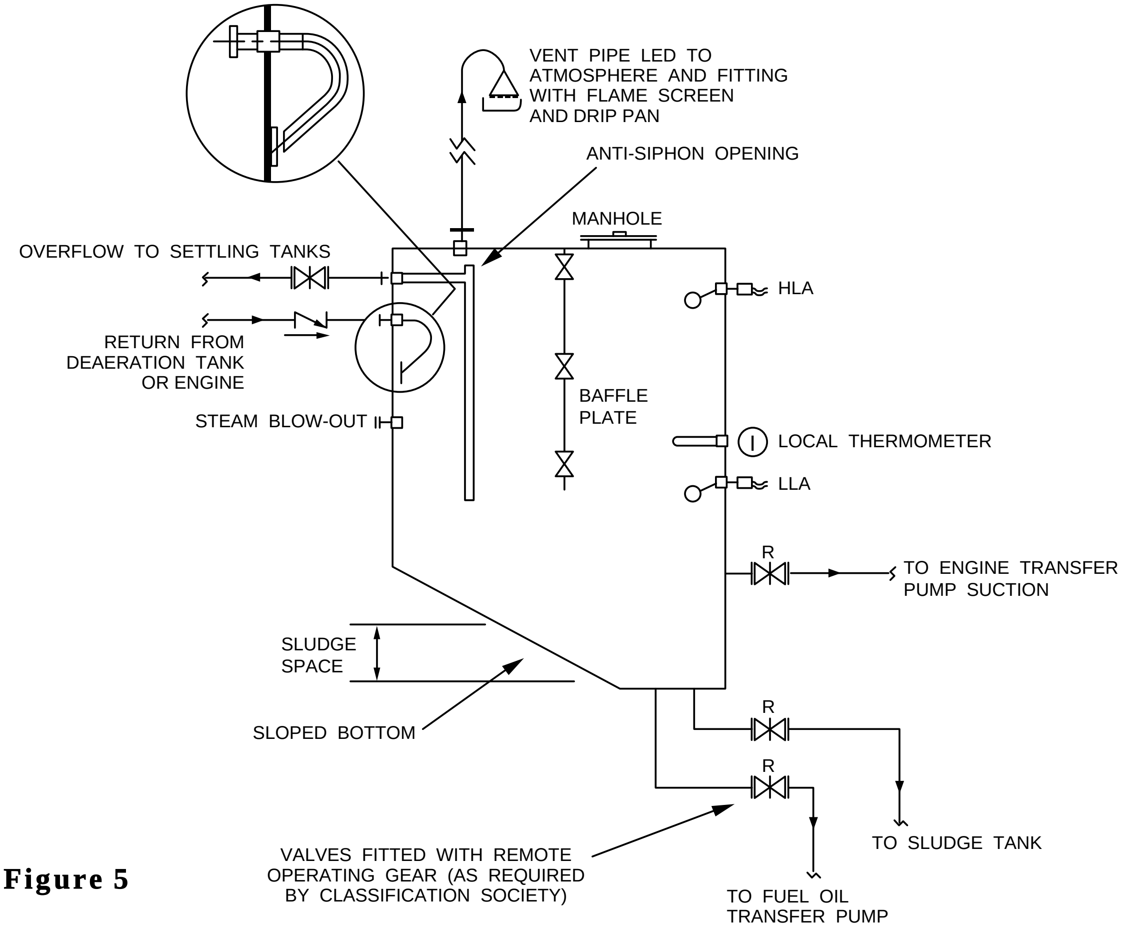


Figure 5

Emergency Pump

An electric motor driven emergency pump may be required in some engine applications for use as backup to the engine driven pump. This is generally a marine society requirement for single engine propulsion applications. Recommended flow rates are shown in the following table and will fulfill the minimum engine requirements at all rated speeds between 700 and 1000 rpm.

Flow Rate L/min (gal/min)				
Engine	3606	3608	3612	3616
Fuel Pump	42 (11)	42 (11)	79 (21)	79 (21)

The emergency pump must deliver the stated flow of diesel fuel at 65°C (149°F) against a head of 500 kPa (73 psi) pressure. Adjust the fuel pressure regulator to 414-690 kPa (60-100 psi).

Fuel treatment systems should be capable of being maintained without interruption in engine operation.

Settling Tank

The settling tank should hold a 24 hour minimum supply of distillate fuel for the propulsion engine, plus the normal expected kilowatt load from the diesel generator sets. Refer to the typical settling tank design (Figure 14) in the *Heavy Fuel Oil* section of this guide.

A heating coil can be installed in the tank. It can be used as a standby heater to bring the fuel to the proper centrifuge temperature. The coil should keep the distillate fuel temperature approximately 20°C (11°F) above the pour point. Fit the heating steam supply with an automatic temperature regulating valve to control fuel tank temperature.

Use screw type pumps to transfer fuel from the bunker tanks to the settling tank. They minimize the possibility of emulsifying water entrained in the distillate fuel. The transfer pump should operate automatically and fill the settling tank in less than two hours.

The following pump characteristics are provided for guidance:

- Operating pressure — to suit conditions of piping system
- Operating fluid temperature — 38°C (100°F)
- Viscosity for sizing the pump motor — 500 cSt

Fuel Cleanliness

Clean fuel is essential. The final filters are engine mounted and tested at the factory and are never bypassed on an operating engine. Optional factory supplied duplex primary filters with 178 micron (.007 in.) cleanable mesh screens collect large debris prior to the engine transfer pump.

Water Separation

With modern high output engines using high injection pressure fuel pumps, it is extremely important to maintain water and sediment levels at or below 0.1%. Depending on how the engines are applied, water and sediment can collect in fuel tanks. Therefore, fuel meeting the required specifications when delivered to the site can exceed limits when used in the engine. Several methods can be used to remove excess water and sediment:

- A water and sediment separator can be installed in the supply line ahead of the transfer pump. The separator must be sized to the handle the fuel being consumed by the engines as well as fuel being returned to the tank.
- Coalescing filter systems work effectively to remove sediment and water. If the level in the day tank is not maintained at a consistent level, install them between the main tank and the day tank. If proper day tank operation is maintained, a smaller system can be used between the main tank and the day tank to clean only the fuel being burned. The filters can plug and careful attention must be given to fuel pressure levels at the injectors to guard against misfiring.
- A centrifuge system can be used, particularly if the fuel quality consistently exceeds the defined limits specified herein.

Centrifuges

Clean distillate fuel with a separate centrifuge system from those dedicated for heavy fuel on the same ship (see Figure 6 on page 28 of this section). Even though the main propulsion engines may be arranged for heavy fuel, size the distillate fuel treatment plant to suit both the main engines and the ship service generator sets. Two transfer pumps, two centrifuges and heaters are normally used.

Use an automatic self cleaning centrifuge. Consult the centrifuge manufacturer to size the flow.

The fuel centrifuge piping system must allow one of the centrifuges to act as a standby. The required flow rate can be approximated as follows:

$$Q = \left\{\frac{P \times b \times 24 \times 1.15}{R \times t}\right\}$$

Where:

Q = Flow required, L/hr
P = Total Engine Output, kW
b = Fuel Consumption, g/kW-hr
R = Density of fuel, kg/m^3
t = Daily separating time in automatic operation: 23 hr

or:

$$Q = \left\{\frac{P \times be \times 24 \times 1.15}{R \times t}\right\}$$

Where:

Q = Flow required, gal/hr
P = Total engine output, bhp
be = Specific fuel consumption, lb/bhp-hr
R = Density of fuel, lb/gal
t = Daily separating time in automatic operation: 23 hr

Note:
- *The centrifuge manufacturer should assist in the final centrifuge selection.*
- *The centrifuge flow has been increased by 15% as a safety factor for operational tolerances.*

Centrifuge seal water and control air requirements must be specified by the centrifuge manufacturer.

Sample Points

The centrifuge operating efficiency is checked by drawing samples from both sides of the centrifuge. Arrange the points as shown in Figure 15 on page 48 of the *Heavy Fuel Oil* section.

Suction Strainer

Install a simplex strainer ahead of the centrifuge supply pump and use a stainless steel basket with perforations sized to protect the pump (0.8 mm (1/32 in.)). The strainer body is normally manufactured from cast iron or bronze.

Centrifuge Supply Pump

Mount an electric motor driven supply pump separately from the centrifuge and size for the centrifuge flow. The following pump characteristics are provided for guidance:
- Operating pressure - to suit conditions of piping system
- Operating fluid temperature - 38°C (100°F)
- Viscosity for sizing pump motor - 500 cSt

Fuel Heater

The heater is sized using the pump capacity and the temperature rise required between the settling tank and the final centrifuge. The heater should be thermostatically controlled and selected to maintain fuel temperature to the centrifuge within ± 2°C (± 4°F). The maximum preheating temperature for distillate fuel is 40° to 50°C (104° to 122°F).

Customer Connections

Engine Fuel Piping (Inside Diameter)

	3606/3608	3612/3616
Fuel Supply	22 mm (7/8 in.)	28 mm (1-1/8 in.)
Fuel Return	22 mm (7/8 in.)	22 mm (7/8 in.)

Flex Connections

Connections to the engine must be flexible hose located at the engine inlet and outlet. Do not attach rigid fuel lines. The factory provided flex connections can be oriented to take maximum advantage of multiple direction flexing.

Fuel Lines

Bypass (return) fuel leaving the engine pressure regulator should be returned to the engine day tank. Any fuel returned directly to the transfer pump inlet must be routed through a deaerator.

The final installation must be hydrostatically tested to at least 1.5 times normal working pressure or to applicable marine society requirements, whichever is greater.

After fabrication and testing, steel piping must be removed and chemically cleaned (pickled) to remove mill scale, dirt, etc. Wash piping with suitable solvent and dry thoroughly. Coat the inside of piping with oil prior to final assembly.

Pressure and Flow Monitoring

Engine fuel lines have pressure variations due to injector spill pulses. Monitoring devices must include dampers or orifices in the lines to minimize pulse effects and obtain accurate readings. Caterpillar supplied gauges have proper damping incorporated in the hardware.

Fuel Recommendations

Caterpillar 3600 engines are capable of burning a wide range of distillate fuels. Also see the *Heavy Fuel Oil* section of this guide.

Distillate Fuel Recommendations

Specifications	Requirements*
Aromantics (ASTM D1319)	35% Maximum
Ash (ASTM D482)	0.02% Weight Maximum
Cetane Number (ASTM D613)	40 Minimum
Cloud Point (ASTM D97)	Not above lowest expected ambient temperature
Gravity API (ASTM D287)	30 Minimum and 45 Maximum
Pour Point (ASTM D97)	6°C (10°F) below ambient temperature
Sulfur (ASTM D2788, D3605, or D1552)	0.5% Maximum (See Sulfur Topic)
Viscosity, Kinematic @ 38°C (100°F) (ASTM D445)	20.0 cSt Maximum 1.4 cSt Minimum
Water & Sediment (ASTM D1796)	0.1% Maximum

*As delivered to fuel system.

The fuels recommended for 3600 engines are normally No. 2-D diesel fuel and No. 2 fuel oil. No. 1 grades and ISO-F-DMB fuels are also acceptable. Other fuel types may be used when economics or fuel availability dictate.

Consider the following fuel characteristics when procuring fuel:

Cetane Number

The minimum cetane number required for average starting conditions is 40. A higher cetane value may be required for high altitude operation or cold weather starting.

Filtering

Fuels should have no more than 0.1% sediment and water. Storage of fuel for extended periods of time can cause fuel oxidation and formation of solids, leading to filtration problems.

Pour Point

The pour point of the fuel should be at least 6°C (10°F) below the lowest expected starting and operating temperatures. The lower pour point of No. 1 or No. 1-D fuel may be necessary in cold weather.

Cloud Point

The cloud point should be below the lowest expected ambient operating temperature. This prevents fuel filter elements plugging with wax crystals.

Sulfur

Fuels containing 0.5% or less sulfur may be used with normal crankcase oil drain intervals using API CF performance oils. With sulfur above the 0.5% level, use API CF oil with an ASTM D-2896 minimum total base number (TBN) of 10 times the fuel sulfur for normal oil drain intervals. See the guide section on *Lubricating Oil* for further details.

Viscosity

Fuel viscosity is important for lubrication of fuel system components and fuel atomization. The *minimum* allowable viscosity at the injectors is 1.4 cSt.

Additives

Fuel additives are generally not recommended. Cetane improvers can be used as necessary. Biocides may be needed to eliminate microorganism growth in storage tanks. Treatment for entrained water may also be necessary in cold conditions. *Consult the fuel supplier about the use of additives to prevent incompatibility with additives already in the fuel.*

Fuel Sulfur Content

The percentage of sulfur in fuel will affect engine oil recommendations. Fuel sulfur is chemically changed during combustion to form both sulfurous and sulfuric acid. The acids chemically attack metal surfaces and cause corrosive wear.

Certain additives used in lubricating oils contain alkaline compounds formulated to neutralize acids. The measure of reserve alkalinity is total base number (TBN). Required TBN values are essential to neutralize acids and minimize corrosive wear.

The TBN recommendation for an oil is dependent on the amount of sulfur in the fuel used. For 3600 engines running on distillate fuel oil, the minimum new oil TBN (by ASTM D 2896) must be 10 times the sulfur percent by weight in the fuel, with a minimum TBN of 5 regardless of the sulfur content (see Figure 7).

In most oil formulations the TBN is a function of the ash bearing additives in the oil. Excessive amounts of ash bearing additives can lead to excessive piston deposits and loss of oil control. Therefore, excessively high TBN or high ash oils should not be used with 3600 engines running on distillate fuel. Successful operation of 3600 engines on distillate fuel has generally been obtained with new oil TBN levels between 10 and 15. See the guide section on *Lubricating Oil* for more information.

Periodically request fuel sulfur information from the fuel supplier. Fuel sulfur content can change with each delivery.

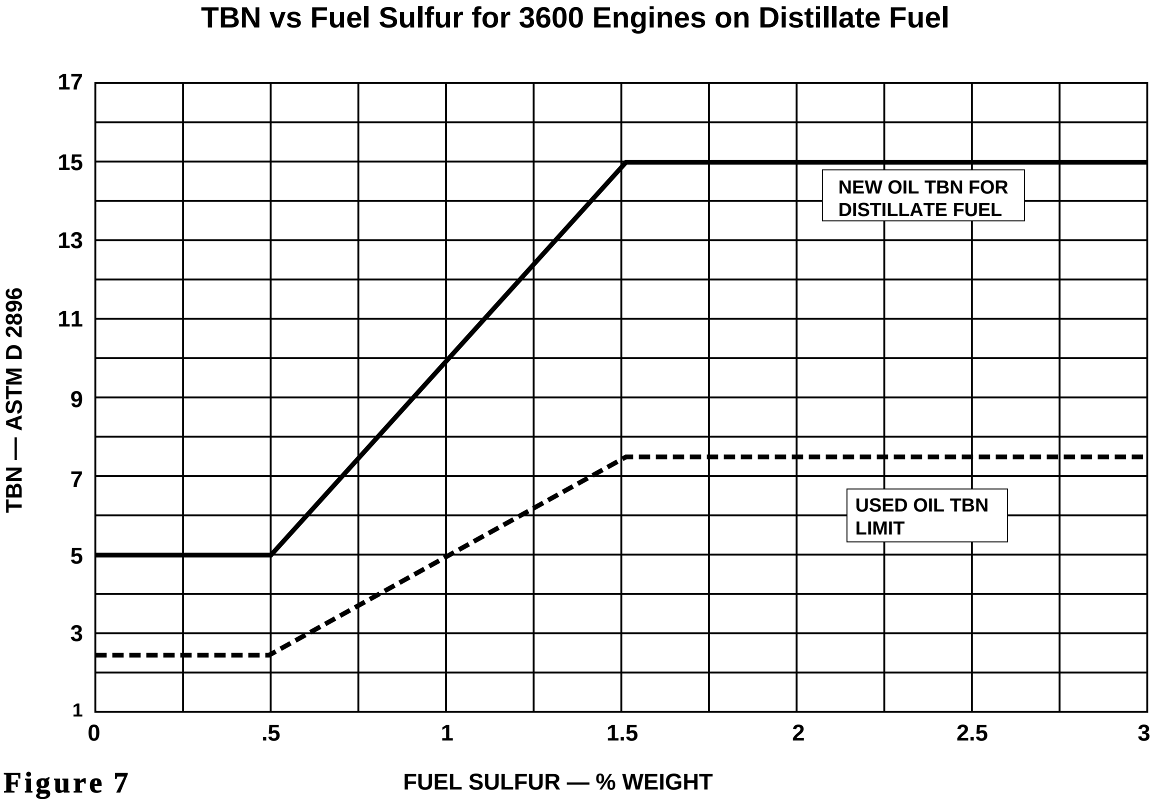


Figure 7

NOTE:
OPERATION AT FUEL SULFUR LEVELS OVER 1.5%
MAY REQUIRE SHORTENED OIL CHANGE PERIODS
TO MAINTAIN ADEQUATE WEAR PROTECTION.

Specific Gravity

Fuel rack settings are based on 35° API (specific gravity) fuel. Fuel oil with a higher API (lower specific gravity) number reduces power output unless the rack setting is corrected. When using heavier fuels (lower API number), a corrected rack setting prevents power output above the approved rating. The Caterpillar dealer will correct the rack setting for non-standard fuels.

Fuel Temperature

The fuel temperature supplied to the engine can affect unit injector life and maximum power capability. Reduced lubrication capability as a result of high temperature/low viscosity fuel may result in plunger scuffing. The *minimum* allowable viscosity at the injectors is 1.4 cSt. *A maximum fuel temperature limit of 72°C (162°F) to the unit injectors, regardless of fuel viscosity, prevents coking or gumming of the injectors.* The maximum fuel viscosity to the unit injectors of 20 cSt prevents overpressure damage to the injectors.

The engines are power set at the factory with 30 ± 3°C (86 ± 5°F) fuel to the engine transfer pump. Higher fuel temperatures reduce *maximum* power capability. *The* ***fuel stop*** *power reduction is 1% for each 5.6°C (10°F) fuel supply temperature increase above 30°C.* If the engine is operating below the *fuel stop* limit, the governor will add fuel as required to maintain the required engine speed and power.

Day tank sizing is critical to maintain the desired fuel supply temperature. Fuel coolers may be required.

Fuel Coolers

Fuel coolers are site specific and sized to handle fuel heat not dissipated by the day tank. The cooler must be located on the return circuit with a three way temperature regulating valve to control fuel return temperature to the service tank (see Figure 4). Submit the cooler design and materials to the appropriate classification society for approval.

The suggested material for a shell and tube type heat exchanger is:

• Shell	Red brass
• Heads	Cast iron
• Tubes	Copper
• Tube sheets	Brass
• Baffles	Brass

A plate type heat exchanger may also be used with titanium plates for sea water cooling or stainless steel plates for fresh water cooling.

Day Tank Sizing as a Heat Sink

Day tank sizing is critical when fuel to the engine is from a day tank without a fuel cooler. The supply temperature must be within specified limits for injector life and maximum power capability.

Day tank temperatures are impacted by:

- Day tank wetted surface area (including tank bottom)
- Engine(s) fuel consumption rate
- Day tank replenishing level
- Storage tank fuel temperature
- Ambient temperature
- Spaces contiguous to the day tank (void tanks, cofferdams, vessel shell plating, etc.)
- Return fuel temperature

Tank temperature calculation are performed in five [5] steps. The first determines the fuel mass in the tank at each time interval. The second step is based on a fuel mix temperature resulting from the engine driven transfer pump flow rate to the engine and the return flow rate to the day tank. The third step determines the day tank fuel height for each incremental time element. Typically, the calculations will be based upon a 30-60 minute iterative time function. The end point for the calculation is assumed to be when the day tank is refilled. The fourth step approximates the heat transfer from the tank to the surrounding environment due to the temperature difference between the fuel mix temperature and the ambient temperature. This convective heat transfer then determines the resultant tank temperature. The fifth step evaluates the impact of the final fuel supply temperature on the engine's maximum power capability.

The included example calculations should only be used to provide general guidance. If the day tank size is marginal use a fuel cooler.

To simplify the following calculations, it is assumed the day tank walls are surrounded by free moving air. If the tank walls are contiguous to the shell plating, heat transfer from the day tank will be enhanced. Conversely, if the day tank is bounded by void spaces and cofferdams, heat rejection from the day tank will be retarded. Typically, most day tanks are located with various combinations of the preceding boundary elements. The individual performing the evaluation must be familiar with the installation as well as the fundamental engineering concepts of the formulas used in the calculations.

Day Tank Calculations

The following information is required to perform the calculations:

- Engine model
- Engine developed power (MCR or CSR)
- Engine speed
- Brake specific fuel consumption (bsfc)
- Initial day tank fuel temperature
- Storage tank fuel temperature (Make-up)
- Ambient air temperature
- Day tank length, width, and height
- Typical full day tank fuel height (assume 95% of tank capacity)
- Engine fuel transfer pump flow rate (see page 6 of this section)
- Fuel heat rejection from the engine (see page 6 of this section)
- Incremental time element

Day Tank Thermal Capacity Calculation

Example:

- Application: Single main engine
- Engine Model: 3612
- Rated Power: 4640 bhp (CSR)
- Rated Speed: 900 rpm
- bsfc: 0.326 lb/bhp-hr
- Initial Day Tank Fuel Temperature = 85°F
- Storage Tank Temperature = 85°F
- Ambient Air Temperature = 95°F
- Day Tank Dimensions:
  - Length (L) = 12 ft.
  - Width (W) = 8 ft.
  - Height (H) = 8.42 ft.
- Fuel Height (@ 95% of total Capacity) (H) = 8 ft.
- Engine Fuel Oil Transfer Pump Flow Rate (q_{xfer}) = 19.0 gpm
- Heat rejection from engine to fuel oil (Q) = 1252 Btu/min
- Incremental time element, (t) = 60 min.

Assume that the day tank will be replenished from the vessel's storage tanks when the day tank level falls to approximately 50-55% of normal operating capacity.

Some of the data above must be converted to other units prior to beginning calculations. The following formulas can be used:

a) Engine Driven Transfer Pump Mass Flow Rate = M_{xfer} (lb/min)
Assume: #2 DO with an API gravity of 35 (7.1 lb/gal)

$M_{xfer} = q_{xfer}$ x 7.1 lb/gal = 19.0 gpm x 7.1 lb/gal = 134.9 lb/min

b) Engine burn rate under full load conditions

1) Burn rate (gpm) =

$$\frac{\text{bsfc x bhp x 1 Hr.}}{\text{Fuel density x 60 min.}}$$

$$= \frac{\text{0.326 lb/bhp - hr x 4640 bhp x 1 hr.}}{\text{7.1 lb/gal. x 60 min.}}$$

= 3.55 gpm

2) Fuel mass flow burn rate = M_{BR} (lb/min)
= 3.55 gpm x 7.1 lb/gal
= 25.21 lb/min

c) Engine fuel return rate under full load conditions:

1) Fuel return flow rate = q_{rtn} (gal/min)
= Supply rate - burn rate
= 19.0 gpm - 3.55 gpm
= 15.45 gpm

2) Fuel return mass flow rate = M_{RTN} (lb/min)
= 15.45 gpm x 7.1 lb/gal
= 109.70 lb/min

d) ΔT_{ENG} of fuel = ($T_{supply} - T_{rtn}$)

$$\Delta T_{ENG} = \frac{Q}{M_{RTN} \text{ x } c_p}$$

$$= \frac{\text{1252 Btu/min}}{\text{(109.70 lb/min x 0.5 Btu/lb-°F)}}$$

= 22.83°F

e) 95% Capacity of Diesel Oil Day Tank, (lb)
Weight density (p) for #2 diesel oil = 52.42 lb/ft^3
$M_{DT} = L \text{ x } W \text{ x } H \text{ x } p_{DO}$
= 12 ft x 8 ft x 8 ft x 52.42 lb/ft^3
= 40258.6 lb.

Step 1

Calculate the fuel mass in the day tank at specific time intervals:

Day Tank Fuel Quantity = M_{DT} - (M_{BR} x t)

Where:

M_{DT} = Day tank contents at a specific time step (lb)
M_{BR} = Engine fuel consumption (lb/min)
t = Incremental time step (min)

Assume the day tank is replenished at 55% of initial quantity of fuel. Prepare a table of volumes as shown below for our example.

Incremental Time (Min)	Tank Fuel Quantity (lb)	Capacity (%)
0	40258.6	100.0
60	38746.0	96.2
120	37233.4	92.5
180	35720.8	88.7
240	34208.2	85.0
300	32695.6	81.2
360	31183.0	77.5
420	29670.4	73.7
480	28157.8	69.9
540	26645.2	66.2
600	25132.6	62.4
660	23620.0	58.7
720	22107.4	54.9
Refill	40258.6	100.0

Step 2

Calculate the fuel oil mix temperature (T_{mix}):

$$\frac{\left[(M_{DT(t-1)} - [(M_{xfer} \times t)])\; T_{DT(t-1)} + (M_{RTN} \times t) \times (T_{DT(t-1)} + \Delta T_{ENG})\right]}{M_{DT(t-1)} - (M_{BR} \times t)}$$

Where:

M_{DT} = Day tank contents at a specific time step (lb)
M_{xfer} = Engine transfer pump mass flow rate (lb/min)
t = Incremental time step (min)
$T_{DT(t-1)}$ = Day tank temperature for previous time step or starting temperature (°F)
M_{RTN} = Engine return mass flow rate (lb/min)
ΔT ENG = Fuel temperature rise across the engine (°F)
M_{BR} = Engine fuel consumption (lb/min)

Values for the example calculation:

$M_{DT(t-1)}$ = Day tank contents from previous time step (lb)
M_{xfer} = 134.9 lb/min
t = 60 min.
$T_{DT(t-1)}$ = Initial day tank temperature is used for first iteration, 85°F
M_{RTN} = 109.70 lb/min
ΔT_{ENG} = 22.83°F
M_{BR} = 25.21 lb/min

$$T_{mix} = \frac{[(40258.6 - (134.9)(60))(85)] + [(109.70)(60)(85 + 22.83)]}{[40258.6 - (25.21)(60)]}$$

= 88.9°F @ t = 60 min.

This calculation is repeated for each increment (t).
Prepare a summary table as shown below for each increment (t).

Incremental Time (Min)	Mix Temperature (°F)
0	85.0
60	88.9
120	92.9
180	97.1
240	101.5
300	106.1
360	110.9
420	116.0
480	121.3
540	126.9
600	132.9
660	139.3
720	146.1
Refill	

Step 3

Calculate the height of fuel contained in the day tank at t = incremental time step. Prepare a summary table for each time increment (t).

$$H = \frac{M_{DT}}{p \times L \times W}$$

Where:

H = Height of fuel in the tank

M_{DT} = Fuel contained in the day tank at each incremental time step

p = Weight density of #2 DO (52.42 lb/ft^3)

L = Length of day tank (12 ft)

W = Width of day tank (8 ft)

Incremental Time (min)	Height (ft)
0	8.0
60	7.7
120	7.4
180	7.1
240	6.8
300	6.5
360	6.2
420	5.9
480	5.6
540	5.3
600	5.0
660	4.7
720	4.4
Refill	8.0

Step 4

Calculate the heat transferred between the fuel in the day tank and the atmosphere, the ΔT of the fuel in the day tank due to the heat transfer, and the resulting fuel day tank temperature.

a) Heat transferred between the day tank and the atmosphere:

$$Q_{TK} = \left[U \times [\,(H \times (2L + 2W) + (L \times W)\,] \times [\,T_{AMB} - \frac{(T_{MIX} + T_{DT})}{2}\,]\right] \times t$$

Where:

Q_{TK} = Heat transfer to/from atmosphere (Btu)

This considers 6mm (0.25 in.) steel plate forming the tank boundaries, and the film coefficient for air and oil. The air side film coefficient is predominant when compared to the oil side film. The tank thickness has a negligible effect.

U = Coefficient of heat transfer, (0.0424 Btu/min • ft^2 • °F)

L = Day tank length (ft)

W = Day tank width (ft)

T_{AMB} = Ambient temperature (°F)

T_{MIX} = Mix temperature of return fuel and fuel in tank (°F)

T_{DT} = Day tank temperature resulting from heat transfer to/from day tank (°F)

t = Incremental time step (min)

H = Fuel height for specific time step (ft)

b) Temperature change in the day tank resulting from heat to/from day tank:

$$\Delta T_{DT} = \frac{Q_{TK}}{M_{DT} \times C_p}$$

Where:

ΔT_{DT} = Temperature change of fuel in the day tank (°F)

Q_{TK} = Heat transfer to/from atmosphere (Btu)

M_{DT} = Mass of fuel in day tank (lb)

c_p = Specific heat of #2 MDO = 0.5 Btu/lb • °F

c) Day tank temperature resulting from heat transfer to/from day tank:

$$T_{DT} = T_{MIX} + \Delta T_{DT}$$

Where:

T_{DT} = Day tank temperature (°F)

T_{MIX} = Mix temperature of return fuel and tank fuel (°F)

ΔT_{DT} = Temperature change of day tank (°F)

These three calculations are interdependent in nature. First, Q_{TK} is determined for the first incremental time step. The resulting value for Q_{TK} is then used to compute the ΔT_{DT}. ΔT_{DT} is then used to determine T_{TK}. This process is then repeated for each incremental time step.

Example a):

$$Q_{TK} = [U\,[\,H \times (2L + 2W\,) + (L \times W)] \times [\,T_{AMB} - \frac{(T_{MIX} + T_{DT})}{2}]] \times t$$

$$Q_{TK} = 0.0424 \times [7.7\,(40) + 96\,] \times [\,95 - \frac{(88.9 + 85)}{2}] \times 60$$

$$= 8283.6 \text{ Btu}$$

Example b):

$$\Delta T_{DT} = \frac{Q_{TK}}{M_{DT} \times c_p}$$

$$= \frac{8283.6 \text{ Btu}}{(38746.0 \text{ lb})\,(0.5 \text{ Btu/lb °F})}$$

= 0.43 °F (From atmosphere to day tank)

Example c):

$$T_{DT} = T_{MIX} + \Delta T_{DT}$$

$$= 88.9 \text{ °F} + 0.43 \text{ °F}$$

$$= 89.3 \text{ °F}$$

This series of calculations is then repeated for the subsequent incremental time steps.

Prepare a summary table for each time increment (t).

Incremental Time (min)	Heat Rejection to/from Day Tank (Btu)	Temperature Chg. in Day Tank (°F)	Day Tank Temperature (°F)
0	-	-	85.0
60	8283.6	0.43	89.3
120	4069.7	0.22	93.2
180	-4.0	0.00	97.1
240	-4022.0	-0.24	101.3
300	-7966.3	-0.49	105.6
360	-11818.7	-0.76	110.2
420	-15561.4	-1.05	114.9
480	-19257.8	-1.37	120.0
540	-22802.6	-1.71	125.2
600	-26253.3	-2.09	130.8
660	-29655.5	-2.51	136.8
720	-32973.6	-2.98	143.1
Refill	-	-	116.9

The last part in Step 4 determines the day tank temperature after refilling ($T_{DT\ refill}$):

$$T_{DT\ refill} = \frac{[\,(M_{DT_{full}} - M_{DT_{tn}}) \times T_{MUF}\,] + (M_{DT_{tn}} \times T_{TK_n})}{M_{DT_{full}}}$$

Where:

$M_{DT_{full}}$ = Capacity of day tank, (lb)

$M_{DT_{tn}}$ = Fuel in day tank prior to refilling, (lb)

T_{MUF} = Temperature of make-up fuel, (°F)

T_{TK_n} = Temperature of tank fuel prior to refilling, (°F)

Example:

$$T_{DT\ refill} = \frac{[(40258.6 - 22107.4) \times 85] + (22107.4 \times 143.1)}{40258.6\ \text{lb}}$$

$$= 116.9°\text{F}$$

Step 5

The last step calculates the maximum power capability of the engine at the resultant day tank temperature for each time interval. A summary table for each increment (t) is also prepared:

***Note**: The engines are power set at the factory with 30 ± 3°C (86 ± 5°F) fuel to the engine transfer pump. Higher fuel temperatures reduce maximum power capability. The fuel stop power reduction is 1% for each 5.6°C (10° F) fuel supply temperature increase above 30°C. If the engine is operating below the fuel stop limit, the governor will add fuel as required to maintain the required engine speed and power.*

$$P_{corr} = P_{rated} \times \left(1 - \left[\frac{(T_{DT} - T_{ref})}{10°\text{F}} \times \frac{1}{100}\right]\right)$$

Where:

P_{corr} = Corrected Engine Power, bhp

P_{rated} = Rated bhp

T_{ref} = 86° (Power setting)

T_{DT} = Actual day tank fuel temperature, °F

Example:

For t = 60, the corrected power of the engine is:

$$P_{CORR} = 4640\ \text{bhp} \times \left(1 - \frac{[\,(89.3°\text{F} - 86°\text{F}) \times 1\,]}{(10°\text{F})\,(100)}\right)$$

$$= 4625\ \text{bhp}$$

Incremental Time (min)	Day Tank Temp. (°F)	Corrected Engine Power (bhp)
0	85.0	-
60	89.3	4625
120	93.2	4607
180	97.1	4588
240	101.3	4569
300	105.6	4549
360	110.2	4528
420	114.9	4506
480	120.0	4482
540	125.2	4458
600	130.8	4432
660	136.8	4405
720	143.1	4375
Refill	116.9	4497

Conclusion

The previous calculations indicate day tank fuel temperatures can have an effect on the maximum power capability of the engine. The example was based upon a fixed pitch propeller application. Typically, a fixed pitch propeller is selected and sized to absorb 85-90% of the engine's name plate rating. In this example, this would equate to 3950-4175 bhp. The lowest calculated corrected power was determined to be 4375 bhp. This would leave a 5-10% power margin and vessel performance would not be affected.

While vessel performance may not be affected in this example, the maximum fuel temperature of 143.1°F will put the fuel viscosity near or below the minimum allowable viscosity of 1.4 cSt at the injectors depending on the type of distillate fuel being used. In addition, the temperature of the fuel in the tank after refill is now 116.9°F instead of 85°F as used at the beginning of the iteration. Therefore, continued operation at full load on this fuel tank would cause the fuel temperature to rise even higher than the maximum temperature shown in this iteration. To protect the fuel injectors a fuel cooler should be used in this application, despite the fact that available engine power is still acceptable.

Aside from the impact on engine performance, maximum fuel tank temperatures are also established by various marine classification societies and regulatory bodies. Their interest is based upon the increased risks of fire that results from elevated fuel temperatures.

Fuel Heaters

Cold weather can form wax crystals in No. 1 or No. 2 diesel fuel if temperatures go below the cloud point. Small amounts of heat added to the fuel before the filters can prevent clogging problems due to wax. At temperatures below the cloud point, fuel will flow through pumps and lines but not filters. At temperatures below the pour point, fuel will not flow in lines or pumps. The use of fuel with a pour point above the minimum expected ambient temperature is not recommended. Fuel heaters will often solve cloud point problems but not pour point problems unless applied to the entire fuel storage volume.

The following are several suggestions for applying fuel heaters:

- Use fuel heaters when the ambient temperature is below the fuel cloud point. Many types of heaters can be used. Heat the fuel before the first filter in the fuel system. *Do not use fuel heaters when the ambient temperature exceeds 15°C (60°F). The maximum fuel temperature at the outlet of the fuel heater must never exceed 72°C (162°F).*
- Use heaters capable of handling the maximum fuel flow of the engine. The restriction created must not exceed the maximum allowable.
- Coolant may be taken from taps on the engine when using the engine as a heat source. Care must be taken to assure that coolant shunting to one system does not adversely affect another system, and that both have adequate flow.

Caution: *Failed water sourced fuel heaters can introduce excessive water into the engine fuel system and cause injector failure. Maintenance responsibility of this type of heater must be clearly defined.*

When fuel heaters are used in ambient temperatures below 0°C (32°F), start the engine and run at low idle until the engine temperature rises slightly. This allows heat transfer to the fuel before high fuel flow rates at high power output occur, reducing fuel filter wax plugging.

Useful Fuel Formulas and Data

The following information can be useful in sizing fuel coolers and heaters:

Specific Gravity (SG) and Density

API Gravity = (141.5/SG) - 131.5

SG = 141.5/(API Gravity + 131.5)

$$\text{SG} = \frac{\text{Density}}{998\ \text{kg/m}^3}$$

Density (kg/m^3) = SG x 998 kg/m^3

$$\text{Density (lbm/gal)} = \text{SG} \times 998\ \text{kg/m}^3 \times \frac{1\ \text{lbm/ft}^3}{16.02\ \text{kg/m}^3} \times \frac{1\ \text{ft}^3}{7.48\ \text{gal}}$$

Mass Flow Rate

$$\dot{M}\ \text{(kg/sec)} = \text{Density (kg/m}^3\text{)} \times \frac{1\ \text{m}^3}{1000\ \text{L}} \times \frac{\text{Flow Rate (L/min)}}{60\ \text{(sec/min)}}$$

$$\dot{M}\ \text{(lbm/min)} = \text{Density (lbm/gal)} \times \text{Flow Rate (gal/min)}$$

Specific Heat (c_p)

The following table shows typical specific heat values for two different API gravity fuels in Btu/lbm-°F:

API Gravity	100°F (38°C)	140°F (60°C)	180°F (82°C)	200°F (93°C)	240°F (115°C)
30	0.463	0.482	0.501	0.511	0.530
40	0.477	0.497	0.516	0.526	0.546

1 Btu/lbm-°F = 4.186 kJ/kg-°C

Heat Rejection

$$Q\ \text{(kW)} = \dot{M}\ \text{(kg/sec)} \times c_p\ \text{(kJ/kg-°C)} \times \Delta T\ \text{(°C)}$$

$$Q\ \text{(Btu/min)} = \dot{M}\ \text{(lbm/min)} \times c_p\ \text{(Btu/lbm-°F)} \times \Delta T\ \text{(°F)}$$

Burning Used Crankcase Oil

With legislation and ecological pressures, it is becoming increasingly difficult to dispose of used oil. Burning of used crankcase oil in 3600 engines is **not** recommended due to the detrimental effects on exhaust emissions. However, if ancillary methods of reducing exhaust emissions to acceptable limits are used, or if emissions are not a problem, burning crankcase oil in 3600 engines is possible with these guidelines:

- Only diesel engine crankcase oils can be mixed with the diesel engine fuel supply. The ratio of used oil to fuel **must not exceed 5%**. Premature filter plugging will occur at higher ratios. ***Under no circumstances should gasoline engine crankcase oil, transmission oils, special hydraulic oils not covered by Caterpillar recommendations, greases, cleaning solvents, etc., be mixed with the diesel fuel***. Do not use crankcase oils containing water or antifreeze from engine coolant leaks or from poor storage practices.
- *Adequate mixing is essential*. Lube oil and fuel oil, once mixed, will combine and not separate. Mix used crankcase oil with an equal amount of fuel, filter, and then add the 50-50 blend to the supply tank before new fuel is added. This procedure will normally provide sufficient mixing. Failure to achieve adequate mixing will result in premature filter plugging by slugs of undiluted lube oil.
- Filter or centrifuge used oil prior to putting it in the fuel tank to prevent premature fuel filter plugging or accelerated wear or plugging of fuel system parts. Soot, dirt, metal, and residue particles larger than 5 microns (.0002 in.) must be removed.

Caution: *Diesel fuel day tank sight glasses may blacken. Ash content of the lube oil in the fuel may also cause more accumulation of turbocharger and valve deposits.*

Continuous Blending

If the installation warrants, used lubricating oil can be blended and used in the engine in a continuous manner. The normal method uses a centrifuge module similar to Figure 8. The following information describes the system:

Centrifuge No. 1
Engine crankcase oil is continuously centrifuged except when the clean waste oil tank is low, at which time the dirty waste oil is centrifuged and directed to the clean waste oil tank.

Centrifuge No. 2
Distillate fuel/oil mixture daytank is continually centrifuged.

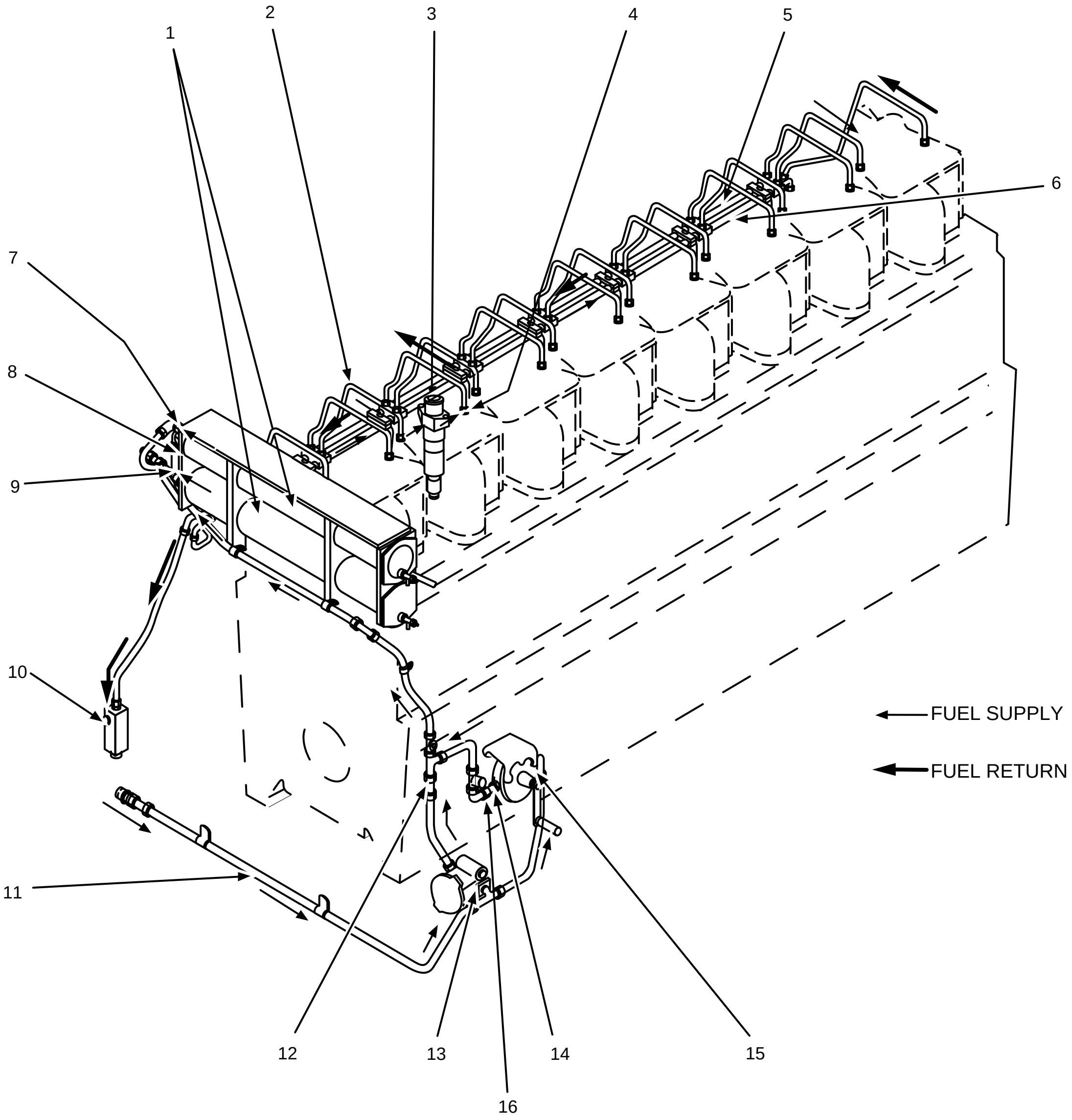
Metering Pump
Adds up to 5% clean waste oil to the distillate fuel (from the main supply tank) when the daytank low level switch calls for more fuel.

Static Mixer
Runs when the metering pump is on to insure a proper homogeneous mixture of the fuel and clean waste oil.

The centrifuge module is electronically controlled and includes the components within the dotted line. Size the system for appropriate fuel delivery.

Reference Material

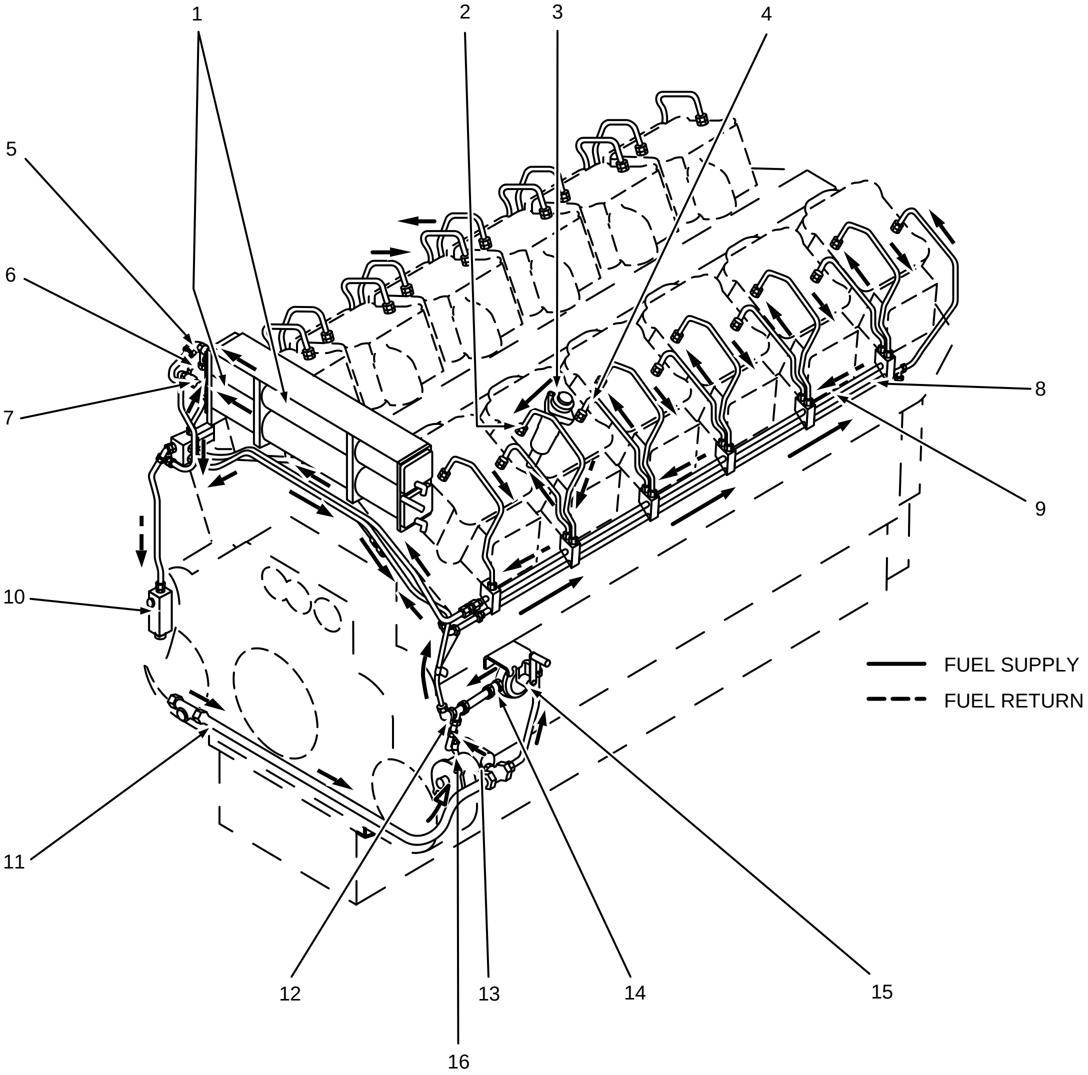
SEHS9031	*Special Instructions - Storage Recommendations*
SEBD0717	*Diesel Fuel and Your Engine*
SEBD0640	*Oil and Your Engine*
LEKQ4219	*EDS 60.1 – Fuel Recommendations for Caterpillar Diesel Engines*



3606 and 3608 Engines Fuel Flow Schematic

1. Fuel Filter Housings
2. Fuel Inlet Line
3. Unit Injector
4. Fuel Outlet Line
5. Fuel Return Manifold
6. Fuel Supply Manifold
7. Check Valve
8. Fuel Filter Change Valve
9. Check Valve
10. Fuel Pressure Control Valve
11. Fuel Supply Line
12. Check Valve
13. Fuel Transfer Pump
14. Check Valve
15. Fuel Priming Pump
16. Emergency Fuel Connection

Figure 1



3612 and 3616 Engines
Fuel Flow Schematic

1. Fuel Filter Housings
2. Fuel Outlet Line
3. Unit Injector
4. Fuel Inlet Line
5. Check Valve
6. Fuel Filter Change Valve
7. Check Valve
8. Fuel Supply Manifold
9. Fuel Return Manifold
10. Fuel Pressure Control Valve
11. Fuel Supply Line
12. Check Valve
13. Fuel Transfer Pump
14. Check Valve
15. Fuel Priming Pump
16. Emergency Fuel Connection

Figure 2

Fuel System Schematic

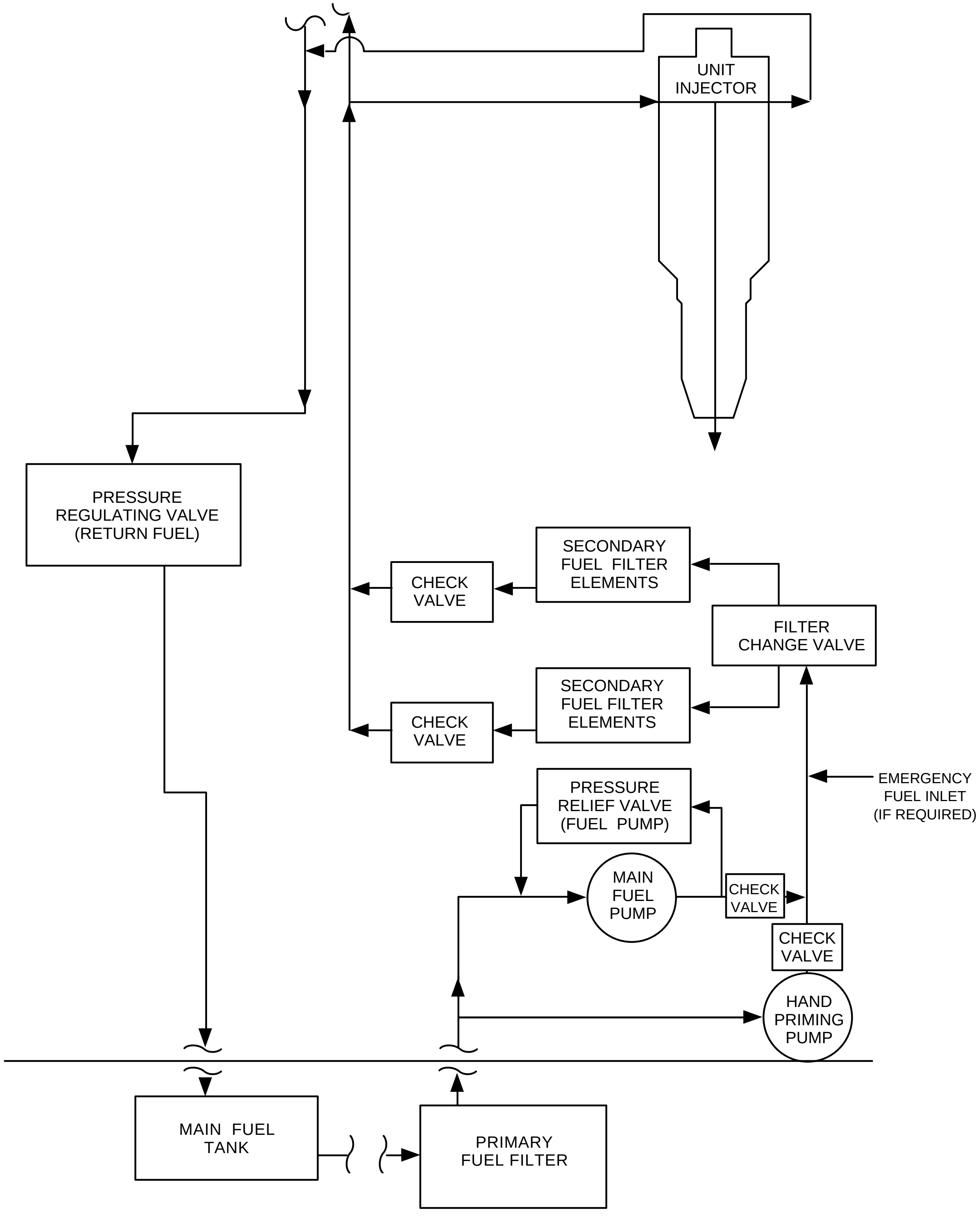
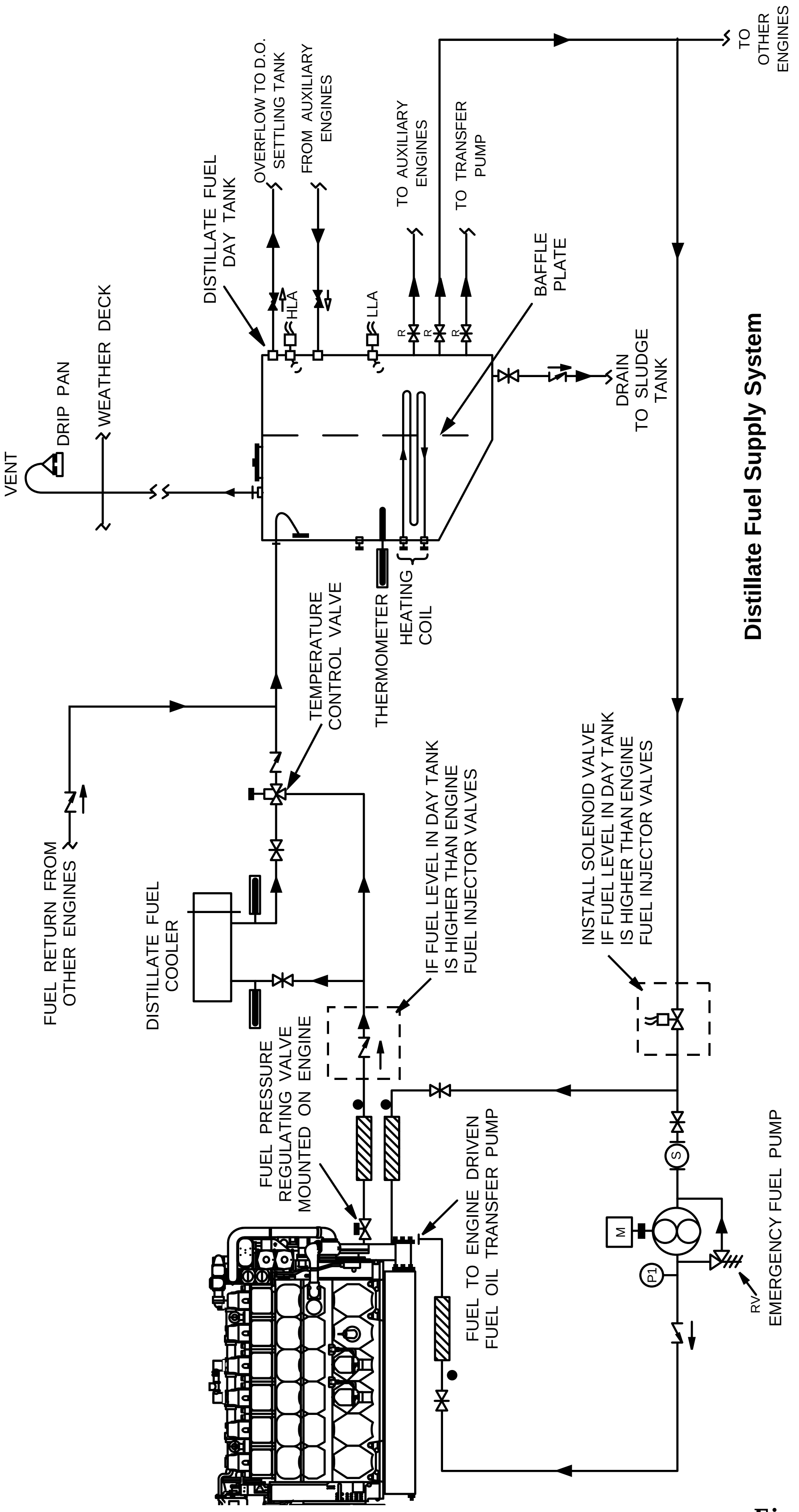
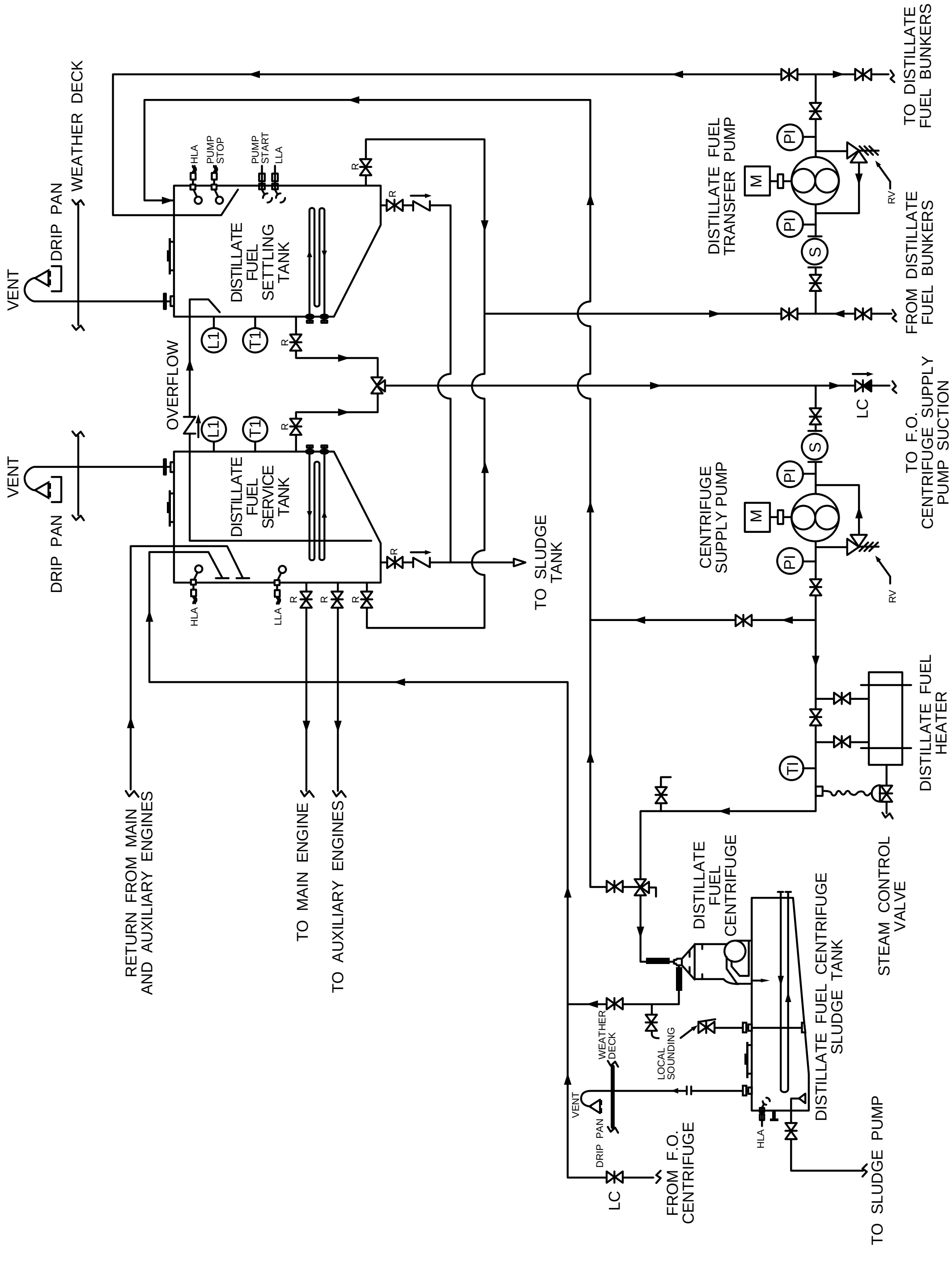


Figure 3



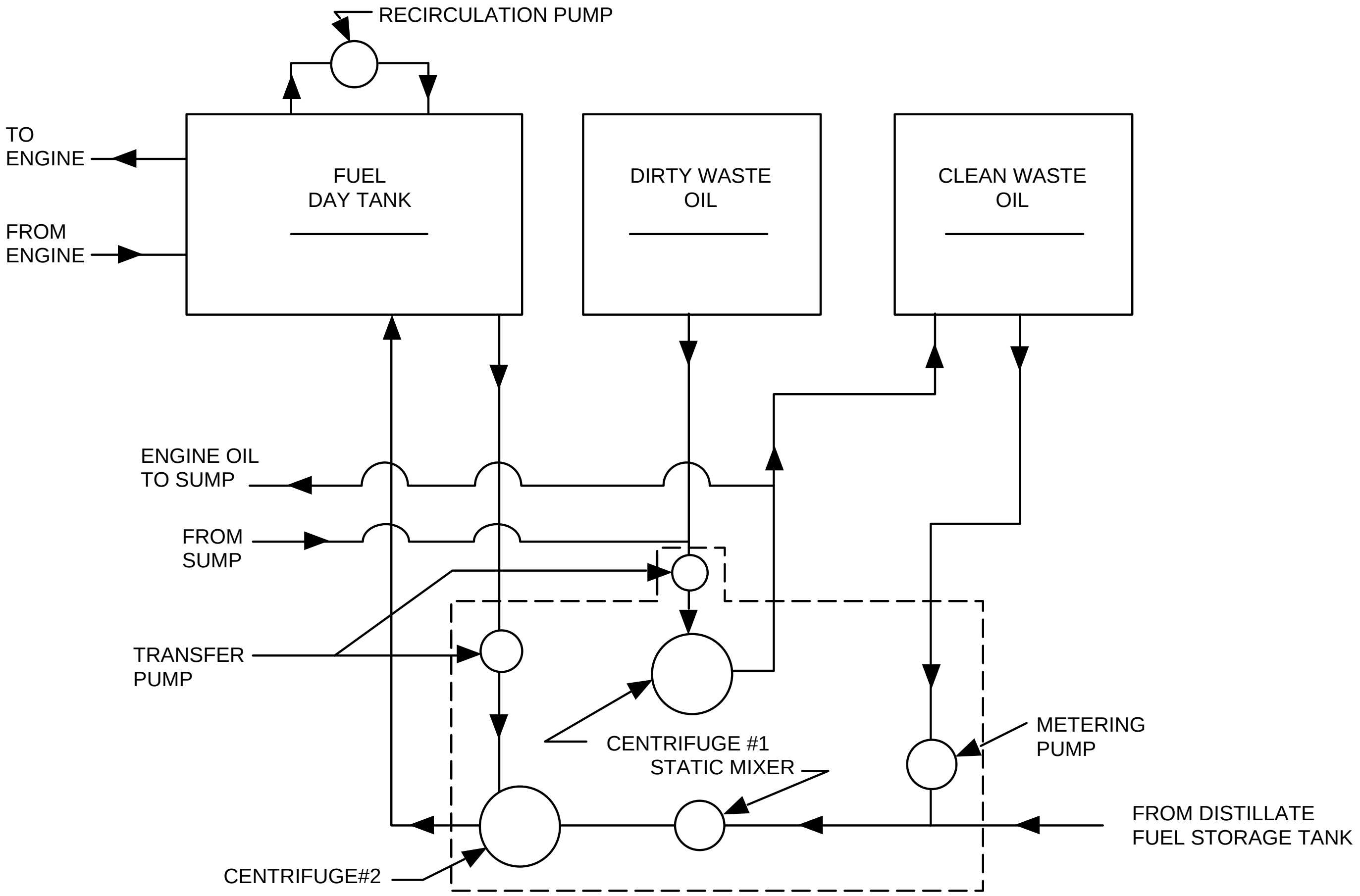
Distillate Fuel Supply System

Figure 4



Distillate Fuel Centrifuge System

Figure 6



Centrifuge Module Schematic
For Burning Used Crankcase Oil
(Continuous Blending Method)

Figure 8