



**Cat® C4.4 ACERT™, C6.6 ACERT,
and C7.1 ACERT
Tier 4 Interim, Stage IIIB Engines**

**application &
installation manual**

**Four- and six-cylinder diesel engines
for agricultural, industrial, and
construction applications**

**Developed to meet EU nonroad mobile machinery Stage IIIB and
EPA nonroad Tier 4 Interim legislation/regulations**

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1.0 Introduction

This manual has been compiled to explain mandatory requirements, provide information for designers, and provide best practice information on the correct application and installation of the Cat® C4.4 ACERT and C6.6 ACERT engines into industrial equipment to meet U.S. Environmental Protection Agency (EPA) Tier 4 Interim regulatory requirements and European Union (EU) Stage IIIB nonroad mobile machinery emissions legislation.

We endeavor to provide information in this manual that is correct at the time of issue. Continuing product developments and changing legal requirements will, however, continue to drive further changes in installation requirements; therefore, attention must be paid to ensure that the latest information is used and valid data is obtained from the engine specification manual.

This manual is not an exhaustive source of instruction or data and should only be used in conjunction with advice from your local application engineers, sales manager, and/or technical support representative.

The following media publications for the relevant engine type should also be used for further technical information:

- Tier 4 Interim Electrical and Electronic A&I Manual – LEBH0005
- Operator and Maintenance Manual (OMM)
- System Operation Test and Adjust (SOTA)
- Specifications (Specs)
- Disassembly and Assembly (D&A)
- Engine Specification Manual (E.S.M.)

Correct practices, procedures, and safety precautions should always be followed.

Please Note: The information provided may be subject to change. Caterpillar has provided this information in good faith and is not liable for how this information is interpreted or applied.

Caterpillar is not responsible for failures resulting from attachments, systems, accessory items, and parts not sold or approved by Caterpillar. Consult the applicable warranties for complete details of Caterpillar warranty coverage.

The manufacturer and customer are reminded that it is their responsibility to ensure compliance with the requirements of the Health & Safety at Work Act 1974 and any other applicable legislation, both nationally and internationally, in relation to the engine installation applicable to the equipment concerned. In giving notice of approval in respect of the installation, Caterpillar does not assume such responsibilities on behalf of the manufacturer or customer and while engine installation approval and advice is an opinion given in good faith, the equipment manufacturer and customer remain responsible as detailed above and must act and insure accordingly.

1.1 How to Use Manual

This manual has been structured so that each chapter corresponds to a different engine system.

The start of each chapter details the mandatory installation requirements relevant to that particular engine system.

These mandatory requirements include emission-related requirements and warranty-related requirements.

All emission-related Installation Instructions are highlighted by the **EM** symbol.

Failing to follow these instructions when installing a certified engine in a piece of nonroad equipment violates federal law (40 CFR 1068.105(b)), subject to fines or other penalties as described in the Clean Air Act.

All mandatory requirements must be adhered to in order to ensure emission compliance and attain full engine warranty.

For full details of the structure of the complete manual, please refer to the table of contents.

For details of electronic and electrical systems, please refer to the Tier 4 Interim Electrical and Electronic A&I Manual — LEBH0005.

1.1.1 Terminology

The terminology used throughout this book is as follows:

AITP	Application and Installation Test Procedure
AT	Aftertreatment
BPV	Backpressure Valve
CDPF	Catalyzed Diesel Particulate Filter
CG	Center of Gravity
CO ₂	Carbon Dioxide
CO	Carbon Monoxide
DOC	Diesel Oxidation Catalyst
DPF	Diesel Particulate Filter
ECU	Electronic Control Unit
E.S.M.	Engine Specification Manual
ETP	Electric Transfer Pump
HC	Hydrocarbon
H ₂ O	Water
ID	Identification
IGB	Installation Guideline Bulletin
MAF	Mass Air Flow
NO _x	Nitrogen Oxides – NO and NO ₂
OEM	Original Equipment Manufacturer
OMM	Operation and Maintenance Manual
PM	Particulate Matter
RF	Radio Frequency
S/N	Serial Number
SOF	Soluble Organic Fraction

1.2 Emissions Standards

Emissions standards differ by country and local emissions standards can impact certain regions and territories. It is, therefore, essential to understand the regulatory requirements of the country where the machine is intended to be sold or operated.

Similar to previous years, the United States has adopted a Tier approach (also used in Canada), and the EU has adopted a Stage approach for use in Europe. While these legal regimes are similar, there are differences in the rating bands, introduction requirements, implementation, in-use compliance, and conformity testing.

The Cat C4.4 ACERT-C7.1 ACERT engines are offered so that they meet both EPA and EU emissions standards. Compliance with other emissions standards is rating specific and can be checked on the power curve.

The regulatory requirements and impacts are summarized below. For further details, please consult your local sales representative.

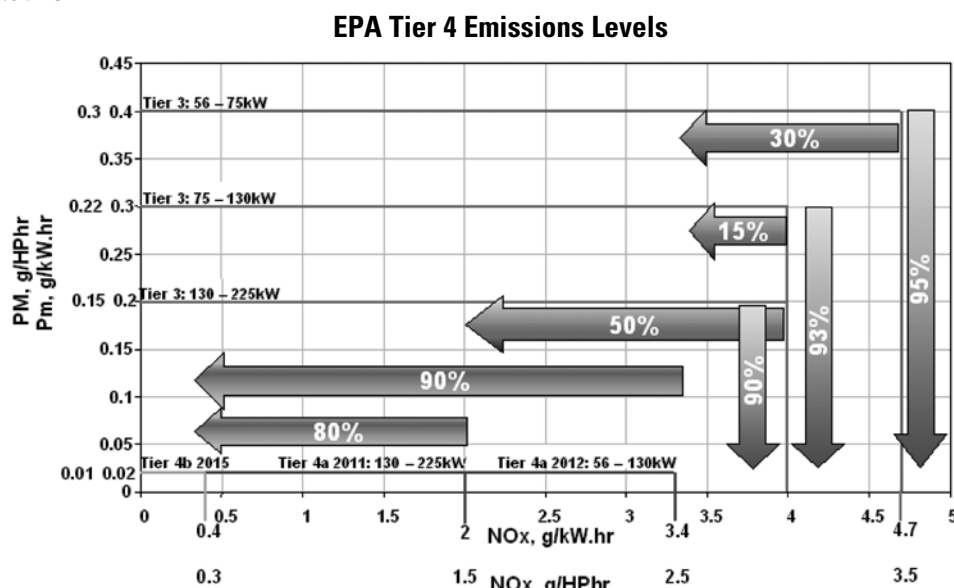


Figure 1.1

EPA Tier 4 regulations concentrate largely on reducing the Nitrous Oxide (NOx) and Particulate Matter (PM) emissions. Figure 1.1 above shows how this reduction compares to previous Tier 3 emission standards.

The introduction of the upcoming emission standards in the United States and European Union has been purposely staggered:

- Tier 4 Interim, Stage IIIB emission standards require a large reduction in PM and small reduction in NOx. For most engine ratings, particulate filters are the most common emissions solution for meeting these stringent emission standards.
- Tier 4 Final, Stage IV emission standards maintain the reduced PM level, but have a larger reduction in NOx. The emissions solution for meeting these additional NOx reductions is NRS (NOx Reduction System).

Unlike previous emissions standards, the new laws require all crankcase emissions to be included in the total system emission values. This is important when selecting open or closed crankcase ventilation, as the laws will require this to be taken into consideration during in-use testing. Please refer to Chapter 10 — Crankcase Ventilation Systems for further information.

1.3 Product Changes

In order to achieve the particulate matter (PM) and nitrous oxide (NOx) reductions required for Tier 4 Interim, Stage IIIB emission standards, both on- and off-engine solutions have been employed. These are discussed briefly below:

1.3.1 On-engine Changes

On-engine NOx reduction technologies are used along with a high-pressure common rail fuel system and single or series turbo charging (rating dependent) with a smart wastegate. All engines are now electronically controlled.

The engine envelope has been kept as close to the current Tier 3 product as possible; however, due to the introduction of new technologies, a small increase has been seen. The actual dimensions are option specific, and it is recommended that no design work be initiated without a full 3D engine model.

There is also an opportunity to make additional improvements and changes to the engine. These include:

- Poly vee belts for longer service intervals
- An optional heavy-duty front end, including a 12-rib belt, heavy-duty alternator, and heavy-duty fan drive
- Hydraulic tappet adjustment giving a service-free top end
- A shunt line connection into the water pump
- An optional SAE B drive providing increased clearance for PTO pumps, etc.
- Optional mounted air conditioning compressors

For more detailed information on the engine layout and customer hook-up points, please refer to the relevant E.S.M.

1.3.2 Off-engine Changes

Off-engine additional exhaust aftertreatment solutions have become a necessity. All include a Diesel Oxidation Catalyst (DOC) and can be packaged with a Catalyzed Diesel Particulate Filter (CDPF) and Cat Regeneration System, depending on engine type and rating.

These come in alternative package arrangements with axial and radial connections. For further details, please refer to the relevant engine E.S.M. and Chapter 5 of this manual.

The addition of these aftertreatment solutions to the engine increases the complexity of the installation, and in many cases, a redesign of the machine and engine compartment is required. Engine and machine integration is now even more critical to ensure acceptable and optimized machine operation.

1.3.3 How These Changes Impact Machine Integration

Some of the other major impacts to machine integration are summarized below.

- Increased envelope required for installation of both engine and aftertreatment solution
- Installation of the aftertreatment in the engine compartment will lead to increased under hood temperatures
- Increased engine heat rejection
- New mechanical and electrical connections
- New system indication lamps and regeneration operator interfaces
- ≤15 ppm ultra low sulphur fuels only (required by U.S. law); in Europe, this may be marketed as sulphur free fuel, and the maximum sulphur content will normally be ≤ 10 ppm, though in certain member states this fuel may contain up to 20 ppm sulphur at point of final delivery to user
- The use of low ash such as API-CJ4

To enable machines wishing to use heavily integrated solutions via a J1939 data link, a high number of additional parameters and functions are provided.

1.3.4 Additional Changes Impacting the Customer

Listed below are various other important changes that have been made which will affect a machine manufacturer during the integration of a Tier 4 Interim, Stage IIIB engine.

- Worldwide ambient clearance for sign off has been increased to 48°C.
- The maximum allowable top tank temperature is now 108°C.
- There are strict requirements on the visibility of the emissions control label and a low sulphur fuel label has also been mandated.
- Machines need to be designed to accommodate in-use testing equipment; please refer to Chapter 10 — Crankcase Ventilation, for further information.
- New application processes and procedures, including revised test procedures, have been implemented to support this change in technology. Refer to Chapter 16 — Installation and Audit Testing. Contact your applications engineer and account manager for further information.
- The U.S. EPA Delegated Final Assembly exemption allows for separate shipment of the engine and aftertreatment, as long as certain regulatory requirements are met, including but not limited to execution of a delegated final assembly contract between the engine manufacturer and customer, customer submission of an annual affidavit accompanied by evidence of proper pairing of engines and aftertreatment components, and periodic auditing of customer facilities to ensure compliance with delegated final assembly requirements, etc. Contact your account manager for further information.

2.0 Engine Selection and Application

2.1 Introduction

The purpose of the engine selection chapter is to help provide a guide and ensure that the correct engine has been selected for the application.

2.2 Engine Selection and Application Mandatory Requirements

All emission-related installation instructions are highlighted by the **EM** symbol.

Failing to follow these instructions when installing a certified engine in a piece of nonroad equipment violates federal law (40 CFR 1068.105(b)), subject to fines or other penalties as described in the Clean Air Act.

2.2.1 Ratings

- **EM** The engine rating must be selected to have the necessary power and torque characteristics for the machine in which it is installed so that it can operate in all necessary environmental conditions.
- **EM** The engine must be selected to comply with all the necessary legislation for the area in which the machine is to be sold and operated. Legislative compliance should be checked on the power curve.
- **EM** An engine that has been certified for constant-speed operation must not be used in a variable speed application.
- The engine must be correctly selected and applied in accordance with the industrial rating tier to which the engine has been developed. Rating classifications can be found listed in the E.S.M.
- The engine must not be subjected to speeds in excess of 3000 rpm (any customer-supplied rotating equipment must be selected taking this into account).
- The engine low idle must not be reset to a value lower than the default setting unless approval from Caterpillar has been obtained.

2.2.2 Labels

- **EM** If the engine is supplied without aftertreatment system components (i.e., under Delegated Final Assembly Agreement), the temporary DFA label must be removed following correct installation of the aftertreatment system.
- **EM** The engine emission control information label must be located in a position that is readily visible to the average person after all installation and assembly are complete.
- **EM** A duplicate emission control information label is supplied with the engine. This duplicate label must be permanently attached to the equipment, even if the label supplied fitted to the engine is not obscured.
 - This label must be secured to a part needed for normal operation and not normally requiring replacement.
 - A procedure must be in place to ensure these labels are fitted and positioned correctly.
- **EM** It is the responsibility of the equipment manufacturer to supply and permanently attach a separate label with the statement “Ultra low sulphur fuel only” to the equipment near the fuel inlet in accordance with regulatory requirements 1039.135. This label is not supplied with the engine.
- **EM** If a remote oil filler option is selected, the oil label supplied with the engine must be fitted near the oil filler cap.
- **EM** If any of the engine labels are damaged or oversprayed after shipment of the engine, it is the responsibility of the equipment manufacturer to replace these labels and fit them in accordance with Caterpillar instruction.

2.3 Industrial Rating Classifications

Industrial engines are classified by rating tiers, which run through from A-E inclusive. Cat C4.4 ACERT-C7.1 ACERT engines are normally classified as rating C; however, the C6.6 ACERT also has ratings classified as rating B and the C7.1 ACERT also has ratings classified as ratings B and D.

An explanation of the A-E rating structure is detailed below. This includes a brief description of the usage and maximum percentage time at full load. Table 2.1 also provides additional information on typical application types, sub application codes, and rating tier classifications. This table should, however, only be used as a guide and reference should be made to the engine selection procedure in Section 2.5 to help ensure the correct rating type is selected.

For an acceptable match, the classification of the rating must be the same or higher than the application requires. For example, an engine classified as IND-C can be used for applications that have been classified as requiring an IND-C, D or E rating, but not used for applications requiring an IND-B or A rating.

2.3.1 IND-A (Continuous)

Continuous ratings are for heavy-duty service when the engine is operated at rated load and speed up to 100% of the time without interruption or load cycling. Operating limits are:

1. No hour or load factor limitation
2. Continuous operation at full load
3. Average load factor to approach 100%
4. Typical operating hours per year is over 4000 hours

Cat C4.4 ACERT-C7.1 ACERT engines are not developed to this rating classification. If this is thought to be an application requirement, please consult your application engineer or technical lead for further advice.

2.3.2 IND-B

IND-B ratings are for moderate-duty service where power and/or speed are cyclic.

Operating limits are:

- Time at full load not to exceed 80% of the duty cycle
- Load factor limited to 85%
- Typical operating hours per year is 4000 hours

Figure 2.1 depicts a typical IND-B duty cycle. Examples of an IND-B industrial application are (reference only — must follow guidelines and duty cycle comparisons):

- Irrigation where normal pump demand is 85% of engine rating
- Oil field mechanical pumping/drilling
- Stationary/plant air compressors

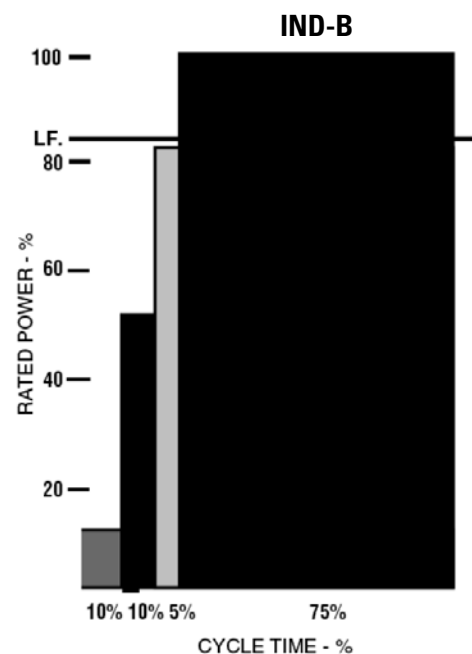


Figure 2.1

2.3.3 IND-C (Intermittent)

IND-C ratings are for service where power and/or speed are cyclic. The horsepower and speed of the engine can be used for one uninterrupted hour followed by one hour of operation at or below 75% of the full load power curve condition.

- Time at full load not to exceed 50% of the duty cycle or one hour max.
- Load factor limited to 70%.
- Full load operation limited to one uninterrupted hour followed by one hour of operation at or below 75% of the full load power curve condition.
- Typical operating hours per year is 3000 hours.

Figure 2.2 depicts a typical IND-C duty cycle.

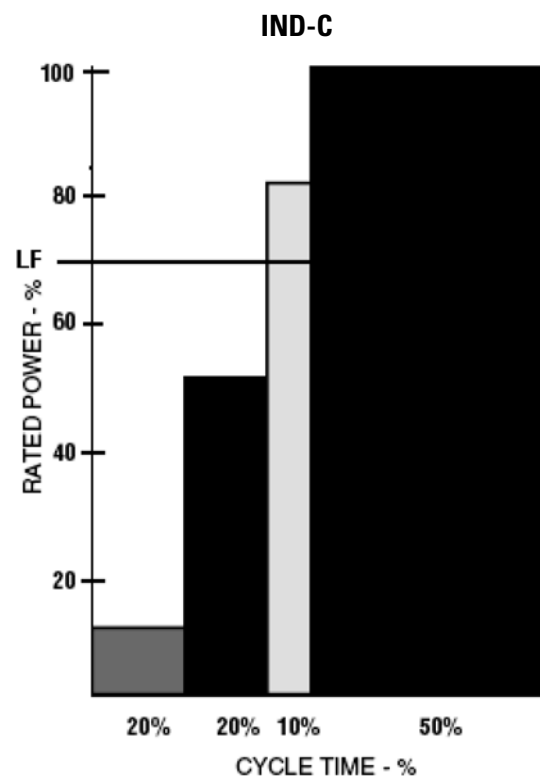


Figure 2.2

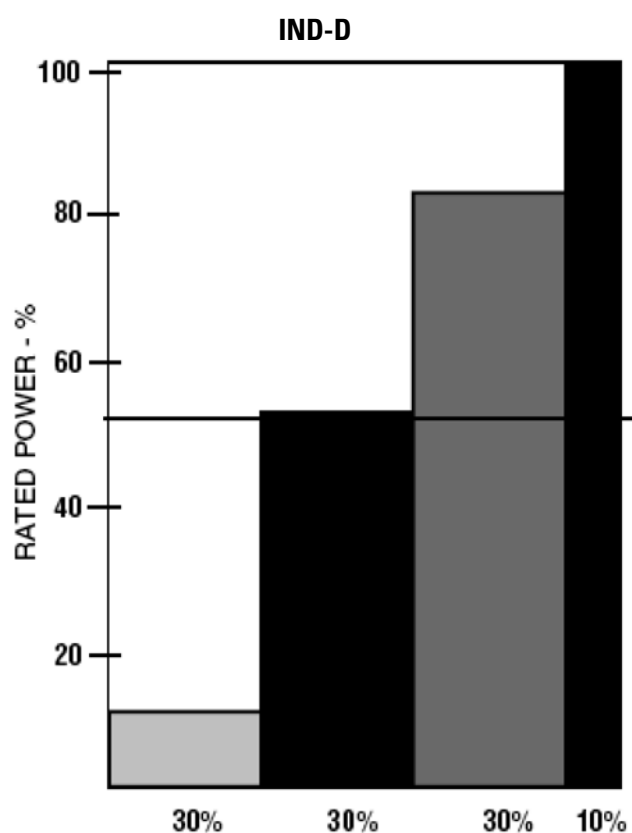


Figure 2.3

2.3.4 IND-D

IND-D ratings are for service where rated power is required by period overloads. The maximum horsepower and speed capability of the engine can be used for a maximum of 30 uninterrupted minutes followed by one hour at intermittent. Operating limits are:

- Time at full load not to exceed 10% of the duty cycle or 30 min max
- Load factor limited to 50%
- Full load operation to a maximum of 30 minutes followed by one hour at intermittent
- Typical operating hours per year is 1500

Figure 2.3 depicts a typical IND-D duty cycle.

2.3.5 IND-E

IND-E ratings are for service where speed and power are required for a short time for initial starting or sudden overload and for emergency service where standard power is unavailable. The maximum horsepower and speed capability of the engine can be used for a maximum of 15 uninterrupted minutes followed by one hour at intermittent or duration of the emergency.

Operating limits are:

- Time at full load not to exceed 5% of the duty cycle or 15 minutes max.
- Load factor limited to 35%.
- The maximum horsepower and speed capability of the engine can be used for a maximum of 15 minutes followed by one hour at intermittent or duration of the emergency.
- Typical operating hours per year is 500.

Cat C4.4 ACERT-C7.1 ACERT engines are not developed to this rating classification; however, it maybe acceptable for these applications to use a rating of a higher classification. Please consult your applications engineer or technical lead for further advice.

Industrial C - Intermittent rating		Industrial D - Rating		Industrial E - Rating	
Application Group	Sub-application code	Application Group	Sub-application code	Application Group	Sub-application code
Tractors – Wheeled	AGR20	Special Harvesters <100hp	AGR22	Refrigeration Units	IND83
Tractors – Fast	AGR21	Combine Harvesters	AGR24	Lighting Towers	IND88
Special Harvesters >100hp	AGR22	Lawn and Garden	AGR25	Aircraft Baggage Handlers	MAT14
Sprayers	AGR26	Wood Chippers <100hp	AGR39	Access Platforms	MAT68
Tractors – Tracked	AGR27	Excavators	CON30	Forklift Trucks	MAT70
Agricultural – Other	AGR28	Backhoe Loaders	CON31	Side Loaders	MAT73
Wood chippers >100hp	AGR39	Wheeled Shovel Loaders	CON32		
Forestry Harvesters	AGR85	Skid Steer Loaders	CON38		
Tracked Loaders	CON23	Mini Excavators	CON41		
Self Propelled Drills	CON29	Road Rollers	CON53		
Bulldozers	CON33	Snow Blowers	IND43		
Scrapers	CON34	Snow Groomers	IND44		
Graders	CON35	Welding Sets	IND81		
Dumpers	CON36	Ground Power Units	IND82		
Trenchers	CON37	Self Propelled Sweepers	IND87		
Pavers	CON51	Telescopic Handlers	MAT40		
Construction – Other	CON69	Cranes	MAT54		
Industrial – Other	IND42	Rough Terrain, Forklift Trucks	MAT71		
Mobile Compressors	IND50	Towing Tractors	MAT72		
IOPU - Concrete Mixer	IND52	Straddle Carriers	MAT76		
IOPU - Rock Crusher	IND56	Yard Shunting Tractors	MATXX		
Petroleum Industry	IND59				
Mining Equipment	IND61				
IOPU – Unknown	IND65				
Locomotive / Rail Traction	IND75				
IOPU - Pump Sets	IND84				
Industrial – Unknown	IND89				

Table 2.1

2.4 Application of Industrial Engine Ratings

Extensive testing is conducted both in the lab and field to identify engine ratings that will provide optimum performance and engine life under varying cycles. Through these tests, it has been possible to establish various ratings which, when properly applied, will provide the kind of engine performance and life customers demand.

Detailed knowledge of a customer's engine operating requirements is essential to establish a proper rating match. To determine the acceptability of a particular rating for a customer's application, the following must be known:

- Function of engine
- Driven equipment description
- Load quantification
- Speed quantification
- Time per application cycle
- Hours/year
- Life expectancy
- Load factor
- Max time at full load/cycle
- Horsepower required
- Aspiration desired
- Parasitic loads
- Ambient conditions — temperature/altitude
- Exhaust manifold type

Using this information and following the engine selection guide below, it should be possible to select the appropriate rating tier and engine with confidence.

2.5 Industrial Engine Selection Guide

The following sections provide detailed information on analyzing industrial applications. The intent of this section is to provide sufficient information to allow determination of the appropriate rating tier level and selection of an acceptable engine model. It can also serve as a check to ensure that the rating selected is suitable for the application and encourages thorough analysis of the actual usage of the machine.

This process involves a detailed analysis of the application duty cycle in terms of time spent at various identifiable load conditions and time spent under various identifiable speed conditions. A step-by-step example depicts how the process uses this information in terms of load factor and speed factor to calculate a rating factor. The rating factor chart allows the appropriate tier level to be identified as one major selection criteria.

The industrial engine selection guide worksheet leads the analyst step-by-step through the process using the duty cycle and other requested information to select a final tier level and engine choice for the application in question.

Commonly, the duty cycle of applications is complex and, due to the variability, is not always easy to predict or determine, therefore, further advice is available from your applications contact.

LOAD FACTOR

Load factor (the average demand on an engine) can roughly be determined through actual fuel consumption. It can be determined by dividing the actual fuel used in a work cycle by the amount of fuel that could be consumed at the stated engine rating during the same time period.

$$\frac{\text{Actual Fuel Consumed (l)}}{\text{Rated Fuel Rate (l/h) x Length of Work Cycle (h)}}$$

A more accurate determination of load factor is through detailed analysis of the duty cycle.

DUTY CYCLE

A duty cycle analysis is critical in the determination of the appropriate rating tier. The duty cycle is defined as the time spent at various powers and speeds. It is best to divide the duty cycle into as many elements of power as possible (rated, percents of rated, and idle) and as many elements of speed as possible (rated, percents of rated, high idle, and low idle). These values are used in the calculations of load factor and speed factor.

Power and Speed Profile for Duty Cycle:

Power (% Rated)	Speed (% Rated)	Time (% Cycle)
100	100	100
Low idle = 10*	Low idle - (25-40)**	
High idle = 10*	High idle = (110)***	

*All idle (low and high) power is assumed as 10% of rated power

**Low idle speed is usually 25 to 40% of rated speed

***High idle speed is usually 110% of rated speed

Example of a Simple Duty Cycle:

Power (% Rated)	Speed (% Rated)	Time (% Cycle)
100	100	50
80	85	10
50	75	20
Low idle = 10*	Low idle - (40)	10
High idle = 10*	High idle = (110)	10

Load Factor Calculation:

Load Factor = Total of % Power x % Time

$$1.00 \times 0.5 = 0.500$$

$$0.80 \times 0.1 = 0.080$$

$$0.50 \times 0.2 = 0.100$$

$$0.10 \times 0.1 = 0.010$$

$$0.10 \times 0.1 = 0.010$$

$$\text{Total} = 0.700 \text{ or } 70\% \text{ Load Factor}$$

Speed Factor Calculation:

Speed Factor = (Total of % Speed x % Time)²

$$1.00 \times 0.5 = 0.500$$

$$0.85 \times 0.1 = 0.085$$

$$0.75 \times 0.2 = 0.150$$

$$0.40 \times 0.1 = 0.040$$

$$1.10 \times 0.1 = 0.110$$

$$\text{Total} = (0.885)^2 = .78 \text{ or } 78\% \text{ Speed Factor}$$

RATING FACTOR

Multiplying the load factor by the speed factor results in a rating factor. This rating factor helps determine the proper rating tier for this duty cycle.

Rating Factor = Load Factor x Speed Factor

$$0.70 \times 0.8 = 0.55$$

By referring to the Tier identification chart in Figure 2.4, this application can be identified as requiring a Tier C rating.

Tier Identification Chart

TIER RATING FACTOR CHART	
FACTOR	RATING TIER
1.00	A
.85	B
.65	C
.45	D
.25	E
.10	

Figure 2.4

2.6 Rating Standards

The stated power output of an engine can vary considerably depending on:

- Whether the power includes or excludes the cooling fan
- Where on the power curve the value is taken
- The tolerance range allowed for power output
- The ambient temperature and barometric pressure
- The restrictions imposed by the air inlet and exhaust systems
- The humidity
- The fuel temperature and specification

To define these variables, power rating standards and test procedures exist. The output of an engine must always be qualified by reference to the standard or regulation used. Cat engines published power curves include the necessary references. Cat engines for off-highway applications (other than electric power generation) are type approved for power output to UN ECE Regulation 120 (ECE R120) which gives power ratings directly equivalent to ISO/TR/14396. These are both power tests conducted with the water pump and alternator (at minimum load) connected, but without cooling fan or other auxiliaries. The tests are conducted with fixed inlet and exhaust restrictions. The conditions under which the power measurement is conducted for ECE R120 and ISO 14396 are equivalent to the conditions for conducting the certification of engines in line with the European and North American emissions requirements, EU Directive 97/68/EC and U.S. regulations 40 CFR 1039 and 1065, respectively. The resultant power values given by ECE R120 and ISO 14396 have been corrected to standard atmospheric conditions.

There are sometimes two power values which are derived from each curve of power versus engine speed. The first one is the highest power delivered by the engine at the engine manufacturer's declared rated speed (rated power). The second power value is the highest power delivered by the engine anywhere on the curve (maximum power). Depending upon the shape of the power curve for a particular engine type, the rated power may be the same as, or different to, the maximum power. For the purposes of determining applicable European and North American emissions requirements in EU Directive 97/68/EC and U.S. regulation 40CFR1039.102, the maximum power is taken as the reference value. The rated power, however, is normally used as the advertised engine power.

Comparison to Other Standards

For earth-moving machinery, power is sometimes quoted according to ISO 9249. It is useful to understand how this power standard compares with ECE R120 and ISO 14396. In the case that the engine cooling fan is of the fixed type (neither disconnectable nor progressive), the power absorbed by the cooling fan at the given engine speed should be deducted from the value obtained by ECE R120 or ISO 14396 in order to perform a comparison. In the case that the engine cooling fan is of the progressive type, the power absorbed at maximum fan slip (minimum fan speed) at the given engine speed should be deducted from the value obtained by ECE R120 or ISO 14396 in order to perform a comparison. In the case that the engine cooling fan is of the disconnectable type (includes an "off" setting), there is no deduction from ECE R120 or ISO 14396 and the values are directly equivalent. If the machine uses an exhaust brake, a further deduction must be made for comparison with ISO 9249 from ECE R120 or ISO 14396 for the power loss caused by the exhaust brake when in the fully open (off) position if not already taken into account.

On-highway regulation ECE R24 has sometimes been used in the past for determination of non-road engine power, though power of non-road engines is no longer within the scope of this regulation. Similarly, on-highway Directive 80/1269/EEC has also been used. These both yield values equivalent to ISO 9249, so in order to make a comparison between either of these and ECE R120 or ISO 14396, it is necessary to make the same deductions as for comparison with ISO 9249.

Various other power rating standards are encountered occasionally; however, these generally have little or no legal significance other than in a particular territory. Any requests for information on such standards will necessitate specific action to determine if any relationship to the Caterpillar standard has been established.

2.7 Performance

2.7.1 Available Engine Power

The most fundamental requirement for an engine installation is that the engine can provide sufficient power for all conditions likely to be met during the intended operation. It must be understood that the engine power specified on power curves is usually gross, and deductions must be made to obtain the net condition, i.e., the real installed available power.

A number of factors must be considered in this respect, including both the required auxiliaries and operating conditions, as well as engine power variation within the published to-tolerance band. Typical considerations may include:

- Engine power
- Tolerance nominal $\pm 5\%$
- Cooling air fan
- Air conditioning compressor
- Power steering pump
- Auxiliary hydraulic pump
- Transmission efficiency
- Ambient conditions affect the gross power output
- Temperature of inlet air
- Ambient air pressure includes altitude effects
- Fuel temperature at engine inlet
- Fuel viscosity and density

The importance of these considerations can be related to the type of machine in which the engine is installed.

In many mobile machines, failure to consider all the factors will probably result in claims of poor machine performance. In other types hard facts become available. Agricultural tractors with P.T.O. facilities are frequently power checked using dynamometers. Equipment such as air compressors and water pumps require a minimum power to allow the machine to operate at its design speed.

In the following sections related to more detailed power matching, the power considered must include consideration of all the above if a satisfactory machine performance is to result.

The power required by a particular machine for a certain operation can be established:

- By calculation
- From the equipment manufacturer
- By comparison with a similar installation
- From the performance of the original engine

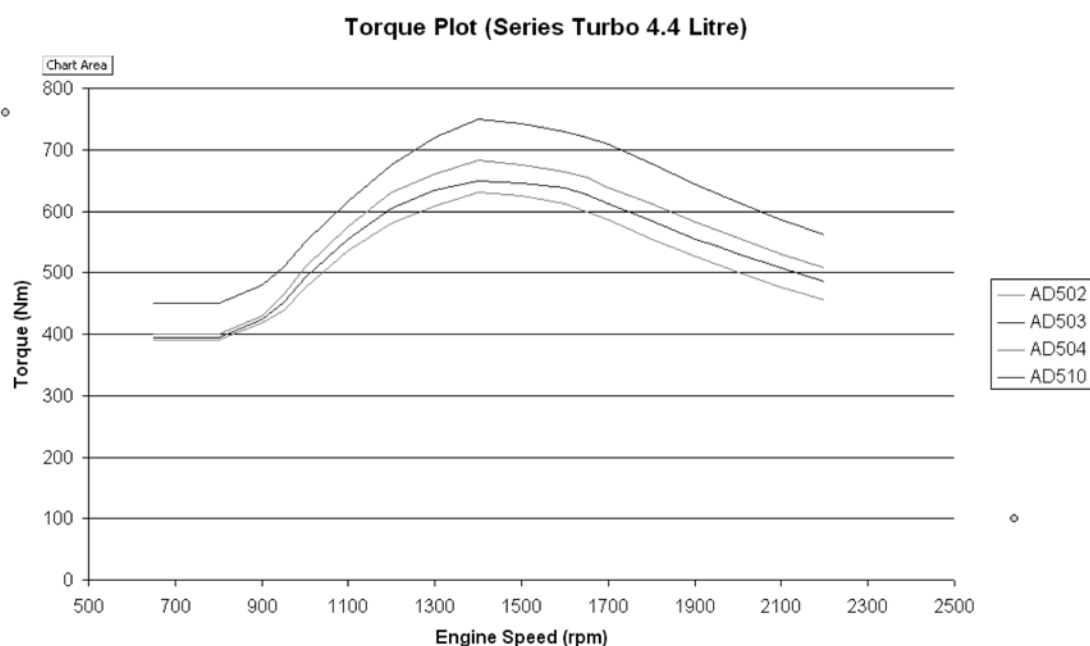
The nature of the application will determine the required engine power, rated speed, torque backup, and governing characteristics.

2.7.2 Power and Torque Matching

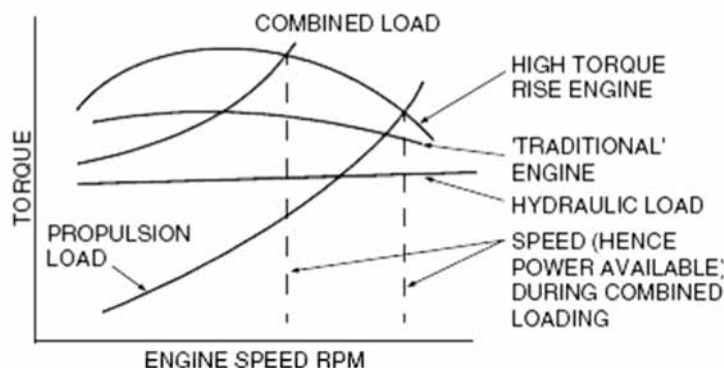
In order to give satisfactory performance, the engine must be correctly matched to the power and torque requirements of the machine over its entire range of transient and steady state operation. The practice, still common, of selecting an engine purely on maximum power and torque is very rarely adequate and is the prime source of customer complaints of low power and poor response.

The diagram below shows a comparison of typical curve shapes.

Typical 4.4 Litre Stage IIIB Torque Curves



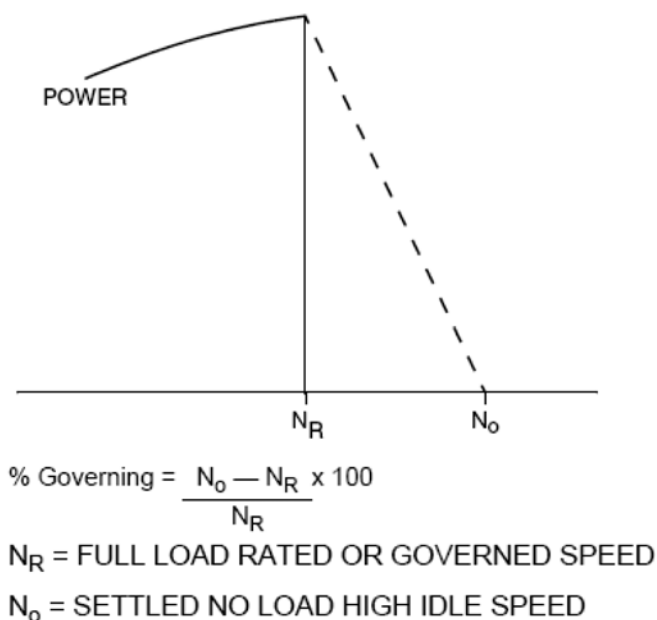
The increase in mid speed torque when related to maximum power has obvious advantages for machines such as agricultural tractors with mechanical transmissions. It also gives considerable benefit to machines using hydrodynamic (torque converter) and hydrostatic transmissions, and which also have hydraulically operated equipment fitted, such as lifting forks and buckets, etc. The diagram shows how under combined hydraulic load and propulsion load the performance is improved.



2.7.3 Governing

The default governor on all Cat C4.4 ACERT-C7.1 ACERT engines is an all-speed governor, also known as a variable speed governor. Min/max and auxiliary governors are optional alternatives. Please refer to the Electronics Application and Installation Guide for further information.

Percentage governing or droop is the speed difference between high idle and full load conditions as illustrated below. It can be programmed using the service tool to suit the application requirements.



2.7.3.1 All-Speed Governing

The all-speed engine governor will attempt to hold a constant engine speed for a given throttle position. The governor senses engine speed and load and meters the fuel supply to the engine such that the engine speed remains constant to or varies with the load in a predetermined manner. This governor type is recommended for use on applications with a constant operating speed and applications with manual transmissions. The all-speed governor is also known as variable speed or full-range engine speed governor.

Alternatively, a min/max governor can be selected where required.

2.7.3.2 Min/Max Governing

The min/max engine speed governor will provide a constant amount of power for a given throttle position. Engine speed is allowed to vary between the low idle and high idle engine speed settings. This governor essentially only governs engine speed when at the minimum or maximum allowed engine speed. In between these limits, the throttle position will cause the engine to produce power proportional to its value. The benefit of this type of governor is smoother shifting for engines with electronic automatic/automated transmissions. The min/max governor is also known as the limiting speed or power throttle governor.

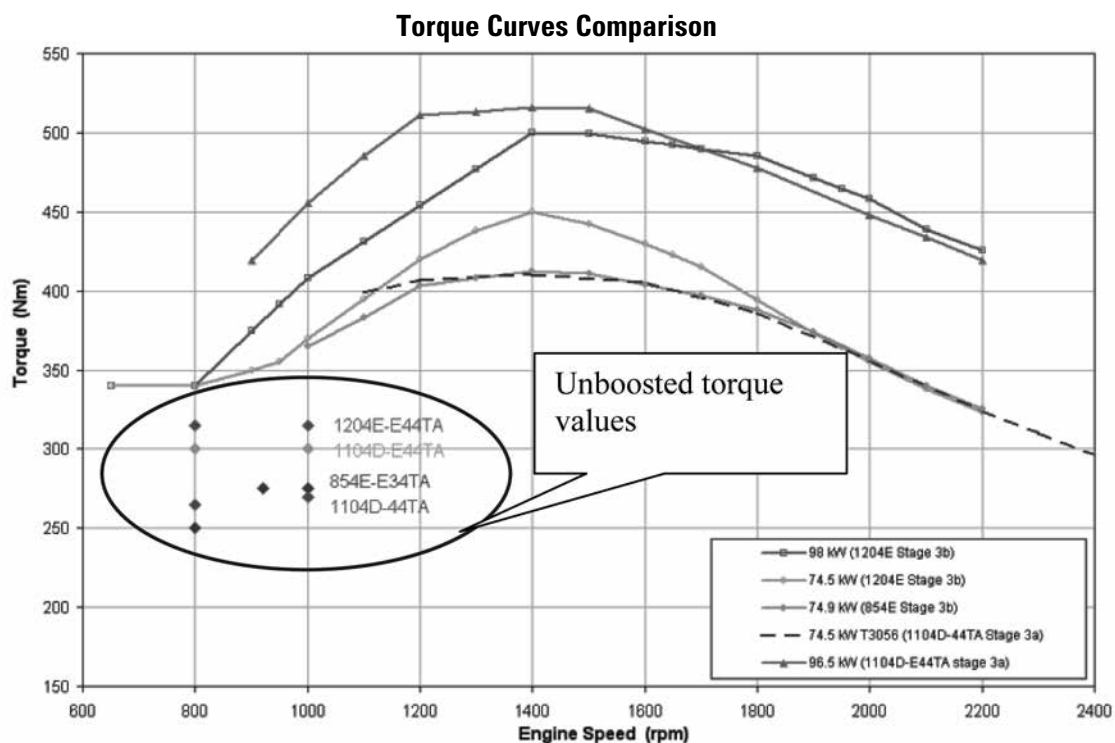
2.7.3.3 Auxiliary Governor

It is possible to control the engine speed by the output shaft speed of another module. Caterpillar does not offer a speed sensor for this component, nor is there any direct speed sensor input, for the following reasons:

- There are a wide variety of speeds to be measured.
- Speed sensor's output signals are low in amplitude and sensitive to electromagnetic interference.
- The engine is often not close to the output shaft to be measured, resulting in poor quality speed signals.

2.7.4 Low Speed Operation (below 1000 rpm)

Despite modern advantages in engine fuel injection and turbocharger design, including the use of smart wastegates to improve the operating speed range of turbocharged engines, it is inevitable that at very low speeds the boost level of a turbocharger is reduced. The fuel quantity which can be burned and corresponding engine torque are lower than indicated on the conventional boosted torque curves.



As can be seen from the diagram, the level of torque at very low speeds is much reduced in comparison with that available at high speeds. If the machine is expected to operate at very low speeds (below 1000 rpm), the load which can be placed on the engine must consider this fact. Basing the load on higher speed torque capability will lead to problems of stall-out or sluggish response.

As do other engine manufacturers, Caterpillar shows engine torque available down to 1000 rpm. Below this speed, it is inevitable that variations between individual engines, as well as the difficulty in testing output at such low speed, result in the power and torque not being guaranteed to the same extent as over the stated speed range. Therefore, if there is a need for a high torque below 1000 rpm, fully comprehensive investigation of engine/machine performance must be carried out at the prototype stage. It may be necessary to provide a means of reducing the maximum load under these conditions. An example would be by limiting hydraulic pump delivery pressure at lower operating speeds.

2.7.5 Transient Response

The previous notes refer to engine operation under steady state conditions. It is also essential to consider the operation of a turbocharged engine under the transient conditions when load is applied or an engine speed increase requested from low engine speed.

The prime reason for this is that the emission of dark smoke must be limited under conditions of engine acceleration, known as Free Acceleration Smoke (FAS). With the introduction of Diesel Particulate Filters (DPF), there will be no visible FAS as the particulates that form smoke are trapped in the DPF; however, the engine calibration controls FAS to avoid rapid accumulation of soot in the DPF which will lead to reduced regeneration intervals and increased fuel consumption. When the engine is running at light or no load at low speed, the turbocharger is itself idling at low rotational speed and provides negligible boost pressure. In general, the full load torque at 1000 rpm is dependant on a degree of boost pressure. Therefore, a smoke-limiting map is written in the software, which limits the amount of fuel that can be injected in accordance with the actual boost pressure (along with other monitored parameters).

Below 1000 rpm, the boost pressure reduces under full load to a level which demands a significant fuel reduction to avoid excessive smoke emission. As speed drops further, boost falls to a very low value and fuel must be limited by the smoke map. This occurs between 1000 rpm and 700 rpm, depending on engine specification.

When an increase in engine speed from idle is demanded, only the unboosted fuel is admitted until engine speed and, therefore, exhaust pressure and heat energy reach a level to allow the boost control to admit more fuel. As speed further increases, so does the exhaust energy; consequently, further increases in fuel take place. Until a point is reached when the full load boost level is achieved, the torque to accelerate the engine is less than the full load value, and the rate of acceleration is reduced during this period. An apparent decay in response results, dependent on both the matching characteristics of the turbocharger and the boost control, and on the load placed on the engine, commonly referred to as turbo lag.

Every effort is made during engine development to minimize this effect by optimizing the smoke map along with injection timing/rail pressure and NRS flow rates. This lag is thereby reduced to the minimum, but under unfavorable circumstances can give rise to complaint.

2.7.6 Engine Speed Points

Various engine operating speed points can be configured to customer requirements within the engine software. These include low idle and high idle, and for certain selected ratings, the engine rated speed can be configured, which defines the speed at which the high idle governor cuts in. These points affect engine operation when installed into a machine and should be configured to meet the specific needs of the application. They are normally set to a default and can be changed within given allowable parameters. Please refer to the Electrical and Electronic Application and Installation Manual LEBH0005 Section 9 for further information on these settings.

2.8 Operating Environment

Climatic conditions, i.e., atmospheric pressure, temperature, and humidity, will all influence engine performance. An engine should, therefore, be selected with sufficient power to meet load demands under all operating conditions. The individual effects of these variables are detailed below.

2.8.1 Air Temperature

High inlet air temperature to the engine can cause loss of power and overheating problems with the cooling system, the lubricating oil, and hydraulic oil systems. This may be due to high ambient temperatures or because the engine is working inside a building or within the structure of a machine with insufficient ventilation.

Low air temperatures will reduce the ability of the engine to start, but by changing the specifications, e.g., fitting with a heavy-duty starter motor and batteries, and using a starting aid, satisfactory starting can be achieved at much lower temperatures.

Reference should be made to the following documents for further information:

- E.S.M. — this specifies the cold-starting equipment necessary for each engine type to meet specific minimum starting temperatures.
- Chapter 11 — Starting and Charging Systems
- Chapter 14 — Cold Weather Operation — describes the various starting equipment available and also the minimum temperature likely to be encountered in different areas of the world.

2.8.2 Temperature, Altitude, and Derate Strategy

All Cat C4.4 ACERT-C7.1 ACERT engines are capable of operation at sea level and ambient temperatures between -25°C and +48°C without requiring engine specification change. Operation between -40°C and +55°C is possible with specification changes.

The standard start aid specification should support starting down to -25°C.

- The ambient is the true ambient. An allowance of 10°C is made for temperature increase at the air cleaner.
- Without derate means without requiring a fuel system adjustment to protect the engine.
- It is accepted that some natural derate may occur, and the aim is to keep this within 3% of published powers.

2.8.3 Maximum Altitude

The objective for the product is to achieve a 3000 m altitude clearance as standard without derate. The minimum acceptable limit dictated by the EPA legislation is 1676 m.

There may be specific customer requests that exceed this target, which will be dealt with separately.

2.8.4 Derate Strategy

Only a natural engine derate will be acceptable below the altitude limits as detailed in Section 2.8.3. An enforced derate strategy will be employed above these limits.

The engine will not fail to operate or derate due to misfueling without appropriate warning.

2.8.5 Installation Angle and Gradients of Operation

The angle of installation can be up to 10° on either side and up to 7° down at the rear. If it is necessary to install the engine at angles greater than these or if it must be installed down at the front, advice should be sought from the Caterpillar application engineering department.

Operating an engine inclined excessively, either sideways or fore and aft, can lead to various engine troubles.

Due to the wide variety of machine types using diesel engines, it is not feasible to specify the angles of operation. For each type, this must be agreed upon with the OEM at the start of the project. This value must be considered during specification of the engine, particularly with regard to the aftertreatment units, lubricating oil/breather systems as a general guide only. It is very unlikely that the maximum grade for a wheeled off-highway vehicle will be outside the range of 25°-35° (except industrial trucks, fork lift trucks, etc).

2.8.6 Dusty Conditions

Machines expected to work in a dust-laden atmosphere, either due to the natural surroundings (dirt road, sandy conditions, etc.) or due to the operation (stone crushers, earth movers, etc.) must use heavy-duty air filters to prevent the entry of dust into the intake system of the engine. Please refer to Chapter 4 — Induction Systems, for further information.

It may be required for the OEM to supply a dust-proof alternator and starter motor along with protective sleeves for electrical connectors. Attention must be given to the suitability of other driven equipment for operating in dust-laden atmospheres.

2.8.7 Explosive Atmospheres

Diesel engines working in an explosive atmosphere or an area of fire hazard must be equipped to conform to local regulations. The degree of treatment to the engine will depend on the type of atmosphere in which it will be working.

Examples of other requirements are: air inlet flame trap, anti-static fan belt, and non-electric starting equipment, depending on conditions.

It is recommended that any special provisions required should be made to the engine system.

3.0 Mounting Systems

3.1 Introduction

The mounting system is critical for meeting Tier 4 Final, Stage IIIB emission standards. The integrity and durability of emission critical components must be maintained under all machine-operating conditions for the life of the engine.

The key additional challenge is the requirement to ensure the relative displacement between engine and aftertreatment does not exceed application guidelines for the flexible installation connection kit. To do this it is important to understand and define the alignment and dynamic movement between the aftertreatment and the engine.

In all cases it is recommended that you contact your mount suppliers in the early stages of the installation design process.

3.2 Mounting System Mandatory Requirements

All emission-related installation instructions are highlighted by the **EM** symbol.

Failing to follow these instructions when installing a certified engine in a piece of nonroad equipment violates federal law (40 CFR 1068.105(b)), subject to fines or other penalties as described in the Clean Air Act.

- **EM** The engine mounting system must not be designed in isolation and must take into consideration the mounting of the aftertreatment.
- **EM** The engine mounts must accurately control relative movement, between engine and aftertreatment, and ensure the gross deflection does not exceed the limits of the flexible installation connection kit for the life of the engine. For further information please refer to Chapter 5 — Aftertreatment and Exhaust Systems.
- The static engine installation angle, from horizontal, must not exceed
 - +/-10° side to side and/or
 - - 7° down at rear.
- Nose down installation not acceptable.
- Any installed angle must be taken into consideration when considering gradeability. Please refer to Chapter 9 — Lubrication Systems, for further information.
- Captive engine mounts must be used for all mobile equipment.
- **EM** The engine must be mounted so that equipment frame deflections do not stress the engine castings and engine-to-aftertreatment connection beyond allowable limits, and must protect the engine and engine-to-aftertreatment connection from excessive machine vibrations and shock loads.
- The engine mounts must limit the engine movement from shock, inertia, or other forces so that the engine cannot make contact with chassis components.
- The mounting system must adequately dampen first and second order vibrations and not induce resonance throughout the normal operating speed range.
- A 4-cylinder engine must not be solidly mounted unless fitted with a balancer.
- Engine mounts must not be subjected to excessive heat that will cause deterioration of the material and may have a consequential effect on the control of engine movement. The material temperature limit is to be defined by the mount supplier.
- The mounts must not be subjected to fluid contamination resulting from oil/coolant servicing that will cause deterioration of the material and may have a consequential effect on the control of engine movement. The material tolerance to fluids is to be defined by the mount supplier.
- **EM** There should be sufficient flexibility in the design to accommodate the accumulation of installation tolerances while not violating any of the above requirements.

C6.6 ACERT and C7.1 ACERT Engines

The dynamic bending moment at the rear face of the block, when fitted with a standard SAE housing that is not bolted to the sump, must not exceed the values in the table below. (Note that it is the housing and housing-to-block sealing/fixing integrity that is the limiting factor.)

Flywheel Housing	Dynamic Vertical Bending Moment N•m	Dynamic Lateral Bending Moment N•m
SAE 1 (C0060/61)	+/- 8200	+/- 5750
SAE 2 (C0044)	+/- 5600	+/- 2800
SAE 3 (C0001)	+/- 3000	+/- 1700

The table above identifies the maximum bending moments in the vertical and lateral directions (for one million load applications). To determine the allowable static bending moment, bulk accelerations of the whole vehicle engine/transmission system must be known for a typical application.

The maximum static bending moment must be calculated from this based on the maximum g loads for your application type.

For example:

Maximum static bending moment at the RFOB for an SAE 1 housing:

- Vertical capacity, average loading 106 cycles. Installation target +/- 3 g
– $8200 \text{ N}\cdot\text{m} / 3 \text{ g} = \pm 2733 \text{ N}\cdot\text{m}$ static vertical bending moment.
- Lateral capacity, average loading 106 cycles. Installation target +/- 2 g
– $5750 \text{ N}\cdot\text{m} / 2 \text{ g} = \pm 2875 \text{ N}\cdot\text{m}$ static lateral bending moment.
- The bending moment at all mounting pads must be limited to:
 - Front mounting pads TBD
 - Flywheel housing mounting pads TBD (associated with 10 g vertical shock loads)

C6.6 ACERT and C7.1 ACERT Engines Fitted with a Structural Sump

For applications where a structural sump is fitted and the transmission/drum flywheel housing/backplate is bolted to the block and sump, the load carrying capacity is significantly increased. Failure of the bolted parts or interface clamped face integrity are the limiting factors.

For applications that use a stressed sump, i.e., tired agricultural tractors without a chassis, where the engine and sump connect the front and transmission/rear wheels, the following are typical bending limits:

- The limit at the rear face of the block/transmission interface in the vertical plane for one million cycles:
+/- 84,000 N•m.
- The limit at the front of the engine at the bolster/block/sump interface in the vertical plane for one million cycles:
+/- 35,000 N•m.

There are currently no lateral limits determined for this application arrangement.

C4.4 ACERT Industrial Engines

The dynamic bending moment at the rear face of the block, when fitted with a standard SAE housing that is not bolted to the sump, must not exceed the values in the table below. (Note that it is the housing and housing-to-block sealing/fixing integrity that is the limiting factor.)

Flywheel Housing	Dynamic Vertical Bending Moment N•m	Dynamic Lateral Bending Moment N•m
SAE3	+/- 3000 N•m	+/-1700 N•m

The table above identifies the maximum bending moments in the vertical and lateral directions (for one million load applications). To determine the allowable static bending moment in the vehicle, typical bulk accelerations of the whole vehicle transmission system must be known for a typical application.

The maximum static bending moment must be calculated from this based on the maximum g loads for your application type.

For example:

Maximum static bending moment at the RFOB for an SAE 3 housing:

- Vertical capacity, average loading 106 cycles. Installation target +/- 3 g
– $3000 \text{ N}\cdot\text{m}/3\text{g} = \pm 1000 \text{ N}\cdot\text{m}$ static vertical bending moment
- Lateral capacity, average loading 106 cycles. Installation target +/- 2 g
– $1700 \text{ N}\cdot\text{m}/2\text{g} = \pm 850 \text{ N}\cdot\text{m}$ static lateral bending moment
- The bending moment at all mounting pads must be limited to:
 - Front mounting pads TBD
 - Flywheel housing mounting pads TBD (associated with 10 g vertical shock loads)

C4.4 ACERT Ag Engine Block Fitted with a Structural Sump

For applications where a structural sump is fitted and the transmission/drum flywheel housing/backplate is bolted to the ag block and sump, the load carrying capacity is significantly increased. Failure of the bolted parts or interface clamped face integrity are the limiting factors. For applications that use a stressed sump, i.e., tyred agricultural tractors without a chassis where the engine and sump connect the front and transmission/rear wheels, the following are typical bending limits:

- The limit at the rear face of the block/transmission interface in the vertical plane for one million cycles:
+/- 40000 N•m.
- The limits at the front of the engine at the bolster/block/sump interface in the vertical plane for 1 million cycles:
+/-24000 N•m

There are currently no lateral limits determined for this application arrangement.

3.3 Mounting Systems Fundamentals

3.3.1 The Nature of Engine Vibration

Reciprocating machines, including the majority of internal combustion engines, are inherent sources of vibration due to the nature of their piston and connecting rod motions. While this inherent vibration can be minimized by careful design and manufacture, some will remain due to imbalance. The nature and magnitude will depend upon engine configuration.

The motion of each piston and connecting rod creates out-of-balance external forces and couples. In a multi-cylinder engine, some of the effects produced by the components of one cylinder may cancel out those from another cylinder, but some of the effects may be additive.

Table 3.1 summarizes the balance characteristics inherent in 4-stroke reciprocating engines.

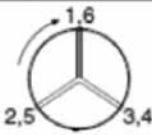
	Cylinder Arrangement	
	4-Cylinder in-line	6-Cylinder in-line
Crank diagram (arrow indicates direction of rotation)		
Firing order	1-3-4-2	1-5-3-6-2-4
Firing impulses per engine rev.	2	3
Engine balance		
External forces:		
Primary	Balanced	Balanced
Secondary	Unbalanced (unless harmonic balancer incorporated)	Balanced
External couples:		
Primary	Balanced	Balanced
Secondary	Balanced *	Balanced

Table 3.1

For a conventional 4-cylinder in-line engine, most of the significant external out-of-balance effects cancel out and only a vertical secondary force remains, i.e., a force having a frequency twice that of engine speed.

When the engine (without harmonic balancer) supports a significant over hung load that moves the center of gravity from the mid-point of the engine, this external couple is not balanced, and the resultant motion is a second order pitch.

3.3.2 Basic Modes of Vibratory Motion

Any unbalanced forces and couples would, if unrestrained, produce translational (i.e., linear) and rotational vibratory movements along and around the principal axes of inertia of the power unit assembly.

The six basic modes of vibration, or degrees of freedom, are illustrated in Figure 3.1 at right:

The six basic modes are:

1. Transverse motion
2. Fore and aft
3. Vertical (up and down – bounce)
4. Roll
5. Yaw
6. Pitch

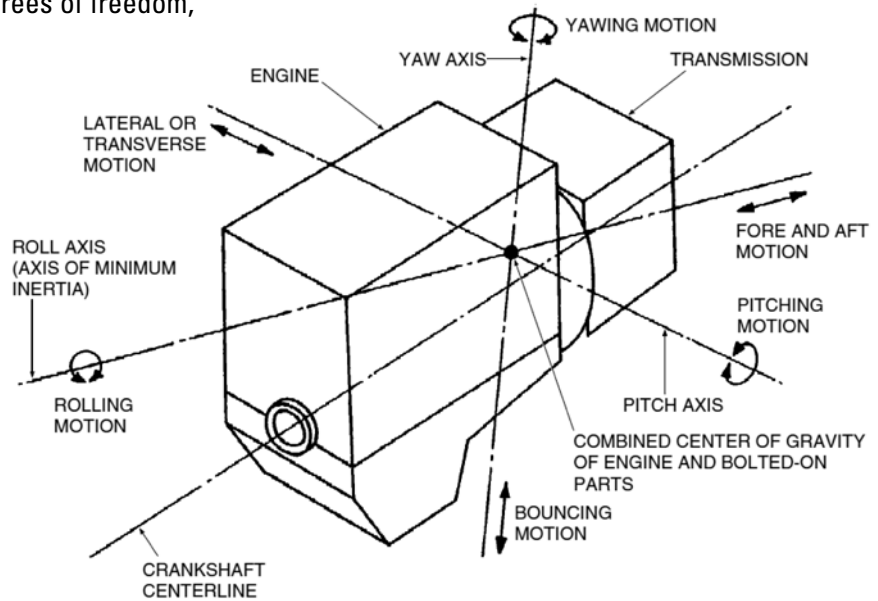


Figure 3.1

An explanation of some of the more commonly used terms is detailed below.

Roll Axis or Axis of Minimum Inertia

The roll axis is the axis about which the vehicle rolls when cornering. This can be determined simply as shown in the diagram below by a line joining the centers of gravity.

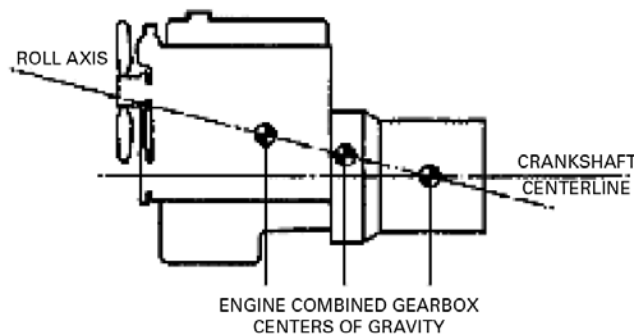


Figure 3.2

In the case of vehicle applications, the roll axis of the engine and gearbox assembly will typically be inclined at an angle of 15° to the crankshaft centerline. Where the bolted-on equipment is much more substantial, e.g. as with compressors or generator sets, the angle of inclination is likely to be correspondingly smaller.

The elastic axes are those axes along which displacement or rotation occurs colinear with the direction of the applied static force or moment. Elastic axis can be calculated from knowledge of mount stiffness, mount orientation, and mount geometry relative to the powertrain center of gravity.

The principal inertial axes are the three mutually perpendicular axes about which the moment of inertia is a maximum or minimum. This can be calculated mathematically if solid based models exist or from test data acquired using modal 6 or trifilar 7 techniques.

The torque roll axis is the axis around which rotation occurs when a torque is applied by the engine. It determines the displacement of an engine due to fluctuating torque and is a function of the powertrain inertial axes relative to the crankshaft line of action. This can be calculated from knowledge of engine mass, inertia, center of gravity, and crankshaft axis, but cannot be influenced by the mounting system.

The angular misalignment between the torque roll axis and the nearest inertial axis will determine how “pure” the engine roll mode will be.

3.3.3 Types of Mounting Systems

It is a major function of the engine mounting system to resist and control motion with minimum transmission of disturbance to the supporting structure.

Vibration can cause failure of components as well as significant operator discomfort. It is, therefore, important that the engine be mounted in such a way as to reduce the transmission of engine vibration to the supporting structure to an acceptable level. In conflict with this requirement is the need to control the motion of the engine to avoid excessive displacements and impacts with other parts of the machine during all possible operating conditions.

It is particularly important to ensure that an adequate mounting system is provided for 4-cylinder engines not fitted with secondary harmonic balancers, especially if the mass of the machines in which they are installed is not substantial.

Designing a mounting system to adequately meet all these requirements is a complex subject requiring expertise and experience.

The two basic types of mounting systems are:

1. Flexible (elastic)
2. Solid

Flexible (Elastic)

Flexible mountings enable the supporting structure to be isolated from engine vibration, the forces generated by the engine being counteracted by allowing the engine itself to move bodily. They do not reduce engine vibration and care must be taken in mounting system design to avoid any resonance which would increase engine movement.

The intention behind an elastic engine mounting system is to provide isolation of an application from engine excitation forces and to protect the engine from application operating forces. An elastic mounting system must also control the envelope in which the engine can displace to avoid overloading of interconnecting services and prevent contact or interference with surrounding equipment.

An elastic mounting system provides an ideal opportunity to reduce forces being passed into an application and hence minimize any consequent noise, vibration, and harshness that might result from engine imbalance forces.

To design effective elastic mounting systems requires a considerable understanding of engine and powertrain properties. Data is required to define engine excitation, powertrain mass, inertia, center of gravity, inertial axes, and torque roll axis, and the geometric location and orientation of all mounts. In addition, and dependent on whether forces are reacted internally or externally, knowledge of the elastic axes may also be required.

Solid

Solid mountings are used where the movement of a flexibly mounted engine is not acceptable, or where the engine itself is an integral part of the machine structure (e.g., as in many agricultural tractors).

This type of mounting is generally not recommended and has clear disadvantages. It provides little vibrational isolation and can subject the engine to severe shock and/or transmit unnecessary vibrations to the operator/cab. There is also a need to ensure tight tolerances on the mounting locations.

In some cases, a combination of solid and flexible mountings may be used. The four main arrangements for mounting of a total installation are:

1. Engine and machine rigidly connected; complete assembly flexibly mounted.
2. Complete machine solidly mounted on a subframe, which is then flexibly mounted onto a solid base.
3. Engine flexibly mounted, independently of machine; engine and machine coupled by means of a drive shaft.
4. Engine and machine independently solidly mounted on a common solid base.

The choice of mounting system will be based upon the relationship required between engine and machine. Where practical, however, the engine and driven machine should be assembled as one rigid unit, either by flange mounting or by means of subframes, so that all power transmission reactions are balanced within the unit.

The vibration characteristics of the total installation will depend on the combined weight of the engine and installation, and on the rigidity of the mounting system.

3.3.4 Basic Theory of Flexible Mounting Systems

Free Vibration

A simple flexible mounting system can in theory be represented by a mass and a spring. If the mass is displaced linearly from its equilibrium position and then released, the system will vibrate freely at its natural frequency.

Simple Mass-Spring System

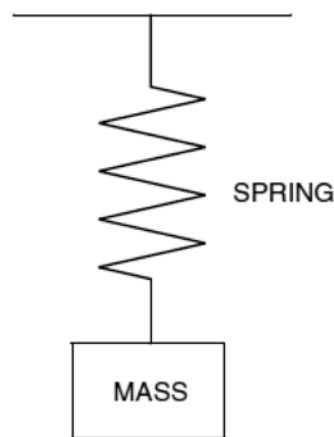


Figure 3.3

This natural frequency is a function of the magnitude of the mass and the stiffness of the spring (being defined as the force required to produce a given spring deflection).

If the vibration of a practical mass-spring system is undisturbed, its amplitude will gradually diminish, until eventually the system is stationary again. The rate at which the vibration decays is a function of the damping properties of the system.

Decay of Damped Vibration

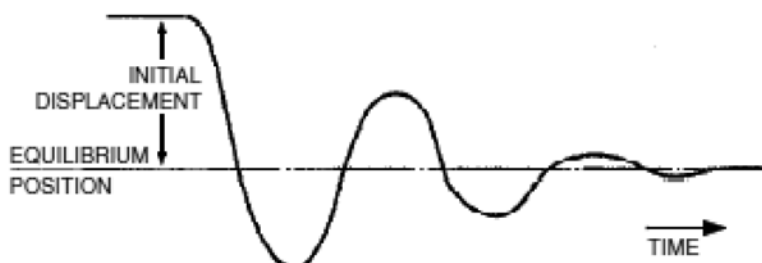


Figure 3.4

Forced Vibration

When a vibration input is applied to a mass-spring system, the system itself will also be caused to vibrate. The nature of this resultant vibration will be a function of:

- The point of application of the input force
- The frequency and magnitude or amplitude of the input force
- The natural frequency of the mass-spring system
- The damping properties of the system

There are two basic forced vibration systems (see Figure 3.5).

- A mass flexibly supported on a base (which is assumed to be rigid and immovable), the mass being subjected to a periodic force of known magnitude and frequency. This represents the situation where an engine is flexibly mounted on a rigid frame or base, and the disturbing force originates from the engine itself. In this case, vibratory force is transmitted through the mounts to the base.
- A mass flexibly supported on a base which is itself subjected to a vibration input of known magnitude and frequency. This is the situation on a mobile application subject, for example, to road surface excitation — in this case, the vibration transmitted through the mounts results in oscillation of the engine.

Forced Vibration of Damped Mass-Spring Systems

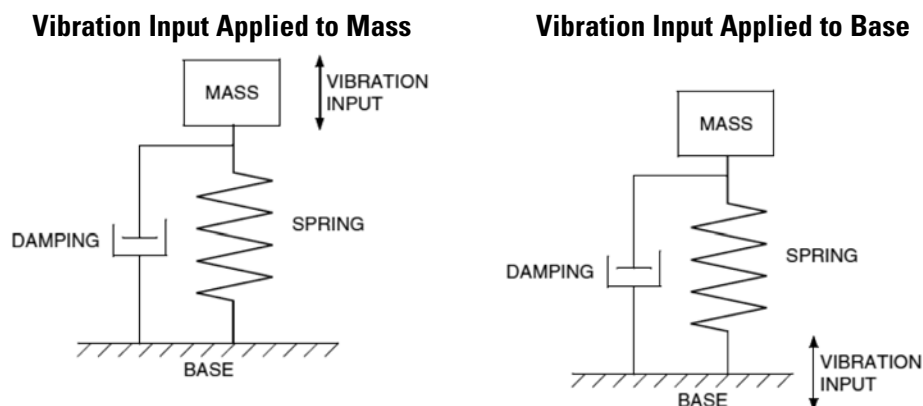


Figure 3.5

Typical vibration output: input response characteristics of forced vibration systems are illustrated in terms of transmissibility. Transmissibility can be defined as (a) the ratio of the transmitted force to the imposed force, and (b) the ratio of the transmitted amplitude to the imposed amplitude. These two ratios are the same.

Therefore, transmissibility represents a measure of the effectiveness of a flexible mounting system as a means of vibration isolation.

Vibration Response Characteristics of Forced Vibration Systems with Varying Degrees of Damping

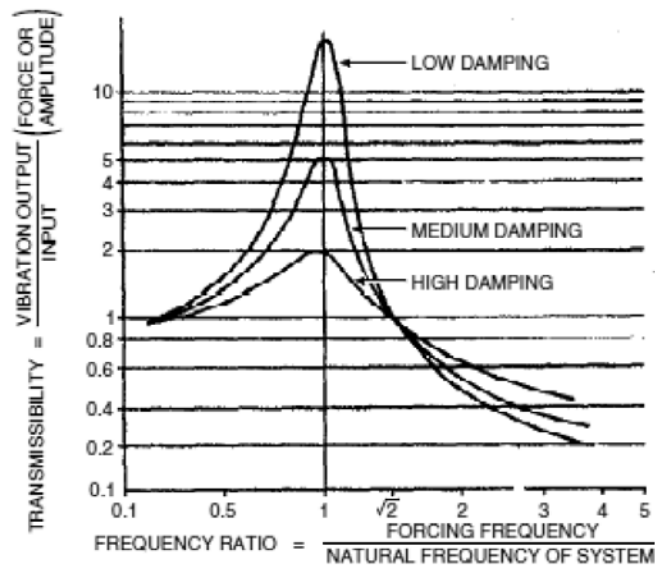


Figure 3.6

From the vibration response diagram it can be seen that:

- When the forcing frequency coincides with the natural frequency of the mass/spring system, resonance of the system occurs, giving very large vibration amplitudes. The actual magnitudes of these resonant vibrations will depend on the damping properties of the mounting system. A resonant condition should obviously be avoided due to the large amplitudes and forces generated, and the consequent risk of physical damage to the mounts, supports, and other parts of the machine which may develop sympathetic vibration.
- The value of the transmissibility, or ratio of response to input vibration, is equal to unity at very low frequencies, and also at twice the natural frequency for the mass/spring system. At higher frequencies, the magnitude of the vibration response becomes less than that of the input. Thus, at a frequency twice that of the natural frequency, the magnitude of the vibration response could be as low as 0.3 times that of the input. Expressed another way, the isolation under these conditions would be approximately 70%. For this reason, it is recommended that a flexible mounting system be chosen with a natural frequency not greater than half the lowest disturbing frequency likely to be encountered.
- High damping is primarily required when it is necessary to operate at a frequency close to resonance, or if transition through the resonance conditions takes place very slowly, with the consequent risk of larger than normal vibration amplitudes. However, if the frequency ratio is favorable (i.e., not less than 2) and resonance conditions are passed through relatively quickly, low damping is to be preferred, since damping represents energy loss. Excessive damping causes a build up of heat in the rubber, resulting in a reduction in its capacity to absorb energy as well as a need for cooling in order to prevent degradation of the rubber. Also, high damping tends to make the rubber less responsive at higher frequency ratios, resulting in impairment of the isolation capacity of the mounts.

3.3.5 Types of Flexible Mounts

Flexible mounts are almost invariably of the rubber-to-metal type, which are marketed in a variety of configurations. A typical selection is illustrated in Figure 3.7.

Types (a) and (b) are simple mounts of metal/rubber/metal sandwich construction, while (c) has a metal insert to give increased stiffness. These types may be used either in pure compression or, more commonly, inclined to the vertical in pairs in order to give the required directional stiffness characteristics by means of a combination of their compression and shear properties.

A more complex type of mounting embodying the same combination of properties in a single unit is illustrated in (d).

Type (e) is used for light-to-medium direct compressive loads where some lateral flexibility is also required. Type (f) is a conical mount designed for maximum load capacity combined with a large deflection in an axial direction. The high loading for a given size is obtained by utilizing the rubber in both compression and shear. Type (g) possesses much higher stiffness as the rubber is in compression only. Types (f) and (g) are both available with provision for overload and rebound control.

Flexible mounts working on hydrostatic principles are also marketed by some suppliers.

Typical Rubber-to-Metal Mounts

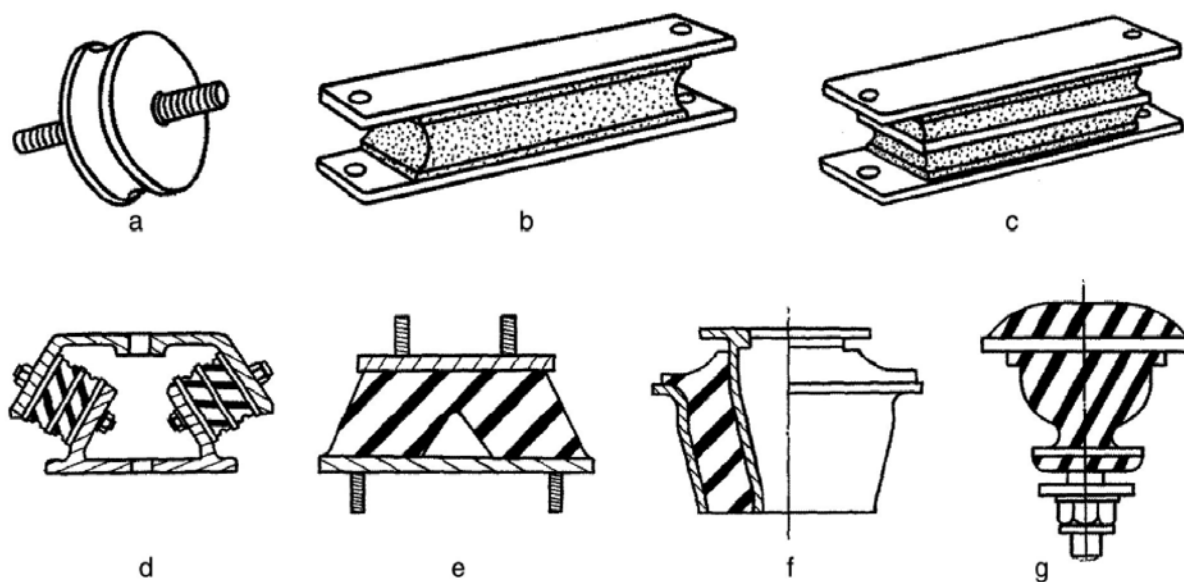


Figure 3.7

3.4 Mounting System Design Considerations

Although the required mounting properties for a particular installation can be determined by purely theoretical methods, the practical selection of suitable flexible mountings to give these properties is an extremely specialized subject. This is particularly true if an optimized system is required that not only minimizes transmission of engine noise and vibration to the vehicle or machine structure, but also controls bodily vibration of the complete power unit and bolted-on driven equipment. Consideration must also be given to minimization of excitation to bolted-on auxiliary equipment (e.g., filters, coolers, etc).

The problem to the installer lies in identifying, from mount manufacturers' published data, the required physical properties of the mounts, namely stiffness (in various directions) and damping characteristics and tolerances.

For this reason, it is strongly recommended that intended mount suppliers be consulted in the early stages of an installation design, since they are best qualified and equipped to give specialized advice on the properties and application of their own products.

The information provided in this section is given as an aid to help guide this process.

3.4.1 General Considerations

- At all engine speeds the mountings should isolate engine vibrations to the machine in order to maximize operator comfort, reduce noise, and ensure durability of any ancillary components.
- For a successful installation, the mountings must be able to withstand, without excessive deflection, the static loadings due to the weight of the system being supported.
- The mountings (and brackets) must be strong enough to withstand all dynamic loadings that may be induced by the type of application.
- The mountings should protect the engine from any stresses caused by distortion of the frame on which they are located.
- If the line of action of engine imbalance force doesn't pass through the powertrain center of gravity, additional moments will be created.
- On mobile and portable equipment, allowance should also be made for cornering, which can give high lateral horizontal loads, and for braking which can give up to 1g in the forward direction.
- Large static bending moments in the vertical plane at the cylinder block/flywheel housing interface should be avoided at all times, since these can lead to broken flywheel housings and damaged cylinder blocks. The magnitude of the bending moment is dependent upon the positions of the mountings and can be calculated by taking moments about the cylinder block/fly-wheel housing interface.
- For an indication of static bending moment values that should not be exceeded for safe operation, refer to Section 3.2 — Mandatory Requirements.

Driveline/Transmission System Resonance

In some applications, it will be necessary to check for driveline system resonance with nodes at the block/transmission system interface.

The bending limits at the interface tabulated above still apply, but the resonance condition and bulk accelerations of the transmission system are not assumed to act simultaneously. If a resonance exists that can be excited in the engine's normal operating speed range, and the mode shape indicates a node at the transmission interface, the resonant bending moment/critical stresses have to be determined by measurement before the installation can be approved.

3.4.2 Flexible Mounting System Considerations

Flexible mounting systems should be designed so that the natural frequency of the mount is not greater than half the lowest disturbing frequency likely to be encountered. This is normally the firing frequency under low idle speed conditions. The characteristic frequencies for various engine arrangements are shown in Table 3.2.

- The internal mode of an engine mount must not be within the frequency (Hz) running range of the engine. If this is not possible, this frequency must not coincide with common operating speeds/conditions of the application.

Minimum disturbing frequency (firing cycles) (assuming low idle speed = 600 rev/min)			
Number of cylinders	Cycles per engine rev	Cycles per minute	Cycles per second
3	1.5	900	15
4	2	1200	20
6	3	1800	30
8	4	2400	40

Table 3.2

- The mount support stiffness should be at least 10 times stiffer than the mount itself.
- The location of the elastic axes is determined by mount inclination and mount location. Positioning of these axes close to the center of gravity will minimize powertrain displacement due to engine mean torque.
- The combined elastomeric mounting system stiffness, powertrain mass, inertia, and center of gravity determine the frequency of the rigid body powertrain modes.
 - The powertrain rigid body modes will be excited if within the excitation frequency range of the application (e.g., a 4-cylinder engine operating in the speed range 720 rpm-2400 rpm will create second order excitation in the frequency range 24 Hz to 80 Hz).
- It should be noted that calculated stiffness assumes:
 - Stiff mounting brackets, cross members, etc. The weight of the chassis or frame should also be substantially greater than that of the engine. If these requirements are not met, the vibration characteristics of the installation may be completely changed.
 - No restraint from exhaust pipes, hoses, linkages, etc., although in practice, this cannot be entirely eliminated. Care should, however, be taken to minimize their effects as paths for transmission of noise and vibration.

Mounts are commonly selected based on understanding the initial displaced position of the powertrain due to its weight, which is important to ensure correct position and alignment. This relies on knowing the static stiffness normally published in a supplier's catalogue.

The dynamic stiffness is important to ensure the rigid body modes of powertrain are controlled within the target frequency range (see Table 3.2). For correct design it is necessary to establish from suppliers the approximate relationship between the dynamic and static stiffness of the mounts being considered. The ratio of dynamic-to-static stiffness may be in the range 1.05-1.25:1 for best quality natural rubber compounds up to 60 durometer hardness, but may be as high as 3:1 for natural rubber with high damping, and even 8 or 9:1 for some synthetic grades.

- Estimates of dynamic deflection should, where applicable, allow both for full torque wind-up and for maximum bump conditions. These can produce vertical accelerations of up to ± 6 g, depending upon application type, i.e., the dynamic forces due to vertical acceleration of an engine assembly can be up to six times the magnitude of the force due to its static mass. Care should be taken to ensure that the lateral and axial displaced conditions are also understood. Refer to the dynamic loading limits outlined within the mandatory requirements for more detail.

- Where high dynamic loads can be expected, it is advisable to fit overload rebound washers, or to incorporate a built-in “snubber” to limit excessive deflections.
- The whole of the rubber in a mount should be stressed as uniformly as possible to ensure the highest possible ratio between resilience and the weight of rubber employed. Stress concentrations should be avoided as these could lead to early local failure.
- The use of a large quantity of soft rubber is preferable to a smaller quantity of hard rubber as the harder grades contain non-elastic additives, which have an adverse effect on their mechanical properties. Excessively soft rubbers should also be avoided as these can lead to bonding problems during manufacture.
- Natural rubber compounds are generally recommended for their good overall mechanical properties over a fairly wide temperature range (-20 to + 70°C) although synthetic rubbers may be preferable in some instances for oil resistance or high temperature conditions.
- The use of interleaves to form compound sandwiches enables mounts to be made stiffer in compression without appreciably affecting shear stiffness. There is, however, an adverse effect on noise transmission properties.
- Having determined the required properties of a mounting system, it should be realized that, due to manufacturing difficulties with rubber components, production variations in their mechanical properties may range $\pm 15\%$.
- Provision must be made where necessary for protection of rubber mounts from oil contamination and excessive heat (e.g., by means of suitable shielding).

In order to gain the best isolation characteristics from a mounting system, it is important to understand the following ways an engine converts torque into drive.

For Flexible Mounting in Applications Such as Hystat, CVT, and Torque Converters

These applications do not need to consider the elastic axis from a mean torque point of view as this is internally reacted.

- If an elastic mounting arrangement is being used, it should be designed with consideration to controlling powertrain movement due to engine excitation forces and application operational forces.

For Flexible Mounting with Mechanical Gearbox

- These applications need to consider the elastic axis in order to ensure control of powertrain displacement under the application of mean torque. A roll restrictor may be required to prevent excessive deflection which could lead to contact with other components or premature failure of the engine to aftertreatment connection.

3.4.2.1 Flexible Mounting Configurations

Number of Mounting Points

Flexible mounting systems may be of the 3-, 4-, 5-, or 6-point type. The number of mounting points chosen depends on the dimensions and weight disposition of the engine and bolted-on driven parts, and the arrangement and duty of the application in which they are to be installed.

Schematic examples of typical mount arrangements are illustrated in Figure 3.8, along with the applications they are commonly found in.

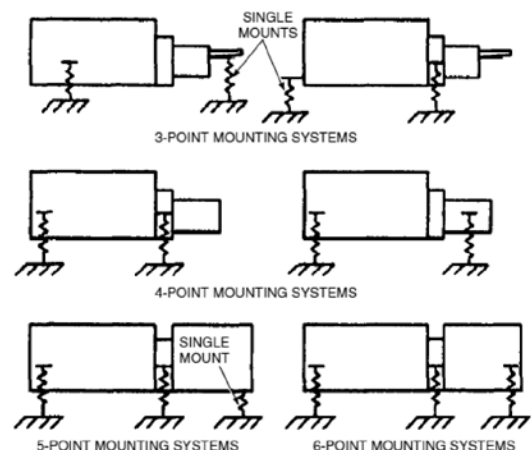


Figure 3.8

Multi-Point Mounting Arrangements

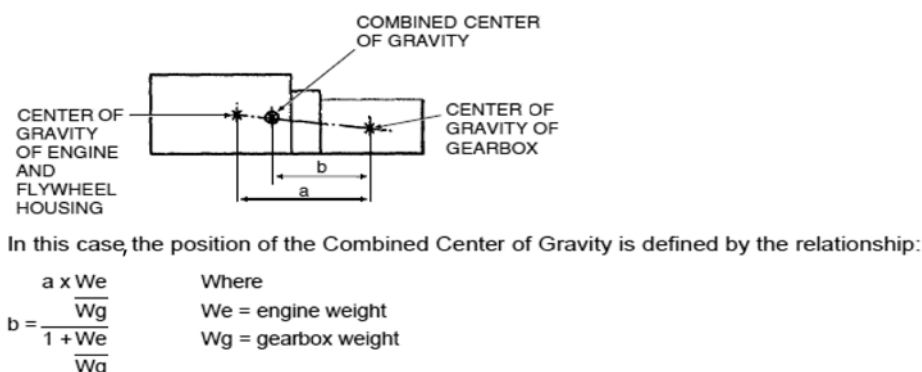
The 3- and 4-point systems are generally preferred because of difficulties in ensuring correct alignment of systems employing larger numbers of mounts and the resulting risk of excessive bending loads on the back end of the engine. It is recognized, however, that in some installations, 5- or 6-point systems may be necessary because of the length and mass of the bolted-on driven parts. Advice from your applications engineer should be sought in such cases.

Location of Mounts and Bending Moments

The locations of mounts are often predetermined, i.e., engines, transmissions, etc., may already be provided with mounting pads.

Where a choice is available, however, the mountings should ideally be symmetrically arranged about the combined center of gravity of the engine and bolted-in equipment. This reduces the excitation of other modes of vibration when the system is vibrating in one particular direction.

The combined center of gravity in the longitudinal plane can be calculated as shown in the example below.



Lateral Location of Mounting Points (End View)

In order to reduce the torsional stiffness of the mounting system, it is also desirable to locate the mountings laterally as close as possible to the center of the engine which minimizes the distance "c" as shown in Figure 3.9. This will give the best isolation for a given set of mounts.

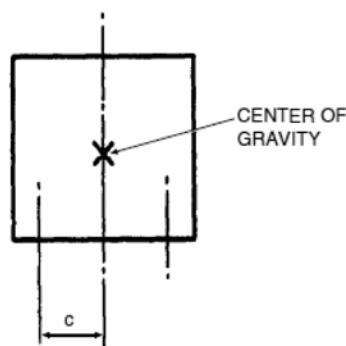


Figure 3.9

Orientation of Mounts

Flexible mounts are usually loaded either:

- In pure compression with their principal axes vertical
- In combined compression and shear with their mounts inclined vertically in pairs

Vertical mounts are widely used in both mobile and stationary installations where a considerable degree of stiffness is required. Inclined mounts were historically used mainly in automotive and similar installations where isolation is required against vertical, lateral, and torsional excitation. They are now more and more common in mobile off-highway applications.

Vertical Mounting Systems

For a simple symmetrical system, the stiffnesses of the combined system are as follows:

$$b = a \times W_e$$

Where:

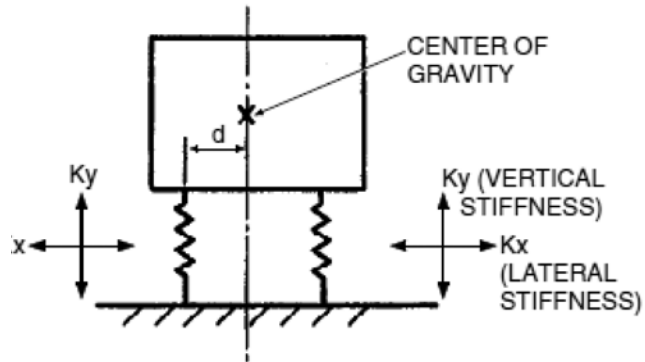
W_g W_e = engine weight

$1 + W_e$ W_g = gearbox weight

W_g Total vertical stiffness
(expressed in units of force deflection) = $2K_y$

Total lateral stiffness = $2K_x$

Torsional stiffness = $2K_y \times d^2$



The values of the vertical stiffness, K_y , and the lateral stiffness, K_x , are specified by the mount supplier. The case of the unsymmetrical vertical mounting system is slightly more complicated.

Inclined Mounting Systems

An effective mounting system may be achieved by means of pairs of inclined flexible mounts. The required vertical, lateral, and torsional stiffnesses of the system are obtained by choice of geometry (positions and angles of inclination of mounts) and compression and shear stiffnesses.

Inclined Mounting Arrangement (End View)

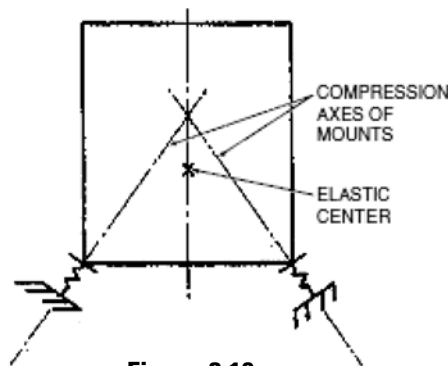


Figure 3.10

An important feature of any inclined mounting system is the "elastic center," which is always located at a point above the mount, but below the geometrical intersection of their compression axes. Its precise position can be determined mathematically from knowledge of the mounting configuration and the axial and shear stiffnesses of the individual mounts.

The properties of the elastic center are such that a linear force applied in any direction passing through the elastic center will cause translation (i.e., linear movement), but no rotation of the supported mass. Similarly, a couple applied about this center will cause no linear movement of the supported mass. The principal modes of vibration through and about the elastic center are therefore decoupled.

In order to take full advantage of these properties, the mounting system should be designed so its elastic center lies on the roll axis, or axis of minimum inertia, of the engine and bolted-on parts.

Although the axis will always pass through the combined center of gravity of the complete mounted system, its precise orientation is difficult to determine except by experiment. A very close approximation can, however, be obtained from a line joining the centers of gravity of the engine and the bolted-on driven assembly.

Although inclined flexible mounting arrangements may in some circumstances be completely unsymmetrical, in practice they usually fall into one of the following categories:

- Two equal mounts, symmetrically located and orientated (as in Figure 3.11).
- Two equal mounts, symmetrically located and orientated, and with their major stiffness principal axes perpendicular to each other (Figure 3.12).
- Two equal mounts, not necessarily symmetrically located or orientated, but having their major stiffness principal axes perpendicular to each other (Figure 3.13).
- Two equal mounts located on the same horizontal axis, unsymmetrical orientation, but having their major stiffness principal axes perpendicular to each other (Figure 3.14).

The arrangements in which the major stiffness axes are perpendicular to each other possess the special property of having the effective stiffness at their elastic center the same in any direction in the plane of the mounts. This may sometimes be advantageous.

Mathematical expressions relating the stiffness properties and the location of the elastic centers for each of these mounting arrangements are given.

Equal Mounts Symmetrically Located and Oriented

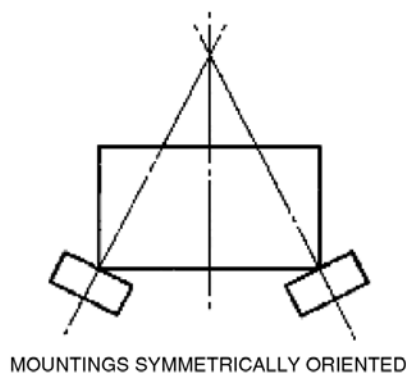


Figure 3.11

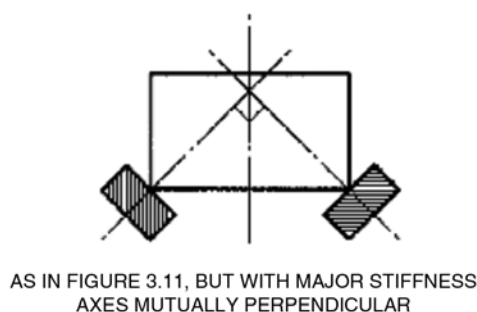


Figure 3.12

Equal Mounts Unsymmetrically Oriented with Major Stiffness Axes Mutually Perpendicular

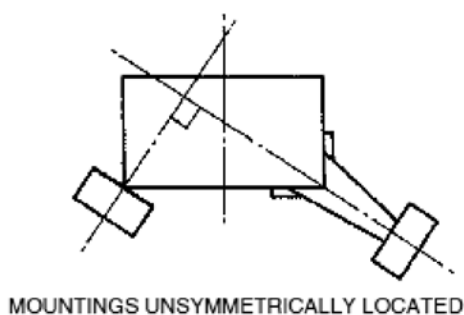


Figure 3.13

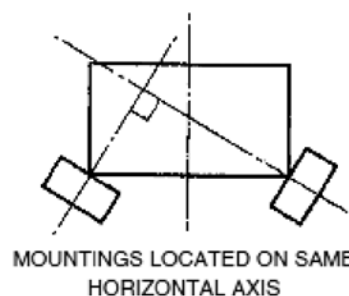


Figure 3.14

Method for Designing Optimized Flexible Mounting Systems

Depending upon packaging constraints, the basic steps in designing an optimum elastic mounting system can be summarized as follows:

- Collect all necessary mass, inertia, and geometric data for the engine, transmission, and potential mount locations.
- Identify potential mounting system arrangements, taking into consideration the need to distribute the supported weight of the installation (number and location of mounts).
- Check that the mounting arrangement being considered provides adequate support and retention, so that the maximum bending moment at the rear of the engine is within application guidelines.
- For each mounting arrangement, calculate the static load acting on each mount.
- In order to simplify installed positioning while minimizing mount variety, an evenly distributed static load should be targeted.
- The operating frequency range of the engines dominant excitation forces needs to be established.
- Ensure the mounts selected have an internal resonance outside of this operating range.
- The type of mounting arrangement, packaging space, static load requirements, operating frequency range, and maximum operating loads should then be provided to the supplier to ensure optimal mount selection.
- The size (volume of rubber) of the elastomeric mount is important for durability and the mount supplier can provide guidance.
- To maintain elastomeric isolation characteristics throughout the life of the engine, the mount material needs to be selected for the environment in which it operates. Protection from excessive temperature and contamination from fuel, oil, or other materials must also be taken into consideration.
- The direction and frequency content of engine forcing needs to be calculated or provided by the engine supplier in order to specify elastomeric mount requirements.
- The rigid body natural frequencies of the powertrain should ideally be designed to be well below the dominant excitation frequency of the engine (e.g., second order idle for a 4-cylinder engine) and also non-coincident with other natural frequencies of the application.
- Brackets used to locate elastomeric mounts and machine side support structure should be an order of magnitude stiffer (10 times) than the elastomeric mount, or good isolation characteristics will not be provided.
- For manual transmissions (externally reacted torque), the elastomeric mounts should be located high up along side the center of gravity or inclined to raise the elastic center as close to the center of gravity as possible. If this is not possible, roll displacement may need to be controlled with a roll restrictor (an additional mount located high up on the powertrain that provides a progressive resistance to torque roll).

3.4.3 Solid Mounting System Design Considerations

For any solid mounting arrangement, the following considerations should be taken into account:

- Mounting brackets/fixings and the mounting frame or base must be as rigid as possible. It is essential that no resonance of the system occurs within the operating speed range of the engine. It is normal practice to ensure that resonance frequencies are greater than 2.8 times firing frequency at the highest operating speed.
- Alignment of engine and driven machine must be carefully controlled (if necessary with provision for adjustment) in order to minimize loading on the coupling, flywheel, and flywheel housing.
- If the engine is mounted via the flywheel housing, the back-end bending moment must be calculated and checked against the permissible value; see Section 3.2 — Mounting Systems Mandatory Requirements.
- For mobile applications, dynamic shock loadings on the mountings must be considered.
- Where a 4-cylinder engine is required to be solidly mounted, a balancer unit is sometimes specified in the engine build in order to minimize the secondary out-of-balance forces inherent with this engine configuration.
- Instruments, radiators, etc. used in the installation should always be flexibly mounted separately from the engine, as vibration transmitted through solid mountings can cause damaging sympathetic vibrations.
- Where an engine is to be solidly mounted in such a way as to be a load-carrying part of the total machine structure (e.g., frameless tractors), it must first be ensured that the engine structure is capable of withstanding the loads to which it may be subjected.

3.4.4 Application Specific Installation Considerations

The choice of mounting system will depend on the inherent vibration characteristics of the engine, the layout of the installation, and the conditions under which it will be required to operate.

The following notes are intended to give guidance in the flexible mounting of engines in particular application types. A summary of the main features is shown in Table 3.3 at the end of this section.

Light Machine Installations Requiring Minimum Transmitted Vibration

Since vibration in vehicles is particularly likely to give rise to criticism and dissatisfaction, the following points should be particularly noted:

- The engine should be controlled to oscillate about the roll axis by ensuring that the elastic centers of the mounts lay on the roll axis.
- The mounting layout should give flexibility in the bounce and roll modes.
- There is adequate flexibility to ensure that the natural frequency is below the running range.
- Connections of services and controls between engine and chassis are sufficiently flexible to give good isolation.
- Some form of overload control may be necessary in order to withstand the effects of external loads (e.g., control forces, clutch operation, etc.).

In practice, the most effective vehicle engine mounting systems are of the 3-point type (for small 4-cylinder engines in machines) and the 4-point type for larger vehicles. Heavy earth moving and construction equipment mounting arrangements are more likely to be of the 4-, 5- or 6-point type, depending on the bulk of the transmission and any other bolted-on equipment. In all cases, inclined front mounts are recommended, as illustrated in Figures 3.15 and 3.16.

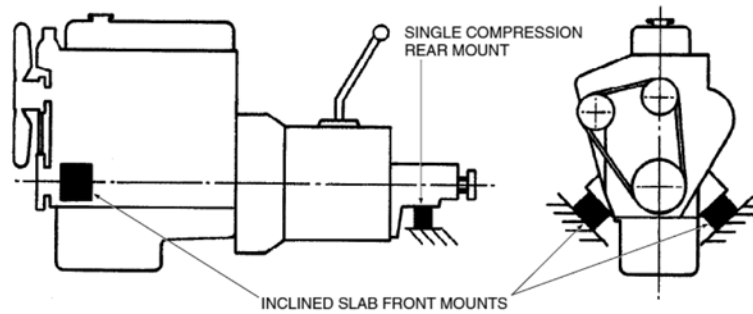


Figure 3.15

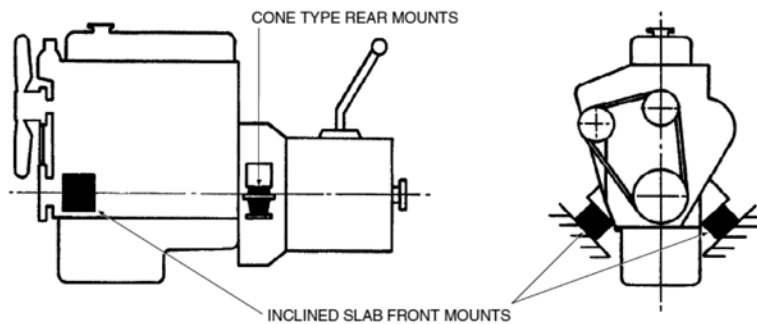


Figure 3.16

Fork Lift Trucks

It is common practice for the rear (i.e., flywheel) end of the engine to be bolted rigidly to the transmission and drive axle, the front of the engine being flexibly mounted by means of cone-type mounts. These provide some degree of isolation, while being sufficiently stiff to withstand the torque reaction from the drive axle. With this type of arrangement it is very important that the engine/transmission line be very rigid, and for this reason, sumps and flywheel housings are often “tied” together.

In cases where the engine and transmission are connected to the drive axle through a universal joint or cardan shaft, the engine should be 4-point mounted by means of cone-type mountings at front and rear.

Combine Harvesters

These may be 3-, 4-, 5- or 6-point mounted. Relatively stiff compression mounts are usually acceptable, the objective being to reduce harshness by attenuation of high frequency vibration, rather than to isolate from low frequency bodily movement of the engine.

Other Mobile or Portable Equipment

Four-point cone-type mounting systems are adequate for most requirements. In the case of portable equipment, which may be towed, provision should be made for longitudinal restraint to allow for breaking loads.

Stationary Equipment

Flexible mounting of the 4-point cone type is often advisable in order to isolate the machine from its surroundings. It may also be used to compensate for small irregularities in foundations, but great care must be taken to avoid undue stressing of mounts.

Application Type	Typical Mounting Arrangement	
	Number of Mounting Points	Mount Types
Light machines, tow tractors, etc.		
Small	3 or 4	{ Front - inclined slabs Rear - Single compression or twin cone-type
Medium and large	4	
Earth moving and construction machinery	4, 5 or 6	{ Cone-type Conical mounts at front of engine; Rear of engine solidly bolted to transmission axle, or supported on cone-type mounts
Forklift trucks	3 or 4	
Combine harvester	3, 4, 5 or 6	Compression mounts
General mobile and portable equipment	4	Cone-type
Stationary equipment	4	Cone-type

Table 3.3

Appendix 3A

Method of Calculating Back End Bending Moment

The static mounting reactions R_1 and R_2 can be determined from the information below.

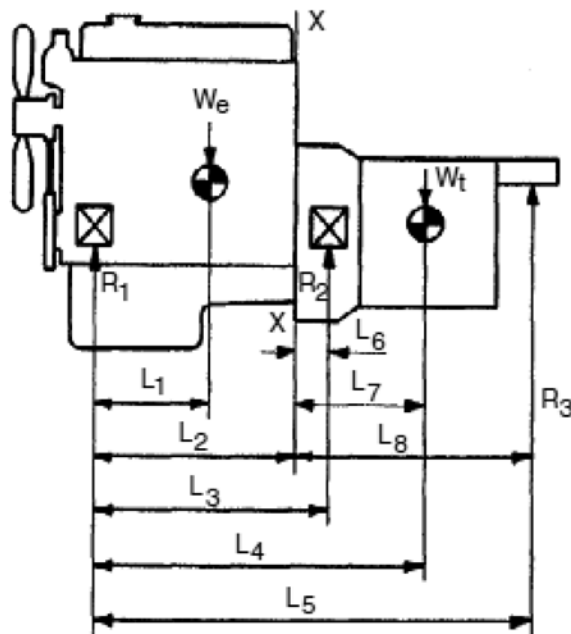
If a tail support is fitted, R_3 will have a predetermined value.

Note: $R_3 = 0$ if no tail support is fitted.

W_e = total weight of engine

W_t = total weight of transmission

(Both these values will be approximately their respective centers of gravity.)



Taking moments about R_1 to find R_2 ,

$$R_2 = \frac{W_e L_1 + W_t L_4 - R_3 L_5}{L_3}$$

Taking moments about R_2 to find R_1 ,

$$R_1 = \frac{W_e (L_3 - L_1) - W_t (L_4 - L_3) + R_3 (L_5 - L_3)}{L_3}$$

To find the bending moment (M_x) between the flywheel housing and cylinder block interface :

$$M_x = R_2 L_6 + R_3 L_8 - W_t L_7$$

As a check for M_x ,

$$M_x = R_1 L_2 - W_e (L_2 - L_1)$$

Note: The above values will be in the STATIC CONDITION.

4.0 Induction Systems

4.1 Introduction

The induction system is one of the most important aspects of an engine installation as it can have a direct effect on engine output, fuel consumption, exhaust emissions, and engine life.

It is, therefore, essential to ensure that the induction system and any associated components are correctly specified and installed to provide a robust and durable system that ensures emissions compliance throughout the life of the product.

With this in mind, the installed induction system must be designed to supply clean, dry, and cool air to the engine with a minimum of restriction. The system must be designed to withstand the shock loadings and working conditions that will be met in service, and must provide reliable sealing and durability with a minimum of maintenance.

Air-to-Air Charge Cooling requirements are covered separately in Chapter 6 Section 6.4.

4.2 Induction System Mandatory Requirements

All emission-related installation instructions are highlighted by the **EM** symbol.

Failing to follow these instructions when installing a certified engine in a piece of nonroad equipment violates federal law (40 CFR 1068.105(b)), subject to fines or other penalties as described in the Clean Air Act.

4.2.1 Air Cleaner

- The air cleaner must have adequate dust-holding capacity to achieve acceptable air cleaner life in representative field applications. See Table 4.2.
- An exhaust augmented system must be used when the dust-holding requirement exceeds 25 g/cfm.
- **EM** There must be a visible air cleaner restriction indicator. The set point must be the correct restriction for the rating and must take into account any restriction across the intake pipe work.
- The air filter element must be serviceable without major component removal.
- The air cleaner itself must not be subject to excessive heat that may result in its deterioration. The temperature limit is to be defined by the air cleaner supplier.

4.2.2 Air Inlet

- **EM** The maximum allowable induction depression, when the air filter is clean, is 5 kPa.
- **EM** The maximum allowable induction depression, when the air filter is dirty, is 8 kPa.
 - These must be tested in accordance with the Air Inlet Restriction Test. (Test procedures can be obtained through your application engineer.)
- **EM** An approved air inlet temperature sensor must be installed within the induction pipe. Please refer to the Electrical and Electronic Applications and Installation Manual LEBH0005 for the sensor and fitment details.
- **EM** The intake air temperature into the turbo compressor must not exceed 10°C rise above ambient.
 - This temperature must be established in accordance with the Air Inlet Temperature Offset Test procedure detailed in TPD1746E obtained from your application engineer.
 - This limit may only be exceeded by exception and with Caterpillar approval. Please contact your applications engineer. Ref. Section 4.4.6 for further information.
- The air inlet must be protected against the ingestion of water, foreign particles from dust or dirt, and recirculated hot air and exhaust gas.

4.2.3 Induction Pipe Work

- The induction system hose material must be of adequate specification to withstand service/working conditions. It is recommended that hoses are specified to meet the requirements listed below; however, temperatures will vary with application, and it is necessary to test each application to ensure the specification selected is sufficient.
 - Maximum working temperature: 200°C
 - Minimum working temperature: -40°C
 - Maximum working pressure: 10 kPa
 - Minimum working pressure: -8 kPa
 - Resistant to fuel oil and lubricating oil on the external surface
 - Cleanliness level as defined in Table 4.1
- The integrity of the pipe work must not be disturbed for routine maintenance procedures.
- All pipe work must have beaded ends when connecting flexible hose.
- The internal bore of any metallic intake pipe must be corrosion resistant.
- Hoses using separate internal reinforcement are not permitted. Reinforcement must be either external or fully integrated into the structure of the hose.
- The intake pipe work must be supported so it does not induce any stress on the turbo inlet.

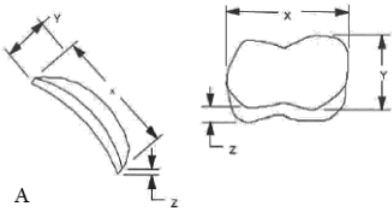
Cat Component Cleanliness Standard For induction system components							
This specification defines cleanliness levels applicable to finished engine components and assemblies.							
All cleanliness standards are based on flushing the specified area with solvent filtering the flushed solvent onto a membrane filter patch, measuring particle dimensions with a microscope and measuring total particle mass with an analytical balance.							
The specified cleanliness must be met at the time of assembly							
Particle to be measured for size are metallic, rust (either free or loosely attached), slag, sand, and other abrasives. If particles are fragile and break up with gentle probing (gentle probing will not tear a membrane filter patch), only the remaining solid pieces are to be measured for specification performance.							
Largest Particle Allowed, in microns (A)			Maximum No. Particles allowed per given particle length, In Microns (a)		Maximum mass allowed (B)		Abrasive (Oxides) >40µM (C)
X	Y	Z	#	X	mg/m2	mg	Allowed
1200	1200	200	4	500-1200	230	16	
			# = Number of particles				
Based on 1E2500A							

Table 4.1

4.2.4 Precleaners

- Precleaners or dust evacuator valves must be matched to airflow of the engine.
- Evacuator valves must be installed vertically.

4.2.5 Exhaust Assisted Evacuation

- **EM** The use of exhaust assisted prefilter evacuation systems is acceptable.
- **EM** The exhaust/scavenge pipe must be connected into the exhaust pipe work after the DPF/DOC to prevent fouling.
- **EM** A check valve must be incorporated into the scavenge line to prevent reverse flow during all conditions.
- **EM** Provision will need to be made to exclude the scavenge line from the system during use in Portable Emissions Measuring System (PEMS) testing.

4.3 Induction System Fundamentals

4.3.1 Air Cleaner Duty Classification

Air filters are generally classified according to duty, which is related to dust-holding capacity. The choice of duty depends upon the engine type, the dust concentration in which it will operate, and the service life required.

The main duty categories are shown in Table 4.2, together with an indication of their usage. It should be noted, however, that these usage recommendations are given as a guide only. It may be necessary, due to the particular conditions of operation, to specify a filter of a “heavier” duty classification than that indicated.

Light duty air cleaners are not considered suitable for industrial, construction, and agricultural applications.

Duty classification	Dust-Holding Capacity (Tested to SAE J726b or ISO 5011)	Suitable Environments	Example Applications
Medium Duty	10g/cfm (353 g/m ³ m)	No significant dust concentrations	General agricultural and construction equipment. Gensets in buildings. FLT in normal factory conditions, airport equipment.
Heavy Duty	25g/cfm (883 g/m ³ m)	Dirt/dusty environments	Rock crushers/screeners, mining equipment. Mobile equipment working in high dust concentrations.

Table 4.2

4.3.1.1 Medium Duty

- For use on and off highway in areas where there are no significant dust concentrations, e.g., generator sets in buildings, Fork Lift Trucks (FLT) in normal factory conditions, airport equipment, etc.
- Normally fitted remotely from the engine and generally with an internal or external precleaner.
- Typical preferred air filters in this category are of the dry element type with an integral centrifugal precleaner stage.
- For off-highway applications, the use of a safety element together with an untreated main element is strongly advised.
- A restriction indicator, correctly positioned, and of the correct setting should always be fitted with standard duty filters (see Section 4.5.6 — Restriction Indicators).

4.3.1.2 Heavy Duty

- For use in all dusty or dirty environments.
- Normally incorporates a highly efficient precleaner arrangement in some cases with automatic dust unloading.
- A safety element must be fitted; this should be treated.
- Normally, the main element is untreated.
- A restriction indicator, correctly positioned and of the correct setting, should always be fitted with heavy-duty filters (see Section 4.5.6 — Restriction Indicators).

Note: For operation in extremely arduous conditions, e.g., aluminum foundries, brickworks, etc., advice of the Caterpillar application engineering department, should be obtained.

4.3.2 Dust-Holding Capacity

Dust-holding capacity is the amount of dust that can be retained by the filter before the restriction reaches the point when servicing must be carried out.

The minimum dust-holding capacity is normally specified for a particular duty of filter as detailed in Table 4.2.

4.4 Induction System Design Considerations

4.4.1 Induction Restriction

The induction system restriction, measured at the turbocharger inlet, is the total restriction due to:

- Air filter restriction
- Resistance to air flow due to pipe friction
- Air velocity effects

If the restriction is excessive, the engine will not receive sufficient air for complete combustion to occur. This may result in a loss of power, increased DPF soot loading rate, poor fuel consumption, and other issues that may impact emissions.

The maximum induction depression must be measured during installation audit testing and is a requirement for installation sign-off. Please refer to the test procedure cited in Chapter 16 for further detail on how to perform this test.

4.4.2 General Recommendations

- The use of a single-stage filter with a safety element is recommended.
- It is recommended that the intake pipe work should be kept as short and straight as possible to reduce induction restriction.
- The diameter of the pipe work should not be less than the diameter of the turbo inlet connection.
- The use of constant torque clamps are recommended.
- The air cleaner and pipe work should be shielded from heat sources that may excessively increase the induction air temperature.
- It is recommended that the air cleaner inlet is located so that the air temperature is kept as close to ambient as possible.
- It is recommended that the air cleaner is isolated from excessive engine or machine vibration.

4.4.3 Air Cleaner Selection

Most air cleaner manufacturers provide advice for selecting air cleaners and it is recommended that their advice is sought in order to make the most appropriate selection for the application, thus making best use of the latest technology.

To serve as a guide only, the following methodology is a simple procedure that can be followed to assist and check air cleaner selection.

Determine Duty Classification/Environment — Medium/Heavy Duty

Determine the worst case (full load rated speed) engine air flow requirement. This data is published for all engine ratings and can be found in the technical data section of the Engine Specification Manual (E.S.M.).

Determine cleaners available and recommended for the specific application type.

Review air cleaner performance curves (generally available from air cleaner manufacturers) showing air cleaner restriction against mass air flow and lab life against mass air flow to determine if the air cleaner is suitable. See the worked example on the following page.

- Air cleaners should always be sized using the clean air induction limit of 5 kPa (50 mbar).

- The minimum lab life for a medium duty filter = 10 hours.
- The minimum lab life for a heavy-duty filter = 15 hours.
- 500 hours service equates to hours lab life at medium duty.
- It is recommended that the Piezo line is always used to determine the clean air cleaner restriction, as this is a more accurate method of measuring the restriction.

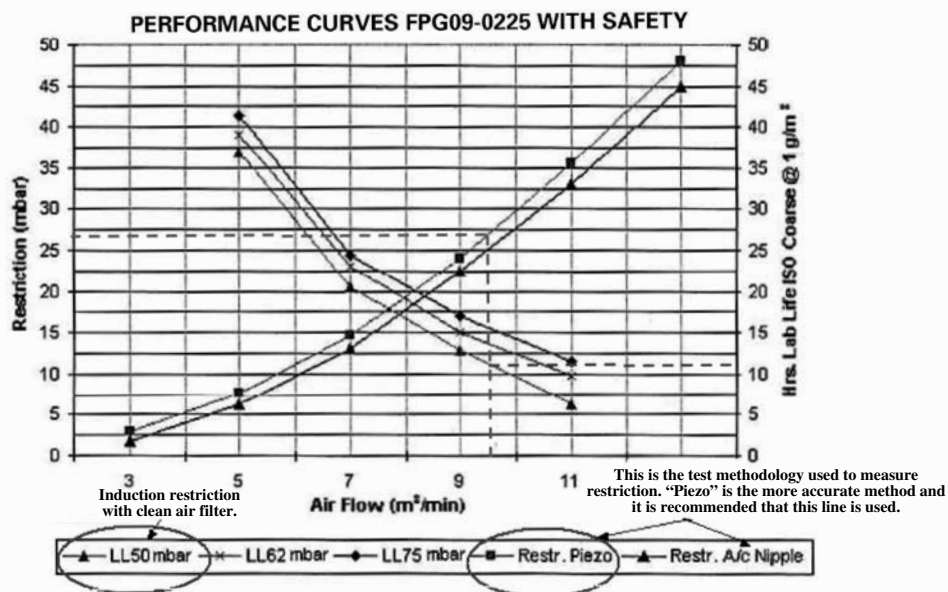
Worked Example:

Engine air flow: @FLRS: 9.6 m³/min

Engine intake restriction with clean filter: 50 mbar (5 kPa)

From the performance graphs below:

- The air cleaner selected has a 27 mbar restriction across the filter in its clean condition, allowing a further 33 mbar for the remaining induction pipe work.
- The air cleaner has a lab life of 11 hours, which equates to over 500 hours of service life. This is greater than the 10 hours minimum and is therefore acceptable for use in this application.



4.4.4 Induction System Pipe Work and Clamps

Careful attention must be given to the pipe work and associated fittings used within the induction system in order to minimize restriction and to ensure that reliable sealing will be maintained under the operating conditions which will be found in service.

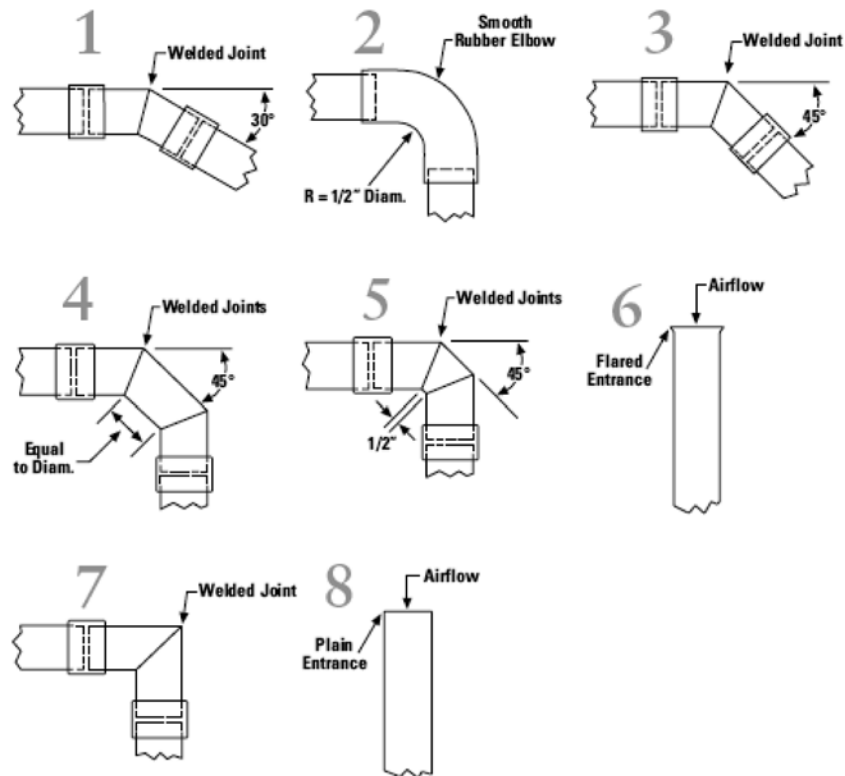
In order to minimize the restriction incurred in the system, pipe work length should be as short as possible, the number of bends kept to a minimum, and bends that cause the least amount of restriction used.

Relative motion between engine and cleaner must be addressed with the use of flexible fittings if required and pipe work adequately supported to ensure no stress is induced on the turbocharger inlet.

Please refer to the mandatory installation requirements for details of material, temperature, and further design requirements.

The Effect of Elbows and Entrance Diameters on Induction Restriction

Generally, the smoother the direction change, such as radiused tubes versus mitered bends, the lower the restriction. A 30° bend, as shown in Illustration 1 below, adds the least amount of restriction, while the 90° bend (Illustration 7) adds significantly more. Remember that even straight pipe causes restriction, and pipe with a cut-off blunt end will add much more than one with a flared inlet end. The slight flare makes a major difference in air turbulence and, consequently, in restriction.



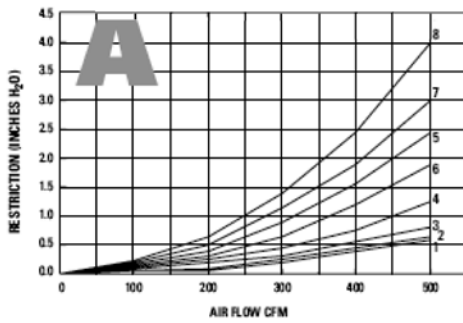
Graphs A, B, C, D and E on page 58 show the amount of restriction of different piping diameters, with various types of bends (Illustrations 1-8) at various airflow levels. You will notice that the smoother the direction change, such as radiused tubes versus mitered bends, the lower the restriction.

When considering air inlets, you may think it odd that straight pipe (Illustration 8) causes the highest amount of restriction. This is because of the blunt end. Compare the restriction curve to Illustration 6, which shows a flared end. The slight flare makes a major difference in air turbulence and, consequently, in restriction.

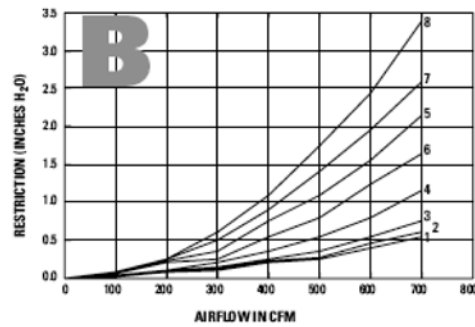
Length of pipe is also a factor, as shown in Graph E. Find the line that represents your pipe diameter at the airflow level you're running to give you a restriction figure for each foot of pipe length; then multiply by the length (in feet) of your plumbing, and you have the amount of restriction added by that length of pipe. Add this figure to the restriction of your air cleaner (and precleaner when used) to know if your system is too restrictive for the engine. Many engine manufacturers specify restriction limits for new "clean" engine air intake systems.

These curves should allow you to do a quick calculation on the plumbing you are planning for your system.

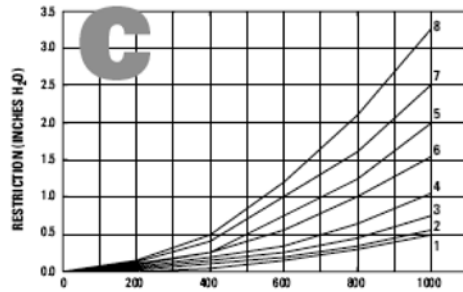
4" Diameter Piping



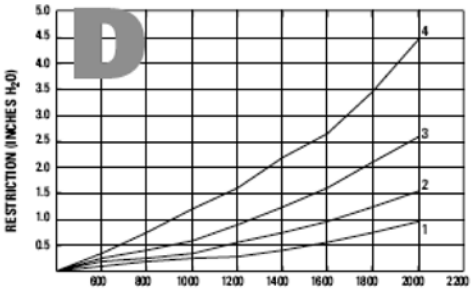
5" Diameter Piping



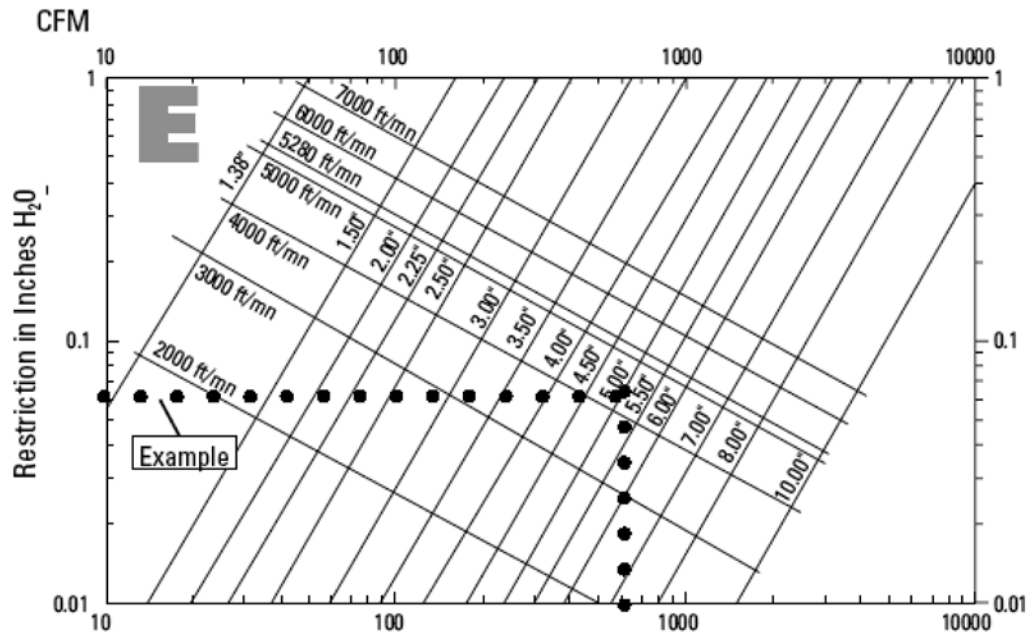
6" Diameter Piping



7" & 8" Diameter Piping



Straight Piping of Various Diameters



Example (assuming a 600 cfm system with 5" piping):

1. At 600 cfm on horizontal axis, draw a line up to the 5" diameter line.
2. Draw a line from the intersection point over to the vertical axis to find the restriction point, in this case .05 H₂O.
3. Calculate .06 x 10 feet of piping = 6" H₂O. This means that the 10 feet of 5" diameter piping adds .5" H₂O of restriction to the engine air intake system.

4.4.5 Air Inlet Location

The position of the air filter inlet, or of the inlet to the air filter extension if fitted, should be such that air is drawn from an area:

- Of the lowest possible dust concentration.
- Shielded from water ingress, including spray and cleaning processes. Water will cause filter damage or plugging, and possible engine and intake system corrosion.
- At a temperature as close as possible to the prevailing ambient temperature.
- Additionally, care should be taken to minimize the possibility of exhaust fumes being drawn into the induction system, since this will result in a reduction in element life and increased air inlet temperatures.

Industrial Applications

In general, in enclosed applications air should be drawn from outside the engine enclosure in order to avoid excessive intake temperatures. Exceptions to this are certain applications using pusher-type cooling fans, where depending on enclosure ventilation arrangements, air temperature in the enclosure may be relatively low close to the ventilation inlets. Care should, however, be taken to avoid local high temperature areas close to the exhaust system.

Agricultural Applications

Many arrangements are used where chaff or similar contaminants are likely to be encountered. In such cases, a prescreener should be fitted to prevent ingress into the main filter.

4.4.6 Air Inlet Temperature

It is always advisable to keep the air temperature entering the engine as close as possible to the local ambient temperature. High intake air temperature means less dense air entering the engine, which may result in increased smoke, less power, increased fuel consumption, overheating, and charge cooler performance issues.

For the majority of machines, the temperature of the air entering the engine is higher than the local ambient. As this temperature varies considerably in different installations and modes of operation, it is necessary to measure this difference for all new applications. This must be conducted in accordance with the defined Air Intake Temperature Offset Test, documented in TPD1746E and must be within the limits detailed in the mandatory requirements Section 4.2.2. If this value is exceeded please refer to IGB 1200-04.1

Once an offset value has been established it must be programmed into the ECU along with other critical machine configurable parameters. The generic industrial software, supplied as standard on all engines, requires the offset value to be programmed into the software to remove the associated fault code. Where engines are supplied factory configured, this parameter can be programmed in the bespoke CEOS for the installation.

It is important that an accurate value is established, as it is used to optimize engine performance under all operating regimes. Failure to enter the correct value may result in premature engine derates.

4.4.7 Air Cleaner Mounting

The air cleaner must be mounted so that the element can be easily accessed with minimal disruption to other components, thus reducing the risk of damage and contamination of the filter during replacement.

The mounting brackets should be approved by the air cleaner manufacturer and must ensure that there is no deformation of the sealing surfaces.

As air cleaners are sensitive to vibration, they may require isolation to ensure the durability of both the brackets and the filter elements.

4.5 Induction System Components

4.5.1 Air Cleaners

Dirt and debris are the major source of engine wear, so it is necessary to use an air cleaner to remove this dirt and debris from the intake air to prevent accelerated wear.

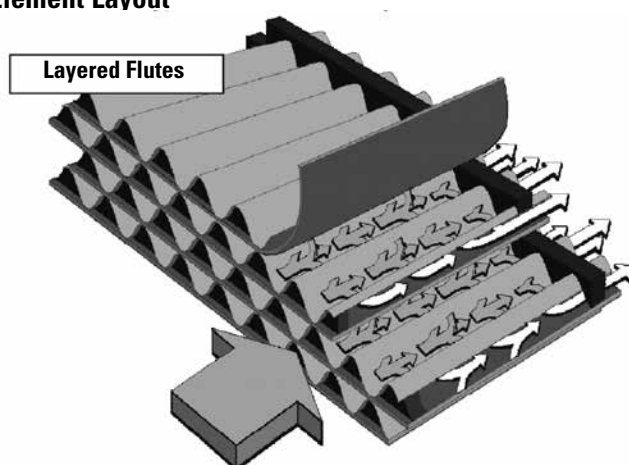
In order to increase filter performance and efficiency, modern air cleaners use the latest material technology using different media types and structures to load and disperse contaminants. This results in reduced media area and core size.

The table below shows the typical performance of an air cleaner with respect to particle size and shows how the filtration efficiency reduces as the particle size decreases.

Particle Size μ	Performance %
< 125	98.5 +/- 1.5
< 75	85.5 +/- 5.5
< 40	51 +/- 2
< 10	19.5 +/- 1

Table 4.3

4.5.1.1 Typical Filter Element Layout



4.5.1.2 Air Cleaner Assembly



4.5.1.3 Air Cleaner Subassembly Showing Internal Components



4.5.2 Safety Elements

The safety element is a secondary element used to protect the engine from the ingestion of dirt or dust in the event that the main element or seal is damaged or removed. This element is normally smaller in area and filters out a slightly larger particle size, thus reducing the pressure drop across it. It is fitted inside the main element and left in place during routine servicing.

The safety element will require servicing at less frequent intervals, and arrangements should be made for this to be conducted in approved conditions.

Safety elements are highly recommended for use in all earth moving, agricultural, and industrial applications.



Figure 4.1

4.5.3 Treated Elements

Certain dry filter types are available with specially treated elements that minimize the effect of contamination by exhaust and other products in order to increase service life.

Treated elements may also give a longer service life in some industrial applications operating in confined spaces.

4.5.4 Vacuator Valves

A vacuator valve is available as an optional feature on some dry cleaner types to provide automatic emptying of dust and water from the filter, thereby increasing service life. It is a rubber valve actuated by the pulsating nature of the induced air flow.

Note: Vacuator valves are available from filter manufacturers in different grades of rubber hardness to match to the engine type and operating speed range. In general, rubber hardness should be reduced as the number of engine cylinders is increased, allowing the valve to respond to the smoother nature of the induced airflow.

Care should be taken in locating the air filter to ensure that the dust/water ejected from the vacuator will not cause damage. Care must also be taken to ensure that there is no possibility of water, etc. being drawn into the filter due to the valve becoming immersed.

4.5.5 Exhaust Assisted Precleaner Evacuation

The exhaust ejector is a device used to scavenge dirty air from the precleaner chamber of the filtration system and exhaust it out to the atmosphere. Ejectors can be selected for the application according to the engine air demand and exhaust temperature.

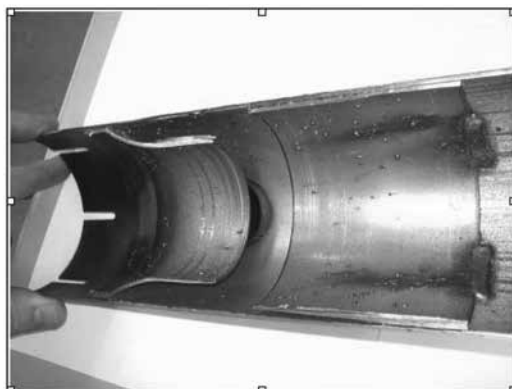


Figure 4.2



Figure 4.3

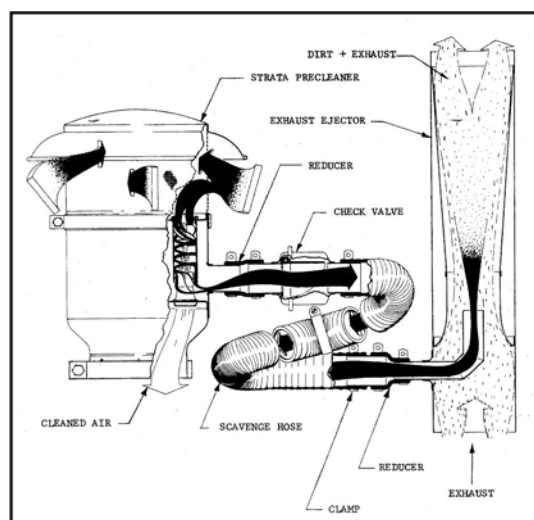


Figure 4.4

4.5.6 Restriction Indicators

A visible air cleaner restriction indicator must be fitted to all installations. This enables maximum service life to be obtained from the filter element without exceeding the engine restriction limit and prevents premature renewal of the element.

There are two common types of indicator:

- A vacuum sensing mechanical floating ball system which can either provide a single or progressive visual indication of air cleaner restriction
- Electronic sensor

The preferred location for fitment of the indicator is in a straight section of pipe work about 50 mm away from the turbocharger inlet. In these circumstances, the setting of the indicator should correspond to the maximum permissible restriction for the particular engine type.

It is common, however, for the indicator to be supplied with and mounted on the air cleaner itself. In these instances, the indicator setting must be reduced to accommodate any additional restriction due to friction and air velocity effects across the pipe work.

4.5.7 Rain Caps

The induction air inlet must be protected against water ingress, including snow, rain, hail etc., and also from other contaminants such as leaves and the nesting of small animals.

The use of a rain cap is now common practice on industrial applications.

Examples of common rain cap designs are shown below in Figure 4.5.

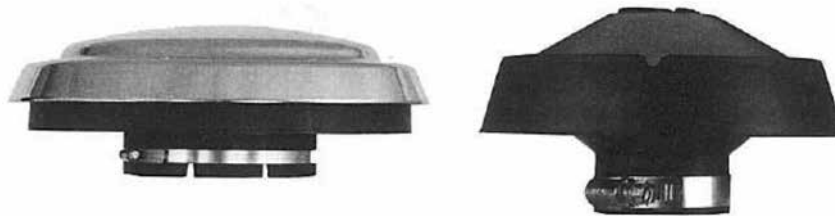


Figure 4.5

4.5.8 Precleaners

These are fitted to the air cleaner inlet or extension pipe in applications where significant dust or other contamination is encountered, e.g., earth moving machinery and certain industrial and agricultural applications.

They extend the service life of the main filter by removing a large part of the dust or other contaminant before passage through the filter. Figure 4.6 shows an airflow schematic of a cyclonic precleaner.

Precleaners operating on a cyclonic principle should not be oversized relative to the rate of airflow for which they are intended, as this will reduce the air velocity, leading to a reduction in the cyclonic dust separating effect.

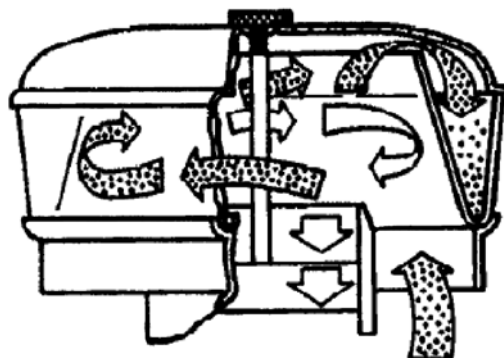


Figure 4.6

4.5.9 Prescreeners

In agricultural and other applications where contamination from chaff, lint, or other coarse material is encountered, a prescreener should be fitted to prevent choking of the air filter. A detachable screen is fitted to the machine hood louvers, which is removed for cleaning when necessary to ensure induction restriction limits are not exceeded.

5.0 Aftertreatment and Exhaust Systems

5.1 Introduction

To meet EPA Tier 4 Interim, EU Stage IIIB emission standards, aftertreatment is included within the engine exhaust system. This aftertreatment is required to enable the engine to produce its published rated power and fuel consumption, and conform to the new emission standards.

This chapter outlines the mandatory requirements and design considerations for the aftertreatment modules and exhaust components.

5.1.1 Safety

Warning: Improper operation, maintenance, or repair of this product may result in injury. Do not operate or perform any maintenance or repair on this product until you have read and understood the operation, maintenance, and repair information.

Burn and fire hazards are possible. Failure to properly connect the aftertreatment/regeneration device, manage the regeneration gas temperature, or properly route the exhaust gases away from the module may result in personal injury.

5.2 Aftertreatment and Exhaust Mandatory Requirements

All emission-related installation instructions are highlighted by the **EM** symbol.

Failing to follow these instructions when installing a certified engine in a piece of nonroad equipment violates federal law (40 CFR 1068.105(b)), subject to fines or other penalties as described in the Clean Air Act.

5.2.1 General Mandatory Requirements

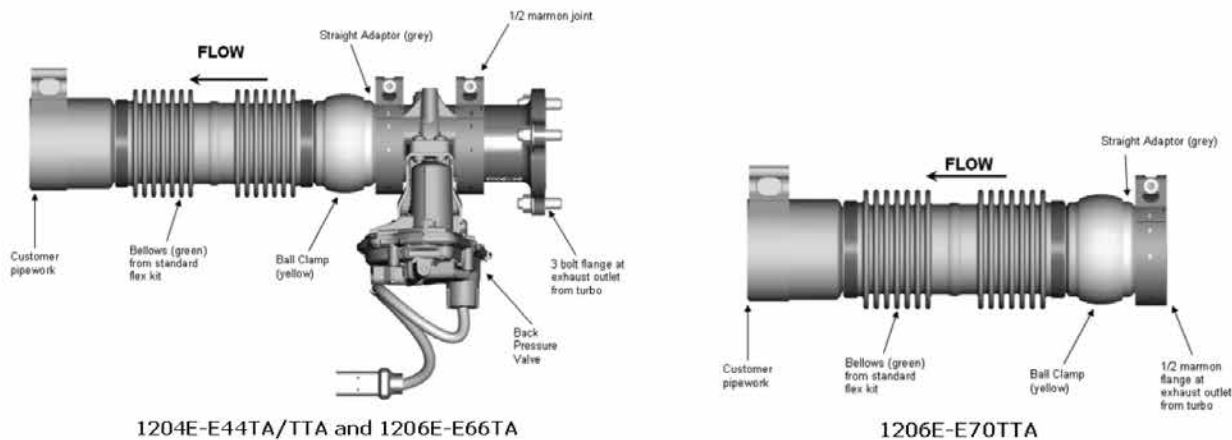
- **EM** The engine must be installed and operated with the aftertreatment that has been matched to the engine to ensure emissions compliance.
- **EM** All joints used between the engine and aftertreatment must be industry standard, leak tight, and durable for 8000 hours.
- **EM** All installations must use a Caterpillar supplied flexible installation kit.
- **EM** Under no circumstances is it acceptable to modify, tamper, or customize the aftertreatment assembly or flex pipe components supplied by Caterpillar.
- **EM** It is not permitted for the aftertreatment canister restraining clamps (on the mounting frame) to be loosened to re-orient the canister.
- **EM** The DOC/DPF end cans must not be re-orientated from the supplied position.
- **EM** Welding components onto the aftertreatment is prohibited.
- **EM** The aftertreatment is not qualified as a spark arrestor. If this is an application requirement, it is recommended to work directly with the applicable bodies (i.e., U.S. Department of Agriculture, Forest Service) to ensure all the necessary requirements are met.
- Painting of any aftertreatment component is prohibited.
- **EM** It is not permitted to use exhaust brakes on any engine model.
- **EM** The use of thermal insulation (i.e., thermal lagging or wrapping) must not be used on any engine or engine system component, including the aftertreatment and engine-to-aftertreatment interconnecting pipe work, without Caterpillar approval. Under no circumstances must any thermal insulation applied to customer pipe work come into contact with the bellows. Refer to Section 7.2 — Thermal Management Mandatory Requirements and Section 7.4.6 — Reducing Heat Transfer.

5.2.2 Aftertreatment and Exhaust System Mandatory Requirements

- **EM** The exhaust system backpressure must fall within the minimum and maximum Start Of Life (SOL) values published within the relevant E.S.M. These requirements may vary depending on engine and/or rating, and care should be taken to ensure the correct values are used. If the requirement is unclear or the data is not available for a particular rating, please contact your application engineer.
 - All testing must be conducted in accordance with the defined test procedure (refer to TPD1746).
- **EM** The flexible exhaust installation kit assembly supplied with the engine requires the installation to be designed to meet the following constraints:
 - Thermal expansion and dynamic movement (combined):
 1. Axial = +/- 11 mm
 2. Lateral = +/- 11 mm
 - Maximum capabilities of adjustable elements:
 1. Angular misalignment = +/- 3°, per ball joint (times 2)
 2. Fore/aft = +/- 15 mm, per slip joint (times 2)
 - These capabilities do not take into consideration any engine or aftertreatment tolerances. These must be combined with installation tolerances to ensure the above are not exceeded.
- **EM** The capability of the system must be verified using the bellows displacement calculator. This can be provided by your application engineer.
- **EM** The exhaust system must be designed to meet the following geometric constraint:
 - Total maximum pipe length from BPV/Turbo to DPF inlet 1.8 m*
 - Nominal OD (to suit slip joint) 76.3 +/-0.3 mm**
 - Wall thickness (typical) 1.5 mm
 - Material specification 304 SS
- **EM** * For systems that exceed the 1.8 m maximum length requirement, a verification test must be conducted to validate the system. It is recommended, however, this test be conducted for all systems, even those within the geometric constraints.
 - Using ET (EST) confirm that a minimum DPF inlet temperature is attained. Please contact your application engineer for further information.
 - Test to be conducted at the minimum ambient starting temperature of the machine.
- **EM** ** All standard supplied tubes may not meet this specification and must be checked to ensure adherence to this requirement.
- **EM** No thermal insulation must come into contact with the bellows section.
- **EM** The flexible exhaust installation kit must be assembled following the correct procedure detailed in Appendix A, Chapter 5.
 - Do not remove the bellows constraint (wrap) prior to installing the bellows.
 - The bellows constraint must be removed prior to running the engine.
- **EM** The BPV, supplied fitted on C4.4 ACERT and C6.6 ACERT engines, must not be re-oriented from its supplied position.
- **EM** The flexible exhaust installation kit must be mounted directly after the backpressure valve (C4.4 ACERT and C6.6 ACERT) or turbo outlet (C7.1 ACERT). No other intermediate pipe work is allowed.

Aftertreatment and Exhaust Systems

- **EM** Any customer fitted pipe must be adequately supported after the flexible section.
 - It must not be bracketed back to any part of the engine.
 - It is recommended that the same rigid structure the aftertreatment is mounted to is used.
 - Seek applications engineer advice for any concerns relating to supporting brackets.



- **EM** If a muffler, dust ejector, or spark arrestor is required, it must be connected after the outlet from the aftertreatment can.
- **EM** The bending moment at the aftertreatment outlet must be kept to a minimum and must not exceed 60 N•m.

5.2.3 Aftertreatment Mounting Requirements

- **EM** The aftertreatment must not be mounted on the engine or the engine system without Caterpillar approval, except when supplied as an installed option by Caterpillar. Under exceptional circumstances, Caterpillar engineering approval can be sought, but extensive validation work will be required. Please contact your application engineer for further information.
- **EM** If the engine uses off-engine aftertreatment which is solidly mounted, it must not be exposed to vibrations in excess of 60 hz.
- **EM** If the engine uses off-engine aftertreatment and both the engine and aftertreatment are solidly mounted, this must be approved by Caterpillar engineering, and extensive validation work will be required. Please contact your application engineer for further information. Refer to Section 5.4.1.2.
- **EM** The aftertreatment must be mounted to a structure that will provide sufficient rigidity to support the aftertreatment mass and be capable of withstanding the maximum loading during a worst-case work cycle (including shock loading) for that application.
- **EM** The aftertreatment must be mounted within the tilt angle capabilities specified on the next page.

EM For the C4.4 ACERT and C6.6 ACERT

- The combination of the aftertreatment installed angle and the application's operational tilt limit in the longitudinal plane of the aftertreatment must not exceed 55°.
- The complete aftertreatment assembly may be mounted at any angle radially about its longitudinal axis provided that:
 - The protruding part of the soot sensor is not within $\pm 10^\circ$ of the lowest point of the aftertreatment can when the application is static on level ground.
 - See Figure 5.1 for detail.

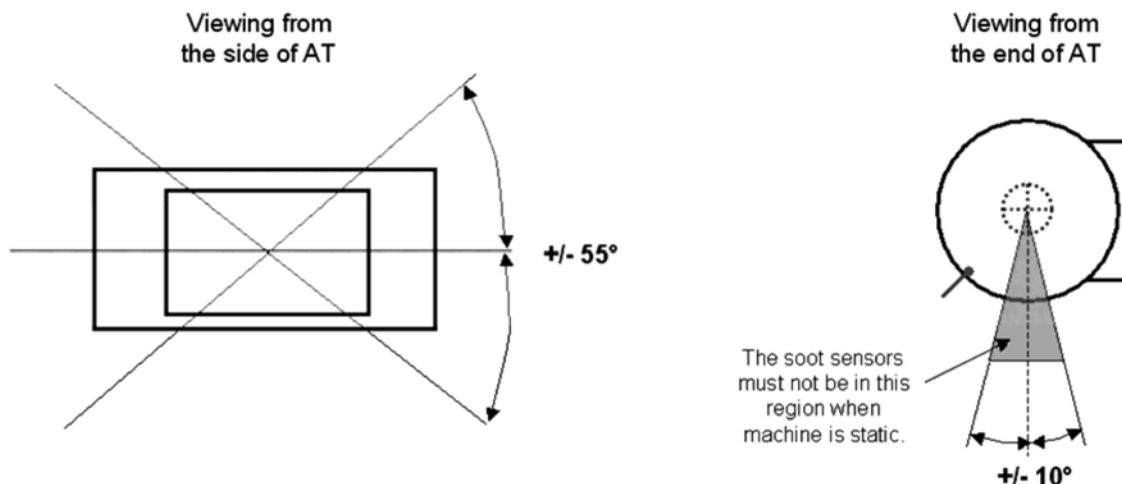


Figure 5.1

EM For the C7.1 ACERT

- The maximum installation angle of the aftertreatment mounting pads from their default position, when looking toward the Cat Regeneration System head, must not exceed the angles depicted in Figure 5.2.
- The installed angle of the mounting pads must be 0° from the default in all other directions/planes.

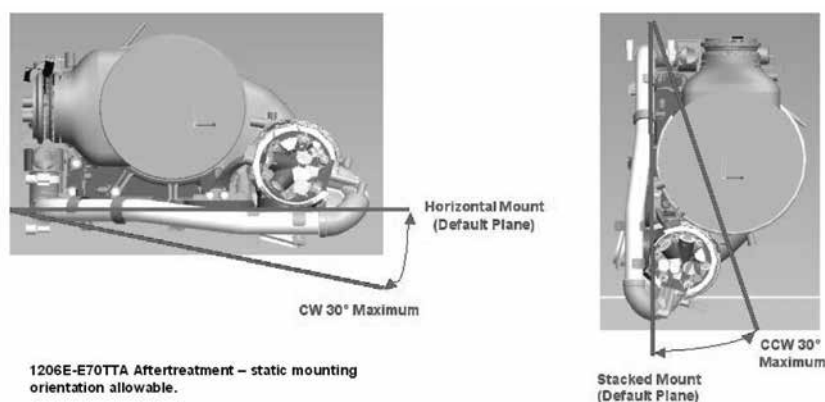


Figure 5.2

- **EM** The aftertreatment is flow-directional and must be installed the correct way around; the can is clearly marked with the flow direction.

5.2.4 Environmental Mandatory Requirements

- **EM** Refer to Chapter 7 — Under Hood Thermal Management, for aftertreatment component temperature limits.
- **EM** The exhaust stack must be designed to prevent water and dirt ingress into the aftertreatment.

5.2.5 Soot Sensor Mandatory Requirements

- **EM** The temperature of the soot sensor electronic box must not exceed 85°C.
- **EM** The soot sensor cables must not be modified.
- **EM** Please refer to the Electronic Installation Manual for additional requirements of the soot sensor.

5.2.6 Cat Regeneration System Mandatory Requirements (C7.1 ACERT)

- **EM** The Cat Regeneration System coolant supply and return lines must have a minimum internal diameter of 10 mm. Please refer to Section 5.5.2.
 - The Cat Regeneration System coolant line must vent during engine start up.
 - Coolant hose material specification should be the same as the engine.
- **EM** The active regeneration system air feed needs to be pressurized and must be taken from a point between the turbo compressor outlet and the charge cooler inlet.
- **EM** The Cat Regeneration System compressed air supply line must be capable of withstanding a working gas pressure of 260 kPa at a temperature of 260°C.
- **EM** The compressed air line must have a minimum internal diameter of 41 mm with a maximum equivalent length of 8 m. Please refer to Section 5.5.1 and Table 5.5.
- **EM** The maximum fuel inlet restriction at the Cat Regeneration System fuel manifold connection must not exceed 20 kPa. Fuel line specification: 2068 kPa (300 psi) working pressure and 4-121°C (40-250°F) operating temperature. Refer to Chapter 8 — Fuel Systems, for further information.

5.2.7 Maintenance and In-Use Testing Mandatory Requirements

- **EM** Where the addition of a sample pipe to the exit of the exhaust stack does not provide a suitable non-diluted sample for in-use testing (e.g., due to excessive backpressure, or use of air entrainment into the exhaust for cooling), adequate provision must be made in the design to enable emission-sampling equipment to be used successfully.
- **EM** The C7.1 ACERT engine aftertreatment has the following serviceability requirements:
 - The Cat Regeneration System spark plug must be given 96 mm clearance to allow for removal and servicing.
 - The aftertreatment must only be lifted by its integral lifting eyes. The aftertreatment lifting eyes are not designed to lift the engine, transmission, or any additional weight.
 - **EM** The aftertreatment must be installed with sufficient clearance to service both the fuel manifold filter and combustion head filter.



5.3 Aftertreatment System Fundamentals

5.3.1 Engine Platform Technologies

The following table shows the aftertreatment technology for each engine platform and power band. These technologies have been selected as the optimal combination to meet emission standards. The following section explains the different technologies and components used.

Tier 4 Interim Engine Systems Strategy				
Engine	Power Rating		Aftertreatment	Type of Regeneration
	HP	KW		
1204E-E44TA	81-148	61-110	DOC/DPF	Low Temperature Regeneration
1204E-E44TTA	140-175	105-130	DOC/DPF	Low Temperature Regeneration
1206E-E66TA	120-175	89-130	DOC/DPF	Low Temperature Regeneration
1206E-E70TTA	188-275	140-205	DOC/DPF/ARD	High Temperature Regeneration

Table 5.1

5.3.2 Technology Component Descriptions

5.3.2.1 Diesel Oxidation Catalyst (DOC)

A DOC is a flow-through honeycomb substrate with a precious metal catalytic coating. The DOC unit assembly has a round cross-section to eliminate non-uniform thermal gradients. As exhaust gas from the engine passes over the catalyst, a chemical reaction takes place, oxidizing carbon monoxide (CO), hydrocarbons (HC), and soluble organic fraction (SOF) of particulate matter.



Figure 5.3

5.3.2.2 Diesel Particulate Filter (DPF)

DPF filters have a cellular structure with individual channels that are open and plugged at opposite ends. Exhaust gases enter the open end, flow through the pores of the cell walls, and exit the filter through the adjacent channel. Soot particles collect on the channel walls and are cleaned out using a regeneration process discussed in Section 5.3.8.

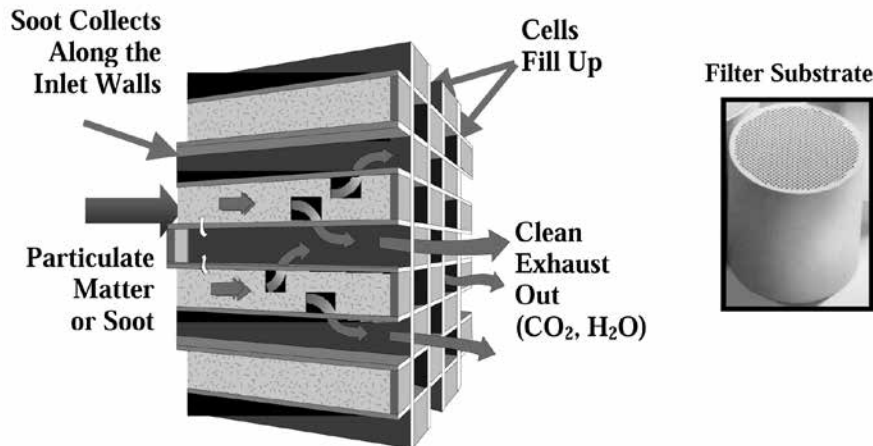


Figure 5.4

The DPF has a catalytic coating made up of precious metals that coat the cellular structure to enhance the regeneration process.

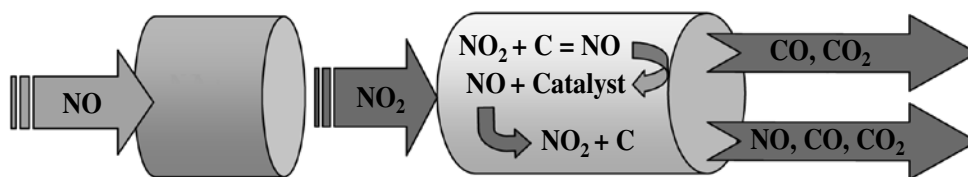


Figure 5.5

5.3.3 Regeneration of Particulate Filters

Regeneration is the process used to remove soot (carbon C) buildup from the DPF filter. The various methods employed are discussed below.

5.3.3.1 Passive Regeneration

Passive regeneration is the process of continually cleaning the diesel particulate filter when engine-operating conditions maintain sufficient exhaust temperatures.

In the DOC, nitric oxide (NO) is converted to nitrogen dioxide (NO₂). When the exhaust temperatures reach 250°C or above, this combines with the soot (carbon [C]) built up in the DPF to form carbon dioxide (CO₂), which then exits the exhaust system as a clear gas.

The DPF is considered to be regenerating when the rate of soot oxidation in the particulate filter meets or exceeds the rate of soot generation by the engine, preventing excessive soot accumulation in the DPF.

The aftertreatment system has been designed to maximize passive regeneration. If there are operating cycles where exhaust gas temperatures are too low to maintain regeneration, a backpressure valve, located post turbocharger exhaust outlet, is modulated to increase the load on the engine and raise the exhaust gas temperature to promote passive regeneration.

5.3.3.2 Active Regeneration — Cat Regeneration System

Active regeneration burns fuel within the exhaust stream to periodically raise the temperature above 600°C to promote oxidation and burn trapped soot. The Cat Regeneration System is used in conjunction with a DOC and a DPF to provide a active regeneration system.

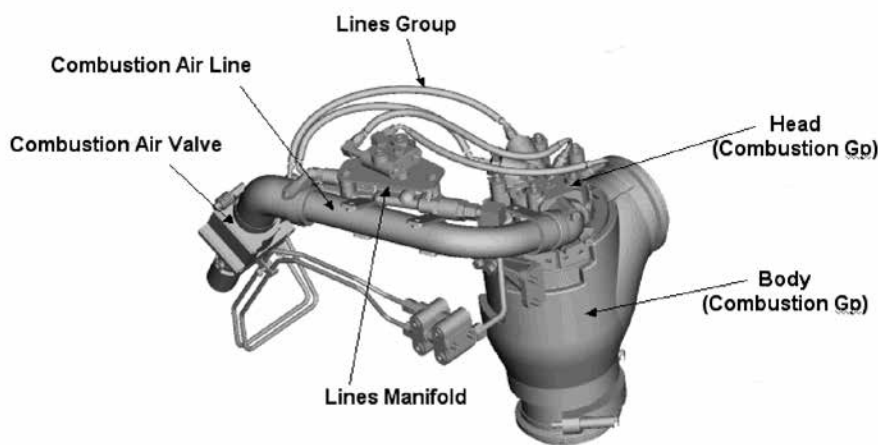


Figure 5.6

5.3.4 Aftertreatment Arrangements

For each engine platform, the selected aftertreatment technologies are packaged together. Details of all the supplied components and location within the exhaust system are described below.

5.3.4.1 DOC+CDPF Passive Regeneration

System Layout

The layout of the exhaust system is shown below in Figure 5.7. The flexible exhaust connection attaches directly to the BPV and onto the inlet of the aftertreatment can (containing the DOC/CDPF). If a muffler, dust ejector, or spark arrestor is required, it must be connected after the outlet from the aftertreatment can.

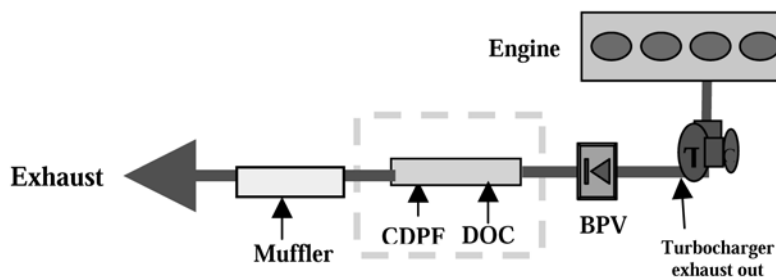


Figure 5.7

System Hardware Overview

The aftertreatment consists of a nonserviceable welded can with an inlet section, DOC/CDPF center section, and an outlet section. This configuration regenerates continuously and is ash service free for 8000 hours. The filter is designed with enough ash capacity that a scheduled ash service will not be required.

The C4.4 ACERT and C6.6 ACERT engines use a BPV to raise temperature when exhaust gas temperature is below soot oxidation levels to assist in passive regeneration and does not require active regeneration.

Breakdown of Components within C4.4 ACERT and C6.6 ACERT Aftertreatment

Figure 5.8 shows the components that make up the aftertreatment for the C4.4 ACERT and C6.6 ACERT engines. The DOC/CDPF is contained within the center section of the can with inlet and outlet end cans welded on. The inlets and outlets are only available in specific orientations as detailed in the Engine Specification Manual (E.S.M.). This whole assembly is strapped onto a cradle, which is then mounted into the application. Attached to this cradle is a bracket to support the product identification chip and temperature sensor connector. Soot sensors are pre-installed in the DOC/CDPF can. Please see the Tier 4 Interim Electronics A&I Manual for C4.4 ACERT to C18 ACERT (currently in draft form soon to be published as LEBH0005) Section 6 for additional details.

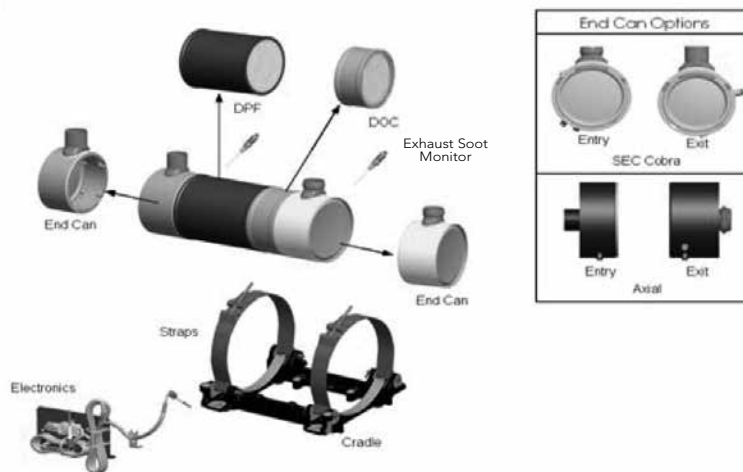


Figure 5.8

5.3.4.2 DOC+DPF+Cat Regeneration System – Active Regeneration

System Layout

The layout of the exhaust system is shown in Figure 5.9. The flexible exhaust connection attaches directly to the turbo and onto the inlet of the Cat Regeneration System, which is in turn connected to the aftertreatment can (containing the DOC/DPF). If a muffler, dust ejector, or spark arrestor is required, it must be connected after the outlet from the aftertreatment can.

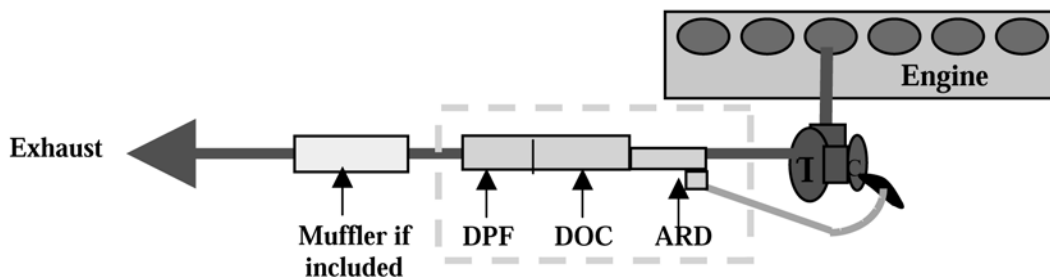


Figure 5.9

System Hardware Overview

For C7.1 ACERT engines, an Cat Regeneration System is included in the module in addition to the DOC and the DPF. The Cat Regeneration System is added to provide high temperature controlled regeneration of the DPF to maximize uptime of the engine system. The Cat Regeneration System can elevate the temperature of the exhaust gas from the engine significantly to assure oxidation of any accumulated soot before the gas is expelled to the atmosphere.

Breakdown of Components within C7.1 ACERT Aftertreatment

Figure 5.10 shows the components that make up the aftertreatment for the 1206E-E70TTA engines. The Cat Regeneration System is connected to the aftertreatment can inlet with a bellows. The DOC sits within the inlet can and is clamped onto the center section containing the DPF, which is then clamped onto the outlet can. This whole assembly is strapped onto a cradle. The inlets and outlets are only available in specific orientations as detailed in the E.S.M. Attached to the cradle is a bracket to support the electronics required for the Cat Regeneration System, the exhaust monitor sensors are pre-installed in the DOC/DPF can. Please see the Tier 4 Interim Electronics A&I Manual for C4.4 ACERT to C18 ACERT (currently in draft form soon to be published as LEBH0005) Section 6 for additional details.

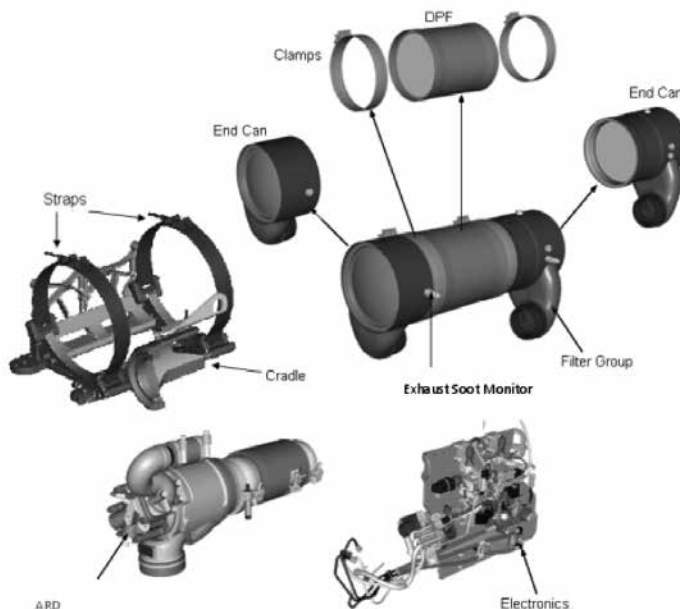


Figure 5.10

5.4 Aftertreatment and Exhaust System Design Considerations

With the inclusion of aftertreatment into the engine system, emissions will no longer be regulated at the engine exhaust outlet, but will be regulated at the aftertreatment outlet. This means that the aftertreatment unit itself and the connecting parts from the engine to the aftertreatment are now considered to be “emission critical components” under the legislative (EPA/EU) regulations. Consequently, they must be very carefully designed and controlled to ensure the emissions regulations are adhered to throughout the life of the product.

Compliance with regulations governing emissions-related components is imperative. In order to comply with these requirements, a number of key elements must be considered when designing the exhaust system. These are detailed in the sections below.

5.4.1 Mounting Requirements For Remote-Mounted Aftertreatment

The engine and aftertreatment should be considered as a system and the installation of these should not be designed in isolation. Please refer to Mounting Section 3 for further engine mounting system requirements and considerations.

For C4.4 ACERT engines an on-engine-mounted aftertreatment is offered and is recommended where possible. This is a fully validated, approved solution and the following mounting system considerations have already been taken into account. The following guidance is, therefore, only applicable to remote-mounted solutions.

The aftertreatment is supplied mounted in a cradle in a specific orientation for the application. The cradle is designed to be hard-mounted either directly on the machine chassis or onto a secondary support structure. The aftertreatment is designed to withstand the same G-load limits as the engine. When selecting a suitable mounting structure and location, the following points must be taken into consideration:

- The structure must provide sufficient rigidity and be stiff enough to support the aftertreatment mass. The mass of the aftertreatment can be found in the E.S.M.
- Any brackets, bolted joints, mounts, welds, or other structural elements supporting the aftertreatment must be able to withstand all mechanical loads seen during operation (including thermal growth) or shipping. Each of these elements may have different load limits, which may depend on the direction of loading or number of load cycles expected during the product's lifetime.
- Any structural elements must provide acceptable strength and durability over the entire temperature range expected to be experienced in the application.
- Welding mounting brackets to the aftertreatment is not permitted; this could lead to failure of the unit and possible emissions non-compliance.
- The orientation of the inlets and outlets must not be adjusted during the installation process.

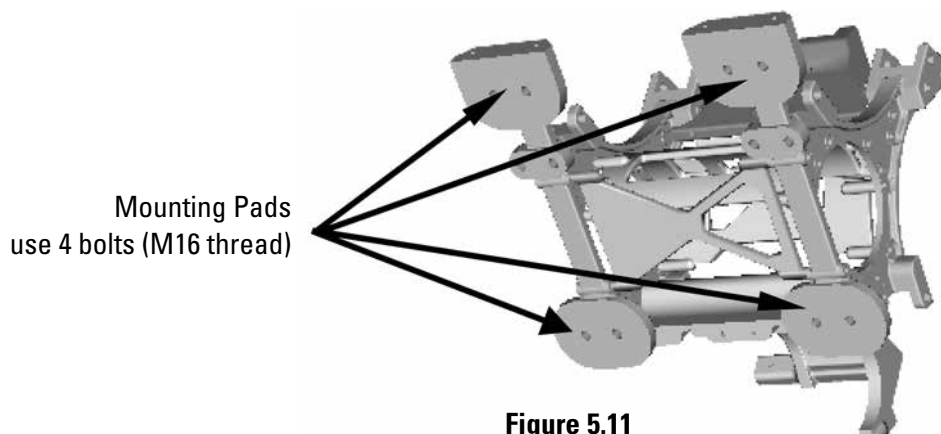
The aftertreatment assembly should be mounted in a location that:

- Allows air circulation around the can
- Is protected from debris or damage from foreign objects
- Has the identity plate clearly visible
- Is easy to access, without major component removal, for any service and maintenance requirements. This is product dependant and it is recommended that reference is made to the Caterpillar Operation and Maintenance Manual (OMM) for the specific engine model when considering these requirements.

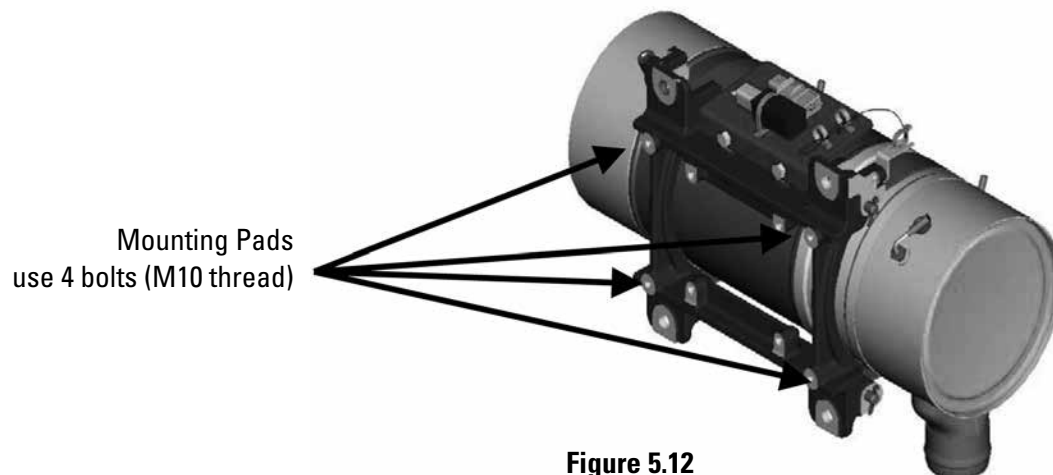
5.4.1.1 Aftertreatment Mounting Pads

The following mounting pads are provided on the aftertreatment cradle.

C7.1 ACERT Cradle Mounting Feet Location



C4.4 ACERT and 1206E-E66TA Cradle Mounting Feet Location



5.4.1.2 When Flexible Mounts May be Required

The aftertreatment has been designed and validated to be durable in a wide variety of applications without the use of flexible mounts. However, certain applications may still require the use of flexible mounts for one of the following reasons:

- The aftertreatment hard-mounted to a particular structure would be exposed to load frequency inputs greater than 60 Hz. System natural frequency inputs greater than 60 Hz will excite the modal response of the system and a harmful resonance condition could occur, causing damage to the aftertreatment.
- If the engine and aftertreatment are both hard-mounted to the same support structure
- If stresses would otherwise be exerted on the aftertreatment mountings due to relative movement on the machine mounting locations (e.g. thermal or due to lack of stiffness in the machine structure)
- The noise generated by a hard-mounted aftertreatment would be objectionable
- Some flexibility in the attachments may make assembly easier and/or reduce assembly stress.

Aftertreatment and Exhaust Systems

If flexible mounts are used, the relative movement must be controlled to ensure the gross deflection does not exceed the limits of the connection between engine and aftertreatment. This must be designed for worst-case in-use operation. The fundamental design choice of either hard mounting or using vibration isolation mounts for the engine and aftertreatment is critical to determining the acceptability of an installation in terms of:

- Exhaust flexpipe capability
- Aftertreatment vibration acceptability

The installation may already have an established engine mounting system, which can be used as a starting point in the design process. The table below summarizes various mounting option scenarios and discusses their advantages and disadvantages.

Scenario	Engine Mounting	Remote AT Mounting	Preferred Scenario	Typical machine type example*
1	Solid	Solid	No	Ag tractors,
2	Solid	Vibration Isolation	Yes	Crushers, Trenchers, Pump sets
3	Vibration Isolation	Solid	Yes	Compressor, Telehandler, FLT, Excavators
4	Vibration Isolation	Vibration Isolation	No	Vibrating compactor, Rock Drill, Bulldozer

*The machines listed are only given as a example of where this mounting scenario may typically be used. This scenario may, however, not always be suitable for this type of machine. All mounting scenarios must be thoroughly evaluated for each machine type.

Table 5.2

Scenario #1: Engine hard-mounted, aftertreatment hard-mounted

This is not a preferred scenario. Although it often provides the best case in terms of flex pipe capability, it is not preferred because the aftertreatment is exposed directly to engine vibration. In some cases this scenario may be acceptable; however, extensive vibration testing will be required. Please contact your application engineer for guidance.

Scenario #2: Engine hard-mounted, aftertreatment ISO mounted

This is a preferred scenario when the engine is hard-mounted to the master structure. This scenario allows the aftertreatment to be isolated from engine and machine vibration sources. A machine vibration source may originate from rotating equipment associated with trenching, drilling, chipping and grinding, road building equipment, etc. Flex pipe relative movement due to isolation mounting is minimized since isolation mounts are only used for the aftertreatment.

Scenario #3: Engine ISO mounted, aftertreatment hard-mounted

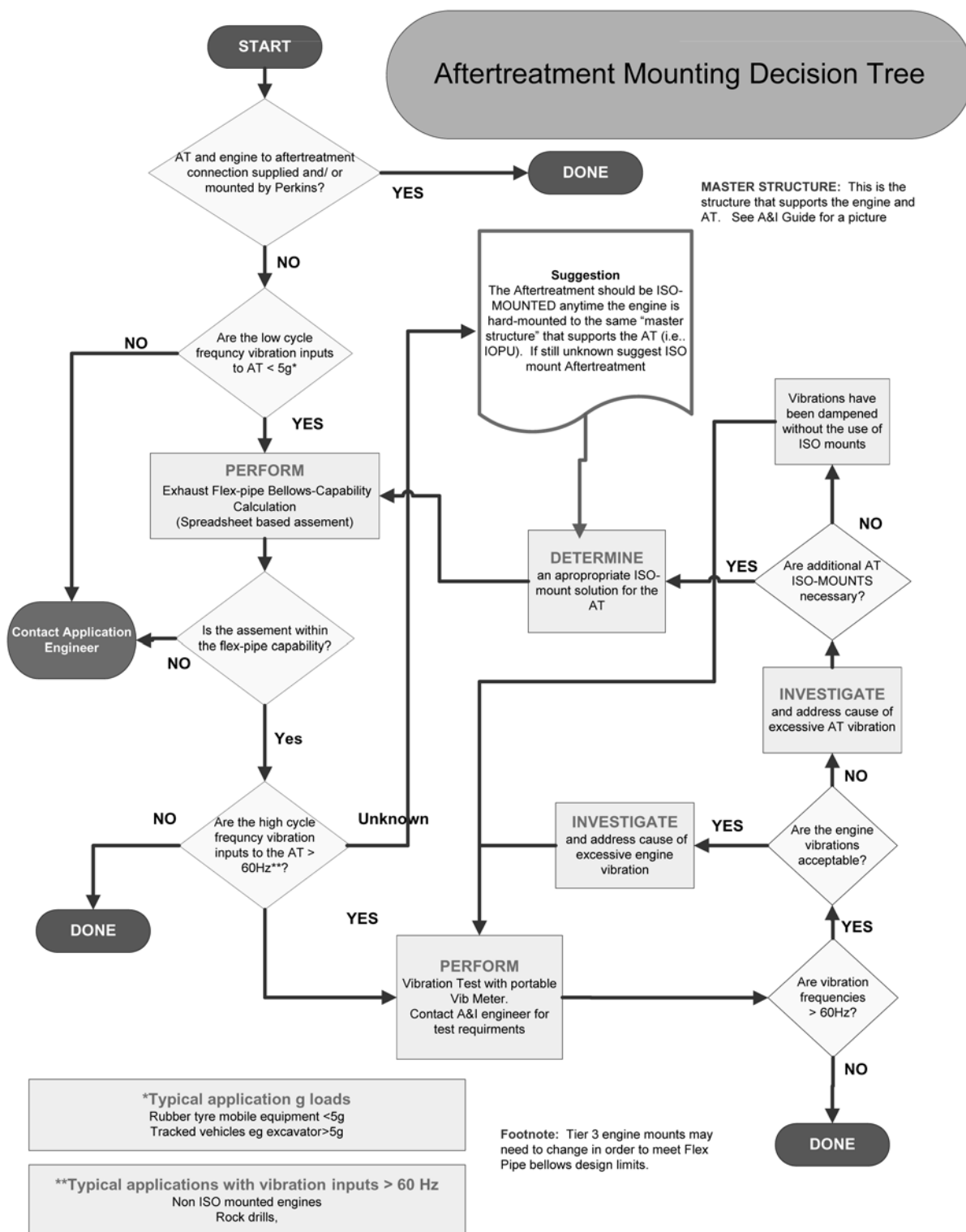
This is a preferred scenario when the engine is attached to the master structure using vibration isolation mounts. This is typically preferred for installations that do not have aggressive machine vibration sources. In this scenario the relative movement of the flex pipe is minimized since isolation mounts are only used for the engine. Please refer to the recommended machine type scenario in Table 5.2 above.

Scenario #4: Engine ISO mounted, aftertreatment ISO mounted

This is not a preferred scenario. When the engine and aftertreatment are both attached to the master structure using vibration isolation mounts, the aftertreatment vibration will tend to be acceptable; however, the relative movement between the engine and aftertreatment can exceed the capability of the flexible Installation kit. This scenario may be required for installations that require the engine to use vibration isolation mounts and also have aggressive machine vibration sources present. Refer to the recommended machine type scenario in Table 5.2 above.

There are often a number of conflicting requirements that need to be considered which may require several iterations before an optimum design is reached. A mounting system decision tree is provided below, which should aid this process and help ensure that all the key requirements have been considered to help provide an acceptable mounting system.

5.4.2 Mounting System Decision Tree For Remote-Mounted Aftertreatment



If the installer can complete the aftertreatment mount decision tree to one of the three “Done” steps, the following aspects of the engine and aftertreatment can be considered acceptable:

- Exhaust flex pipe capability
- CEM vibration acceptability

If the installer cannot complete the aftertreatment mount decision tree to one of the three “Done” steps, further analysis will be required. Acceptability should not be considered final until approval from Caterpillar application and installation engineering is provided.

In the next release of this manual, further information with regard to acceptability of installations that cannot reach one of the three “Done” steps will be provided.

5.4.3 Engine to Aftertreatment Interconnecting Pipe Work

In order to provide a robust and durable connection between the aftertreatment and the engine a flexible connection is required in order to accommodate:

- Dynamic movement for worst-case engine operation/duty cycle
 - From engine on engine mounts and aftertreatment on chassis or support structure. To include start/stop and shock loading
- Thermal expansion
 - From turbo or BPV to aftertreatment
- Vibration
 - From engine or from chassis
- Misalignment
- Tolerance stack-up (static)
 - Between engine and aftertreatment interfaces

A flexible exhaust installation kit is available as part of the engine offering and must be selected as part of the engine specification. These options have been specifically designed and tested to provide a robust and durable connection between the engine and aftertreatment, provided the mandatory installation requirements are adhered to (reference Section 5.2).

5.4.3.1 Tolerance Stack-Up

It is essential to ensure that the exhaust components and corresponding pipe work are designed and positioned so that the limitations of the flexible exhaust Installation kit are not exceeded. In order to do this, it is recommended that the system be designed around the capability of these components and the adjustable elements of the assembly orientated to allow for any misalignment.

To ensure these requirements are adhered to, the amount of static misalignment, due to tolerance stack-up, between the engine and aftertreatment interfaces must be calculated. The sources of static misalignment are listed below with appropriate values where available.

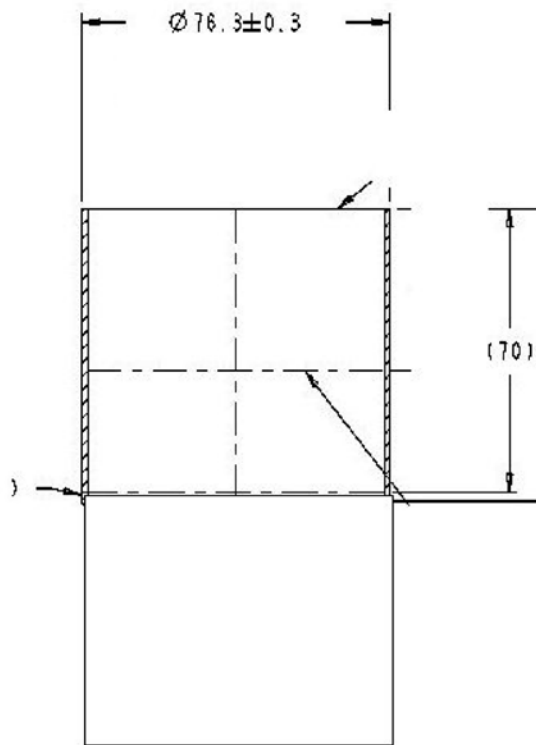
- Engine mounting pad to engine exhaust outlet is: ± 1.5 mm in X, Y, Z Axis.
- Aftertreatment mounting pad to aftertreatment inlet connection is:
 - For C4.4 ACERT and C6.6 ACERT ± 3 mm longitudinally, ± 1.5 degrees rotational
 - For C7.1 ACERT ± 3.6 mm longitudinally, ± 3 degrees rotational
- Engine mounting pad to chassis mounting point (including flexible engine mount) — customer assessment required
- Chassis mounting point to aftertreatment mounting point — customer assessment required
- Customer-supplied pipe work — customer assessment required

5.4.3.2 Pipe Size

The customer-supplied exhaust connection, between the bellows and DPF inlet, must have an external pipe diameter of 76.3 ± 0.3 mm to match the slip joint design provided on the bellows and DPF inlet adapter. The pipe must have a minimum diameter of 1.5 mm to meet the durability requirements of the flexible installation kit.

The internal diameter should remain constant but if necessary may be reduced provided that:

- Calculations and test are conducted to ensure the pressure drop requirements are met
- At least 70 mm of 76.3 OD pipe are maintained at each connection point as indicated below.



It is imperative that the diameter and minimum length requirements are adhered to, to ensure that both the leak rate and pressure drop limits of the exhaust system meet legislative requirements.

5.4.3.3 Pipe Length

It is currently recommended that the total length of the connection between the turbo outlet and the aftertreatment inlet is no more than 1.8 meters for all C4.4 ACERT through C7.1 ACERT products. This is to help ensure that the aftertreatment inlet temperature meets requirements and to give optimal conditions for regeneration of the DPF.

Where longer sections are required it would be beneficial to thermally wrap (lag) the pipe to retain the heat along its length to give the required aftertreatment inlet temperatures.

5.4.3.4 Pipe Material

The material selection is an important part of ensuring that the system will continue to perform over the life of the application.

- For the pipe supplied by the customer, between the flexible installation kit and the DPF inlet, the material must be 304 or 321 stainless steel. This is required to match the flexible installation kit material and ensure a leak-tight connection is maintained under all thermal conditions.

5.4.4 Exhaust Flex Pipe Capability Calculator

The Cat flex pipe calculator should be used to determine if the installation satisfies the required flex pipe capability. This calculator must be used with the aftertreatment mounts decision tree to determine aftertreatment vibration acceptability. The flex pipe calculator is available from your application engineer.

The installer-designed engine and aftertreatment-installed system must satisfy two criteria to ensure acceptable flex pipe durability:

- Radial capability
- Axial capability

The flex pipe calculator requires several inputs including the following:

Engine

- Installed mass of the engine and all loads cantilevered off the flywheel housing
- Installed center of gravity for the engine and all loads cantilevered off the flywheel housing
- Number of engine mounts
- G-load
- Engine mount positions
- Engine mount stiffness

Aftertreatment

- Mass
- Center of gravity
- Number of CEM mounts
- G-load
- Aftertreatment mount positions
- Aftertreatment mount stiffness

The calculator uses this information to determine radial and axial movement at the flex pipe. Based on this movement, the calculator will designate the radial and axial flex pipe capability as acceptable or unacceptable. All installations must achieve flex pipe radial and axial acceptability.

5.4.5 Joint Loading

Table 5.3 below shows the maximum allowable dynamic load on the aftertreatment inlet and outlet connections.

All pipe work and connections to these joints should be carefully designed, assembled and adequately supported in order to minimize the joint load, prevent induced stress and avoid vibration and resonance.

Exhaust Component Interface	Joint Type	Maximum Allowable Dynamic Load
ARD Inlet (C7.1)	Ball	27 N•m
DOC/DPF Inlet (C4.4 – C6.6)	Ball	60 N•m
DOC/DPF Outlet	Slip joint	60 N•m

Table 5.3

The dynamic joint load can be calculated using the following formula:

$$M = maL$$

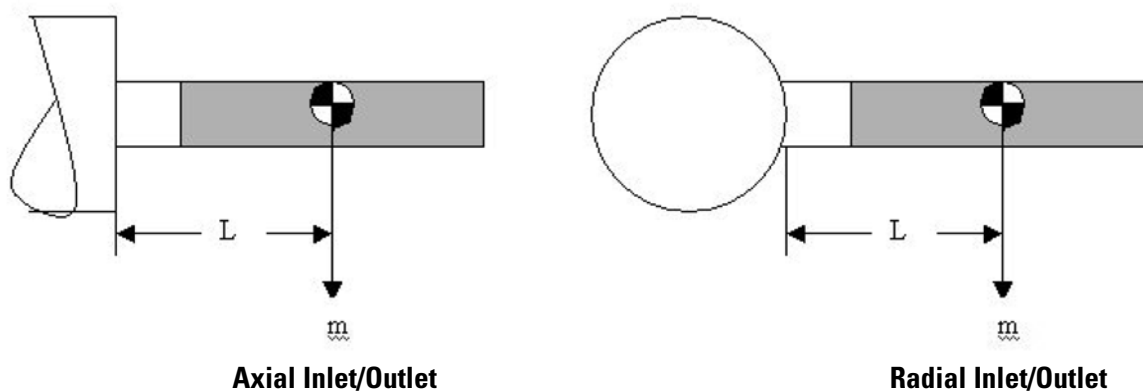
Where:

M = Dynamic load in Newton-Meter, $N\cdot m$

m = Mass of the pipe supported by the joint in kilogram, kg

a = Acceleration, maximum amplitude of the CG location of the supported pipe in meters/second squared, m/s^2

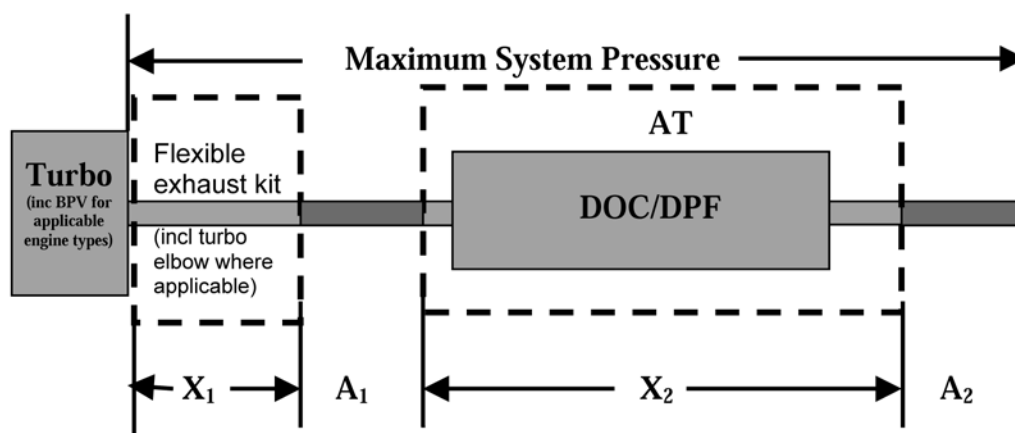
L = Distance from the CG of the supported pipe to the aftertreatment joint in meters, m



5.4.6 Backpressure Requirements

Please refer to Mandatory Installation Requirements Section 5.2.2.

The total system backpressure is a sum of the individual contributions of all the exhaust system components, as shown in the diagram below:



The maximum system pressure (backpressure) of the exhaust system is achieved when the aftertreatment is fully loaded with ash, this is known as the End Of Life (EOL) condition.

From the diagram above:

$$EOL = X_1 + X_2 + Y + A \text{ (kPa)} = \text{Total System Pressure}$$

Where:

A = total apportioned pressure drop for customer pipes ($A_1 + A_2$)

X_1 = turbo/ BPV adapter, bellows, aftertreatment adaptor

X_2 = aftertreatment

Y = 100% ash loading

Chapter 6 of the relevant E.S.M. provides values of the maximum exhaust backpressure limits at the EOL and also at the minimum and maximum Start Of Life (SOL) conditions.

The allowable pressure drop across customer-supplied pipe work can be approximated by taking the minimum SOL value from maximum SOL value i.e.:

Approximate DP (customer pipe work) = Max SOL – Min SOL

For factory designed and supplied aftertreatment and exhaust systems (e.g. IOPU and 4-cylinder engine-mounted solutions) customer apportionment of pressure drop for venturi, dust ejectors, mufflers, etc. is after the aftertreatment outlet.

The backpressure must be measured in accordance with the defined test procedure reference TPD1746. For most C4.4 ACERT and 1206E-66TA engines the minimum SOL limit will be met by the exhaust system components supplied with the engine. For the 1206E-70TTA, additional exhaust system components may be required to meet this lower limit; however, before this is done, the condition of the test should be checked to ensure that the machine reached the full load rated speed condition. EOL figures are given in the E.S.M. to comply with legislative requirements but are not needed for system design or installation sign-off.

5.4.7 Noise Attenuation

Please refer to Noise and Vibration Section 13 for further information.

The use of a silencer within the exhaust system is application-specific. Should a silencer be required, it must meet the backpressure limits and be fitted after the aftertreatment. However, due to the good noise attenuation properties of the DPF substrate, in some applications the DPF can replace the silencer without any additional provisions for noise attenuation.

5.4.8 Exhaust Pipe Outlets

Exhaust outlets must be provided with an appropriate means of preventing water ingress. This can be accomplished by several methods but these can impose restrictions that can significantly increase the backpressure so careful consideration must be taken during selection.

The use of a rain cap, exhaust flaps, slots within the exhaust pipe, or angled outlets are commonly used methods.

It is most important to select the direction of the tailpipe exit so that the exhaust gas:

- Is not drawn into any dry element air cleaner, subsequently rapidly clogging the element and reducing service life.
- Is not drawn back through the radiator by a puller fan installation. This is likely where exhaust exit and radiator entry are both on top of the machine.
- Is directed away from the sight lines of the machine operator.

Consideration should also be given to the noise regulations or requirements that must be met (i.e., bystander, operator, etc.) as some advantage may be gained by directing the outlet away from microphones or observers.

The exhaust pipe can accumulate a considerable amount of condensed moisture, especially when the pipe is long. To avoid internal corrosion, a condensate trap with an open drain can be provided at the lowest point in the system.

The exhaust pipe should avoid touching or passing close to the air cleaner, fuel and lubricating oil filters, fuel tank or piping, injection or lift pumps, radiator or sump, alternator, starter motor wiring, or any electronic components. If this is unavoidable, suitable heat shields should be employed.

5.4.9 Spark Arrestors

The DPF has been tested to SAE J350, which confirmed that the DPF was capable of capturing particles of a size considered to be a spark hazard.

It should be noted that SAE J350 may not be sufficient to achieve certification to applicable local regulations. The DPF cannot, as a component, be USFS (U.S. Forestry Service) certified as a spark arrester because USFS certification, using their current draft standard, has requirements in addition to spark arresting.

5.5 C7.1 ACERT – Cat Regeneration System Connections

Aftertreatment Components Identification – Electronic, Exhaust, Air, Fuel, Coolant

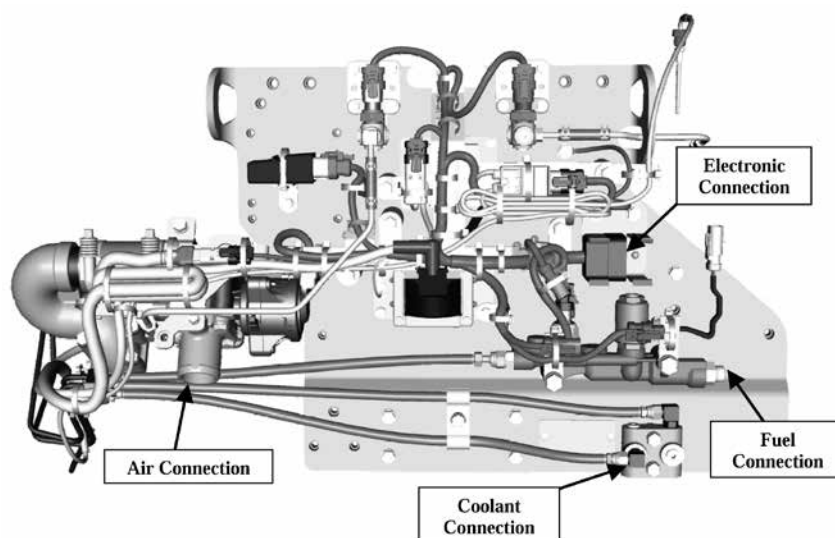


Figure 5.13

Aftertreatment Connections Table

Connection	Type	Size	System Pressure Drop (kPa)
ARD Combustion Air	Hose Barb	1 3/4" OD (1.62" ID) Hose	See Table Below
Fuel (Customer - Manifold)	ORFS	11/16" Tube/Hose	20 kPa: Priming Pump to ARD Head
Coolant (Supply & Return)	STOR	10 mm Minimum ID Hose/Tube -4 – 7/16 x 20	3 m max . distance both lines
Electrical (Harness)	Connector	40-Pin Square	N/A
Electrical (Soot)	Connector	Direct Connection 1 or 3 meter cables	N/A

Table 5.4

Aftertreatment and Exhaust Systems

5.5.1 Air Supply for Cat Regeneration System Combustion

The Cat Regeneration System requires an air supply for combustion. This air supply needs to be pressurized and must be taken from a suitable tapping on the turbo compressor outlet pipe and plumbed into the barbed hose fitting provided on the Cat Regeneration System air valve.

The hose must meet the material specification detailed in the mandatory requirements Section 5.2.6. It is recommended to use a hose of 1.75 inch OD (1.62 inch ID). Table 5.5 below illustrates how to design for pressure drops in the combustion air-line. Each application will use a T-fitting connecting the compressed air from the turbo to the combustion air valve on the aftertreatment. The total length allowed for this line is 26 ft. One 90° bend could take up 2.3 of the total allowable 26 feet of 1.62 ID pipe.

Total feet of 1.62" ID pipe allowed = 26

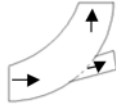
			90Deg Bend with bend radius = pipe diameter	45Deg Bend with bend radius = pipe diameter	Sharp/mitter 90 deg (bend radius= 1/2 pipe D)	Sharp/mitter 45 deg (bend radius= 1/2 pipe D)	Straight pipe	Contraction Pipe ID to 1.62"ID on AT	Total
Equivalent Feet with 1.62" Pipe Diameter	5.3	12	2.3	1.4	9.2	5.8	1	---	--
Equivalent Feet with 1.75" Pipe Diameter	3.6	8	1.8	1.1	6.1	1.6	0.8	2.3	--
Equivalent Feet with 2.0" Pipe Diameter	2.1	4.8	1	0.6	3.7	1	0.4	4.8	--
Example 1 w/ 1.62"		1	3	1			5		25.3
Example 2 w/ 1.62"	1		3	1			12		25.6
Example 3 w/ 1.62"		1			2		5		35.4
Example 4 w/ 1.62"	1		6	2			23		44.9
Example 1 w/ 1.75"		1	3	1			5	1	20.8
Example 2 w/ 1.75"	1		3	1			12	1	22.0
Example 3 w/ 1.75"		1			2		5	1	26.5
Example 4 w/ 1.75"	1		6	2			23	1	37.3
Example 1 w/ 1.75"		1	3	1			5	1	15.2
Example 2 w/ 2.0"	1		3	1			12	1	15.3
Example 3 w/ 2.0"		1			2		5	1	19.0
Example 4 w/ 2.0"		1	6	2			23	1	26.0

Table 5.5

5.5.2 Coolant Supply for Cat Regeneration System Cooling

The head of the Cat Regeneration System must be cooled to prevent component failure. The coolant for the Cat Regeneration System is obtained from the engine coolant system circulated through the Cat Regeneration System head and returned to the engine.

The coolant lines must meet the requirements detailed in the mandatory requirements Section 5.2.6. It is recommended to use a 10 mm minimum line ID for the supply and return coolant lines. The maximum length using the 10 mm hose is 3 meters.

Figure 5.14 below shows the recommended locations for the feed and return lines. Straight Thread O Ring (STOR) fittings 4 (7/16 x 20) are provided on the aftertreatment. Reference SAE J1926 (ISO 11926).

Connection ports are

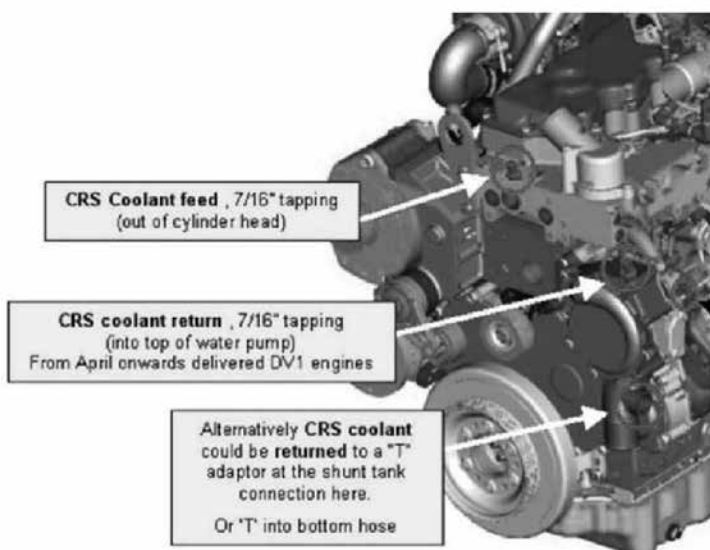


Figure 5.14

5.5.3 Fuel Supply for Cat Regeneration System Pump

Please refer to Chapter 8 — Fuel Systems, for the mandatory requirements for the electric pump required for Cat Regeneration System.

The fuel supply for the Cat Regeneration System is obtained from the engine primary fuel system. The Cat Regeneration System has its own fuel pump that is used only for Cat Regeneration System fuel supply.

Cat Regeneration System Fuel Supply Pump



Figure 5.15

5.6 Service and Maintenance

Please refer to OMM for detailed service requirements.

Access will be required for maintenance of the following:

- The Cat Regeneration System head must have clearance of 96 mm for spark plug service.
- The DPF section will need to be removed during an ash service.
- 200 mm is recommended between the engine valve covers and aftertreatment when mounted above the engine for engine service.

5.7 Thermal Management

Please refer to Chapter 7 — Thermal Management, for detail of the component temperature limits and suggested methods to reduce and control temperatures within the engine bay.

The overall engine-out temperature has not increased from Tier 3 but the addition of the aftertreatment and muffler, if fitted, will increase under hood temperatures due to radiated heat. Ways to dissipate this heat and improve airflow across the engine and aftertreatment will be necessary, particularly over sensitive electronic components.

5.8 Design Considerations for Electrical Components

Please refer to the Electrical and Electronic Application and Installation Manual LEBH0005 for details of the control systems, harnessing, and connection of the aftertreatment.

All aftertreatment contains electronics and subsequent wiring harness connections.

Appendix 5A

EM Flexible Exhaust Installation Kit Components

These details are intended as a guide only and it is recommended that reference is made to the technical drawing for each component before any design work is initiated.

Slip Joint and Cup Joint Details

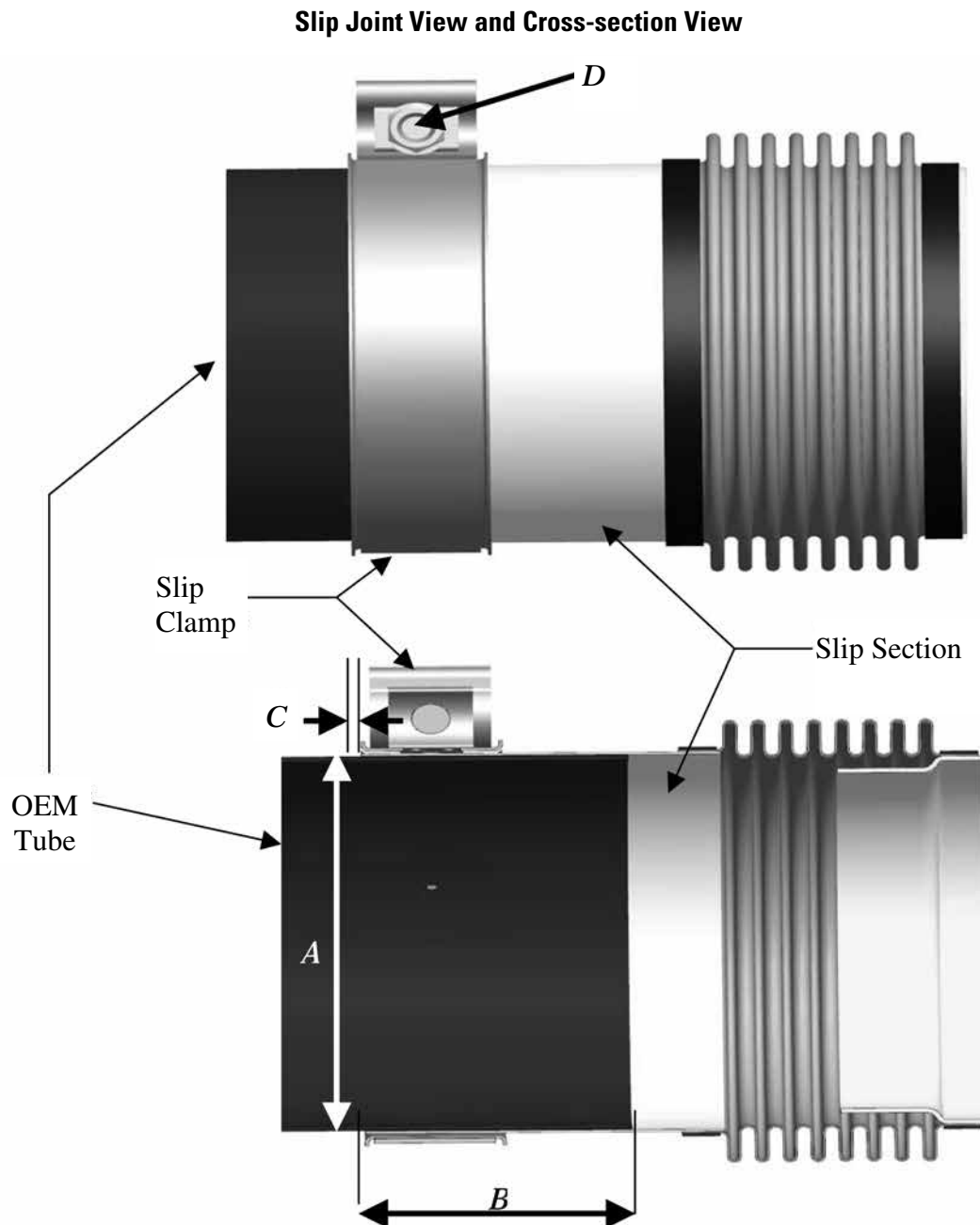


Figure 5.16

Cross reference Table 5.6 and Figure 5.17 below for the slip joint dimension and torque specifications.

Dimension	Description	3-Inch Tube
A	Male Tube OD	76.3 ± 0.3
A2	Length To Hold Tube OD	70 mm
B	Nominal Tube Insertion into Slip with ± 15 Slip	55 mm
B2	Min Insertion into Slip with ± 15 Slip	40 mm
B3	Max Insertion into Slip with ± 15 Slip	70 mm
C	Clamp Position from end of Slip	1.5 ± 1.5
D	Slip Clamp Torque	$55 \pm 8 \text{ N}\cdot\text{m}$ @ 120 rpm max

Table 5.6

Slip Joint Orientation Requirements

The band clamp must be aligned with the slip joints slot as illustrated in Figure 5.17 below for leak-tight integrity.

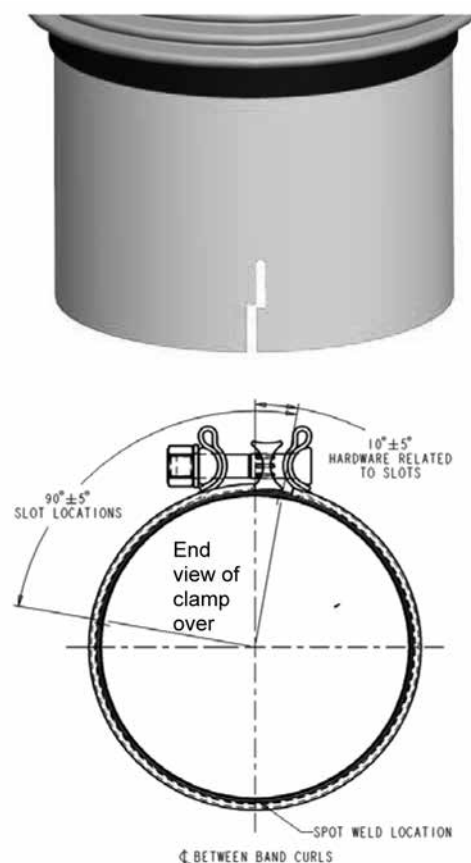


Figure 5.17

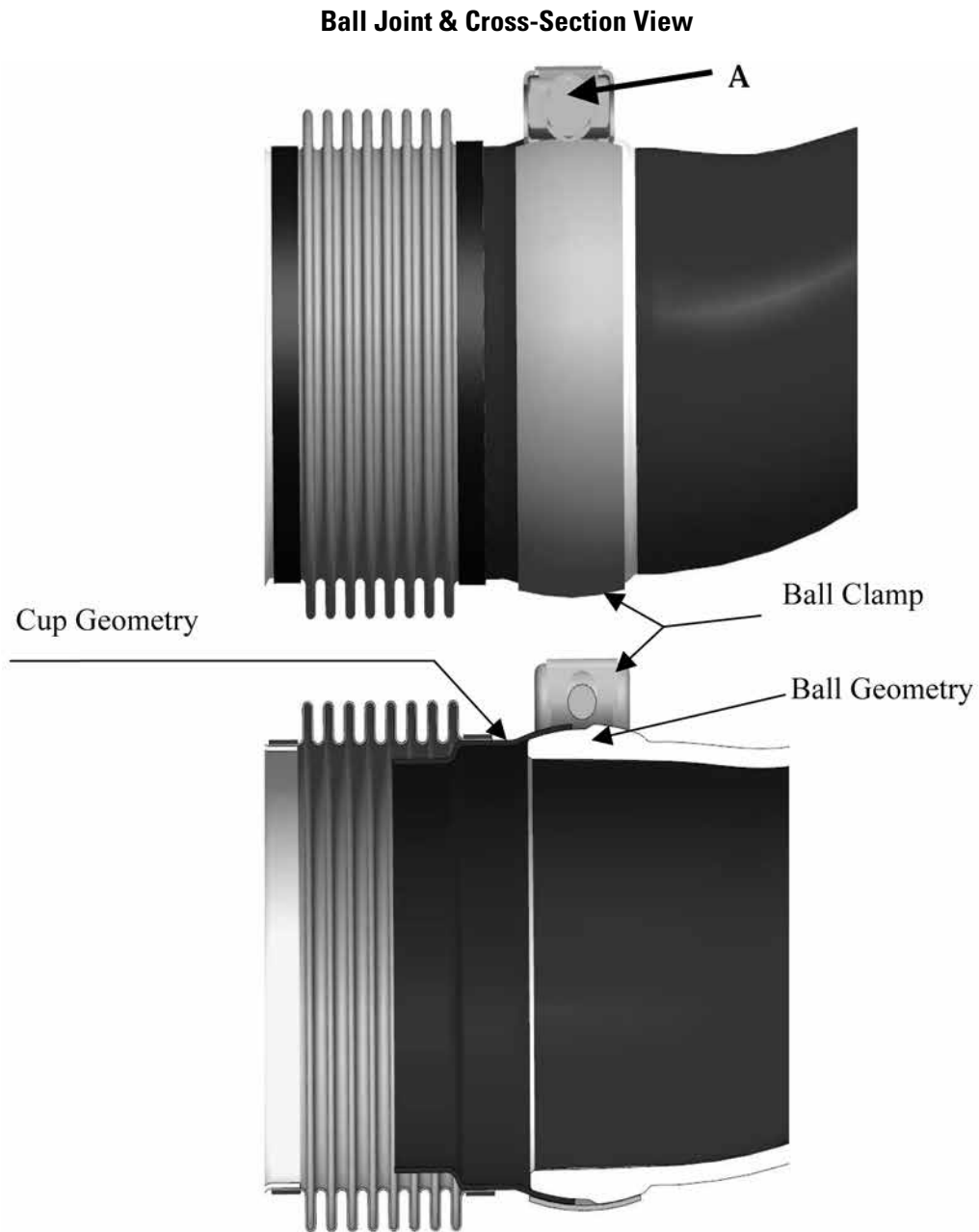


Figure 5.18

Dim.	Ball Clamp Torque Required		
	3" Tube	4" Tube	5" Tube
A	$35 \pm 2 \text{ N}\cdot\text{m}$ @ 350 rpm maximum		

Table 5.7

EM Flexible Exhaust Installation Kit Assembly Procedure

1. Parts Identification (see Figure 5.19.)

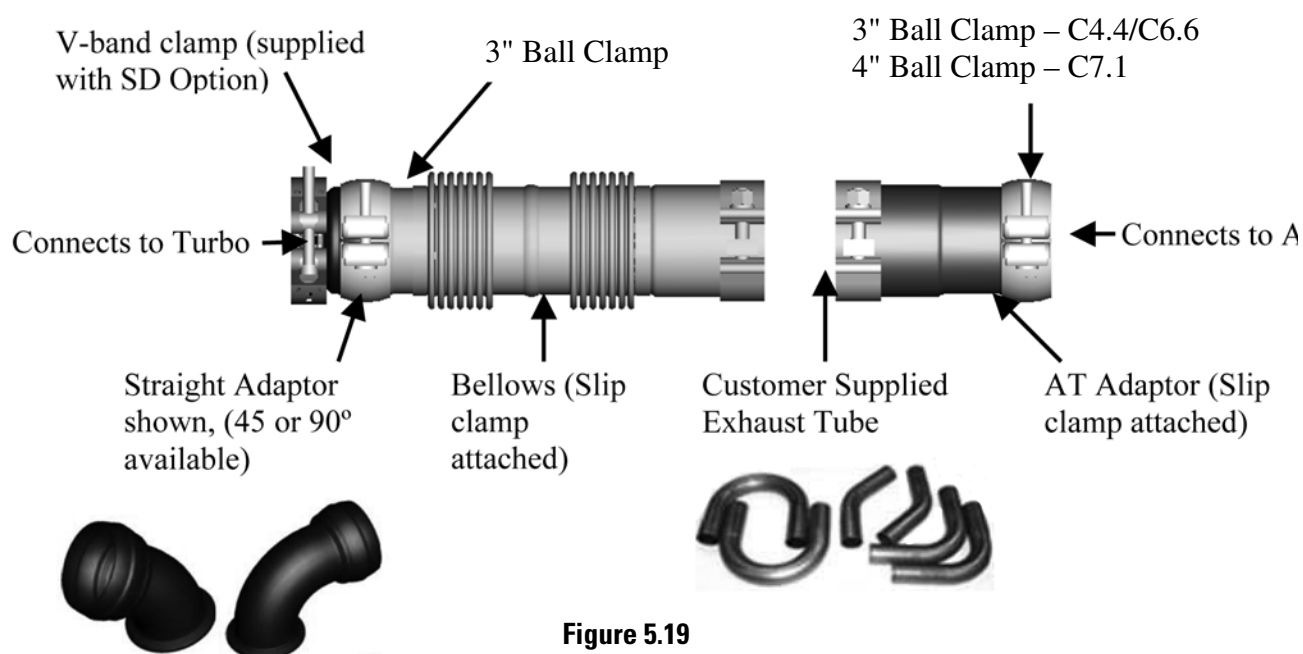


Figure 5.19

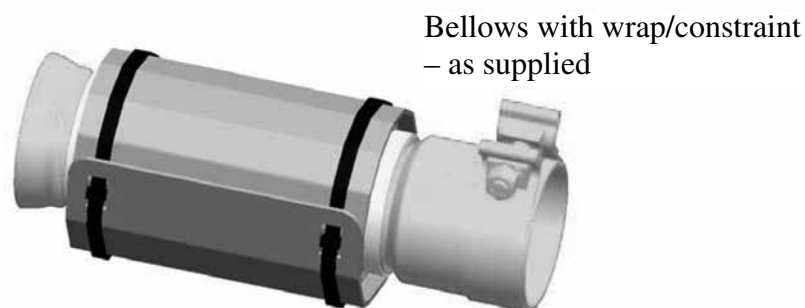


Figure 5.20

2. Joints Identification

All Joints identified below are designed to eliminate tolerance stack-up between engine and aftertreatment.

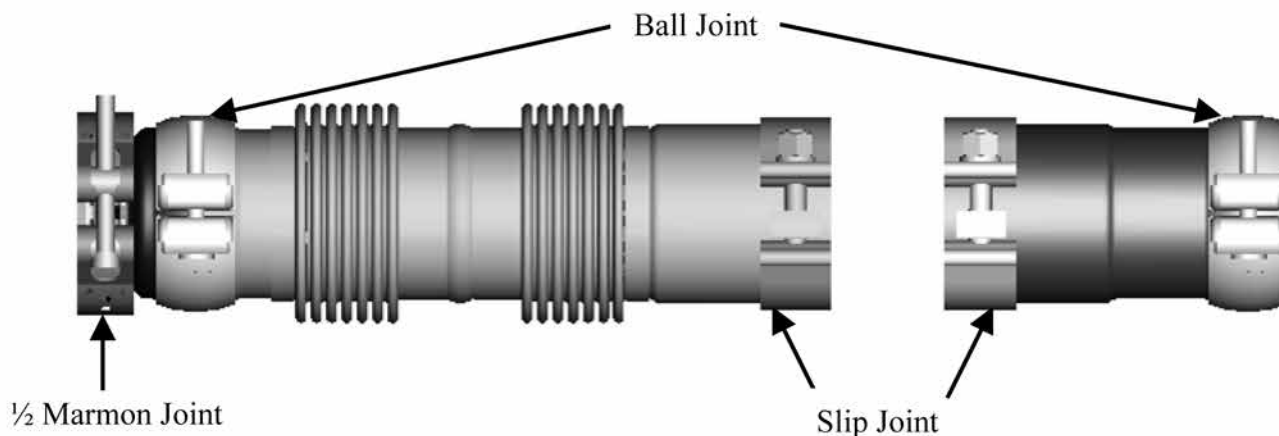


Figure 5.21

3. The bellows wrap is not an alignment tool, it is used to protect the bellows and increase stiffness to assist the installer in assembling the bellows without the use of an alignment tool.



Figure 5.22

4. Insert customer exhaust tube into bellows slip joint (slotted end). Insert other end of customer exhaust tube into aftertreatment adaptor. The tube should slide in without forcing. The final assembly will be referred to as the flexpipe assembly.

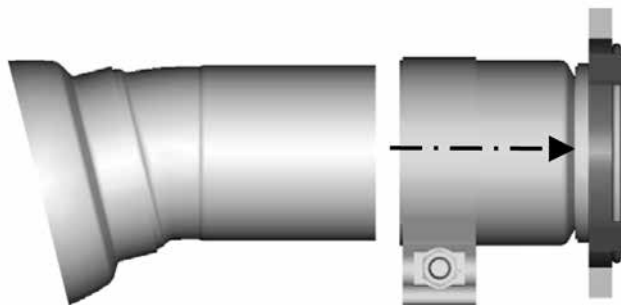


Figure 5.23

Aftertreatment and Exhaust Systems

5. Slide a 3" (C4.4 ACERT/C6.6 ACERT) or 4" (C7.1 ACERT) ball clamp over the aftertreatment adaptor.

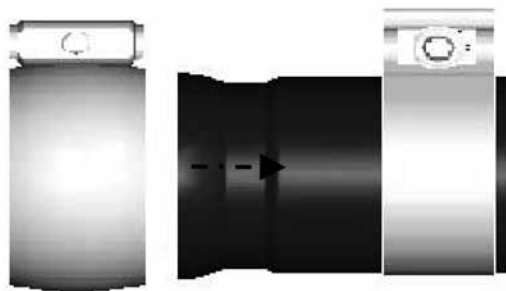


Figure 5.24

6. Fit straight adaptor (or 45°/90°) onto BPV (C4.4 ACERT/C6.6 ACERT) or turbo (C7.1 ACERT) and orient as required. Hand-tighten V-band clamp.

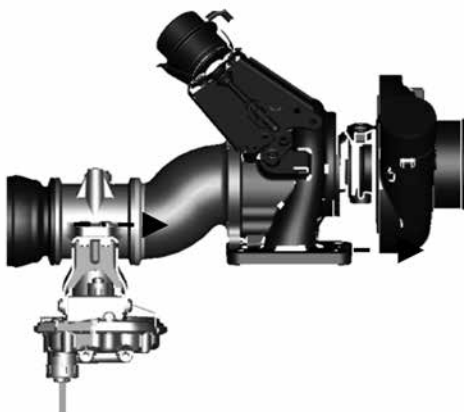


Figure 5.25

7. Slide a 3" ball clamp over the straight adaptor (or 45°/90°).

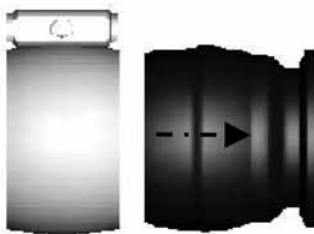


Figure 5.26

8. Offer the flexpipe assembly up to the installation, adjust the slip joint as desired to provide the needed clearance for fit.
9. Align the ball joint at the CEM. Pull or push in on slip joint and adjust until ball joints are butted together tightly on both ends.

10. Verify that the cup of the ball joint does not touch the radius of the ball (see Figure 5.27).



Figure 5.27

11. Slide ball clamp over ball joint, ensuring that the edges of the clamp are equidistant and centered between the radiuses of the ball joint. Pre-tighten the clamp by hand (see Figure 5.28).
12. Align the remaining ball joint and tighten that ball clamp by hand.



Figure 5.28

13. Torque the ball clamp to $35 \pm 2 \text{ N}\cdot\text{m}$. Then torque the second ball clamp. Ensure proper alignment prior to torque.
14. Cut the cable ties without disturbing the bellows assembly and remove the wrap carefully.
15. Ensure that the end of the exhaust tube is not visible in the slot and the minimum insertion depth mark (inked or engraved) cannot be seen.
16. Torque slip clamp to $55 \pm 8 \text{ N}\cdot\text{m}$.

Note: Customer will need to include installation procedure for any unique insulation and/or brace/supports into this process documentation.

6.0 Cooling Systems

6.1 Introduction

All internal combustion engines produce heat as a by-product of combustion and friction.

Within the engine the pistons, valves, and cylinder head are all water-cooled and the lubricating oil temperature is maintained within acceptable limits through the use of a water-cooled, engine-mounted cooler.

The introduction of new technologies, such as aftertreatment, auxiliary emissions control strategies, and two-stage turbocharging, with increased boost temperatures and pressures, has led to significant additional heat loads.

It is essential to manage both the heat to coolant and the induction air temperature to maintain engine life, performance, durability, and emissions compliance for the life of the engine. The integration between engine and machine is critical.

In all cases a system must be designed to maintain engine temperatures within the specified limits under the most extreme ambient conditions and operation that the machine will encounter.

This chapter outlines the mandatory requirements and design considerations for engine cooling and charge air cooling systems.

6.2 Cooling System Mandatory Requirements

All emission-related installation instructions are highlighted by the **EM** symbol.

Failing to follow these instructions when installing a certified engine in a piece of nonroad equipment violates federal law (40 CFR 1068.105(b)), subject to fines or other penalties as described in the Clean Air Act.

6.2.1 General Requirements

- The system must have a pressure cap that maintains system pressure within the range of 0.90 to 1.1 bar.
- The total external restriction across the cooling system (engine water outlet to water pump inlet) must not exceed 35 kPa.
- The engine must be run on a 50:50 water/ethylene glycol (antifreeze) mix.
- If water and a Supplemental Coolant Additive (SCA) is used, the maximum top tank temperature must be reduced to 100°C.
- Coolant recovery systems are not approved.
- Coolant should only be taken from the engine using the approved connections in the authorized locations (cab heater, compressor, and aftertreatment module).

6.2.2 Top Tank Temperature

- **EM For all applications — unrestricted use**

The maximum top tank temperature must not exceed 108°C.

- **EM Restricted use only — requires applications approval**

The maximum top tank temperature must not exceed 112°C*.

- **EM** This must be tested in accordance with the defined test procedure ref TPD1746.

- The water pump inlet pressure must be maintained at or above the threshold shown on the graph in Figure 6.1, e.g., 1.45 bar (absolute) @103°C water pump inlet temperature.
- *The increased top tank temperature may only be used for approved ratings and applications that meet strict conditions. Please contact your application engineer for further information.

6.2.3 Hot Shutdown Mandatory Requirements

- The total accumulative discharge on repeated hot shutdown must not exceed 10% of the total system volume.
- The water pump inlet pressure must be maintained above the threshold (reference Figure 6.1) for four successive hot shutdowns.
- All tests must be conducted in accordance with the relevant test procedure ref TPD1746.

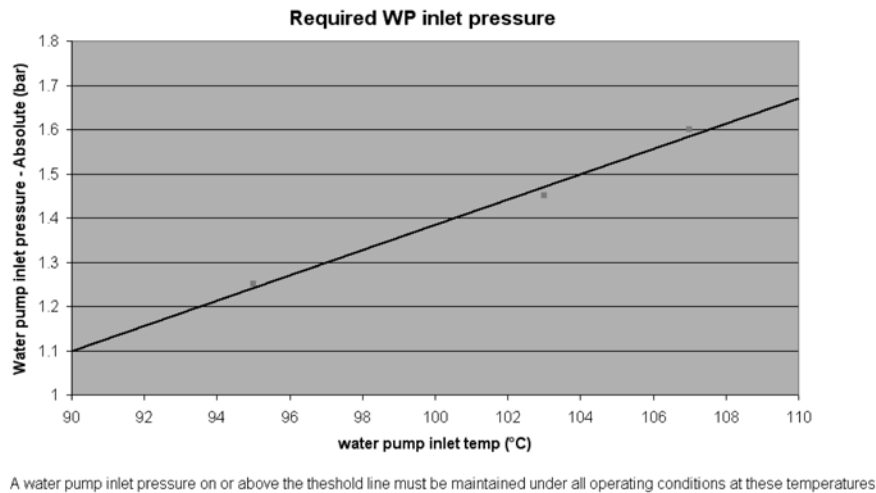


Figure 6.1

6.2.4 Auxiliary Header (Shunt) Tank and Radiator Top Tank Design

- The tank volume should be a minimum of 16% of the total system volume. The maximum volume should not be exceeded.
- The coolant expansion volume must be no less than 8% of the total cooling system volume.
- The coolant level must be clearly visible on the side of the tank, or a coolant level sensor with appropriate indicator must be used.
- The tank should be baffled to slow the vent flow and aid deaeration.
- The header/shunt tank should be the highest point in the system. If this is not possible, this point should be vented separately.
- The pressure cap must be located in an area where air/gas is present under all tilt conditions.
- There must be sufficient volume in the shunt tank to ensure that the fill/shunt line is submerged in coolant at all machine-operating conditions including slew or gradients.

6.2.5 Shunt/Fill Line Design

- The fill line must be no less than 25 mm inside diameter.
- The fill line must continuously run downhill and contain no dips or sags that may hinder venting.

6.2.6 Venting

- The cooling system must adequately vent air during cooling system fill and be capable of filling at a rate of between 6 and of 10 L/min (the system should not be allowed to false fill, i.e., the filling must be continuous with no air locks resulting in the coolant level remaining static).
- A complete fill on level ground must be achieved.
- Flow through the vent lines should not exceed 5% of full systems flow. To achieve this, it is recommended that the vent lines are no greater than or are restricted to 6 mm.
- Vent lines must terminate in the tank above the normal coolant level under all tilt conditions.
- Vent lines must include no dips or sags and must continuously run upwards.
- If more than one vent line is used, these must terminate in separate connections in the tank. They must not be tied together.
- For shunt tank arrangements.
- The radiator must be vented.
- The highest point in the system must be vented.
- The NRS cooler will not drain through the engine and must be drained using its own drain port.

6.2.7 Coolant Hoses

- Coolant hose material specification SAE J20R4.
- Hoses using internal reinforcement are not permitted. Reinforcement must be either external or fully integrated into the structure of the hose.
- All spigots must be lipped.

6.2.8 Cab Heaters

- The maximum internal diameter for cab heater hoses is as follows:
 - C4.4 ACERT, 12 mm maximum I.D.
 - 1206E, 12 mm maximum I.D.

6.3 Mandatory Installation Requirements — Fans

Where Caterpillar supplied fans are being used, the minimum clearance to the front and rear edges of the fan blades is 25 mm; however it is recommended to have a clearance of at least one projected blade width to obtain optimum noise and airflow performance. Where a torsional damper is fitted to the front of the engine, clearance of the fan blade to the damper must be 50 mm.

6.4 Charge Cooling System (ATAAC) Mandatory Requirements

6.4.1 System Limitations

- **EM** The maximum pressure drop across the charge air cooler and pipe work must not exceed 10 kPa at Full Load Rated Speed (FLRS). Measured from turbo compressor outlet to the NOx Reduction System (NRS) inlet spigot.
- **EM** The charge cooler outlet temperature must be between 35°C and 55°C in a 25°C ambient. In ambient temperatures above 25°C the minimum charge cooler outlet temperature must be 35°C and the maximum must not exceed 30°C Rise Over Ambient (ROA).
 - These temperatures must be measured at the engine air inlet connection with the engine at FLRS and must be tested in accordance with the TPD1746.
- **EM** The maximum permitted charge cooler outlet temperature measured at the engine air inlet connection must not exceed 55°C in a 25°C ambient or below, @ FLRS. In ambient temperatures above 25°C it must not exceed 30°C ROA at FLRS.
- **EM** All testing must be conducted in accordance with the defined test procedure referenced in Chapter 16.
- **EM** If a variable speed or demand fan option is selected, the fan must be full speed/flow at the following conditions:
 - Charge air cooler outlet temperature: 55°C.
 - Maximum permitted engine coolant outlet temperature: 108°C or 112°C if permitted.

6.4.2 Pipe Work

- The ATACC pipe work and associated hoses must be designed to operate under the following operating temperature and pressure conditions.

Engine Type	Turbo	Max. Working Temp (°C)	Max. Working Pressure (kPag)
C4.4 ACERT & C6.6 ACERT	Single Stage TA	220	220
C4.4 ACERT & C7.1 ACERT	2 Stage TTA	250*	330

Table 1

- Hose connections should have a minimum burst pressure of 689 kPa at 316°C (TBC, guidance based on historical data for Cat engines).
- All pipe work and hoses must meet Caterpillar cleanliness specification TBC.
- Hoses must be capable of withstanding a negative pressure of 5 kPa to prevent collapse.
- Hoses should be designed to meet a minimum temperature inline with the minimum ambient temperature for the machine specification as sold.
- All pipe work must allow relative motion between the cooler core and engine, allow for thermal expansion and contraction and be capable of withstanding flow and pressure pulsations.
- All pipe work must be adequately supported so that no stress is induced on the compressor outlet connection.
- The internal bore of the intake pipe must be corrosion resistant.
- All pipe work must include full 360° hose beads.
- Constant torque retention clamps must be used.
- Hoses using internal reinforcement are not permitted. Reinforcement must be either external or fully integrated into the structure of the hose.

6.4.3 Active Regeneration System Air Feed (C7.1 ACERT only)

EM The active regeneration system air feed needs to be pressurized and must be taken from the turbo compressor outlet. Refer to Chapter 5 — Aftertreatment and Exhaust Systems, for further information on the requirements of the engine to Cat Regeneration System interface.

*For applications with high underbonnet temperatures it may be necessary to ensure that the maximum temperature limit of the charge air hose is not exceeded.

6.5 Cooling System Fundamentals

The heat energy released by the combustion of fuel in a diesel engine is distributed approximately in the proportions shown below. These proportions may be representative of full load rated speed conditions but will vary according to machine operation and duty cycle.

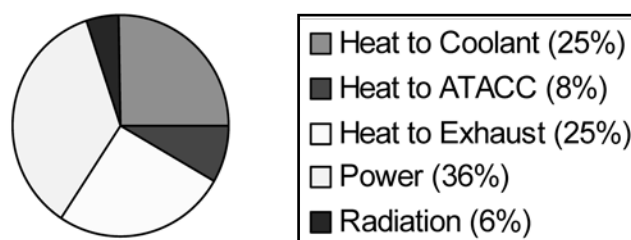


Figure 6.2

The function of the cooling system is to dissipate to the environment that part of the heat energy which is not converted into power or passed directly to atmosphere by the exhaust gases or by radiation from the engine surfaces.

In addition, depending on the application type and design, it may also be required to dissipate heat rejected from the transmission, water-cooled exhaust manifolds, and, for Tier 4 Interim engines, there is also a significant contribution of heat from the aftertreatment systems. Management of this additional heat load is covered in Chapter 7 — Under Hood Thermal Management, which outlines methods to help control under hood temperatures.

6.5.1 Engine Cooling Circuit

The basic components of an engine cooling system are the coolant, water pump, engine oil cooler, thermostat, radiator fan, and the radiator/s.

In operation, the water pump pushes coolant through the engine oil cooler and into the cylinder block. The coolant then flows through the cylinder block and into the cylinder head where it flows to the hot areas of the cylinder head. After flowing through the cylinder head the coolant goes into the thermostat housing. When the engine is cold, the thermostat is closed and the coolant bypasses the radiator and circulates only around the engine and cab heater circuit. As the temperature increases, the thermostat opens and the coolant flow to the radiator increases along with the pressure in the header tank until the thermostat is fully open.

The thermostat maintains the correct engine temperature. The amount it opens and the percent of coolant flow to the radiator depends on the load on the engine and the outside air temperature.

The fan pushes or pulls air through the radiator and around the tubes that extend from the top to the bottom of the radiator. When the hot coolant goes through the tubes in the radiator, the flow of air around the tubes lowers the temperature of the coolant. The coolant then flows back through the water pump.

Coolant expands as it is heated. Expansion tanks are used to contain the increased volume and provide header pressure through the use of an air space.

A pressurized cooling system allows the coolant to circulate at a higher temperature without boiling and heat is transferred more rapidly due to the greater coolant and air temperature difference, effectively reducing the size of the required radiator core.

6.5.2 Coolant Temperature Curves

The curves below show the boiling point of water and 50:50 water glycol mix against altitude, for an unpressurized system and for systems using 7 and 14 psi pressure caps.

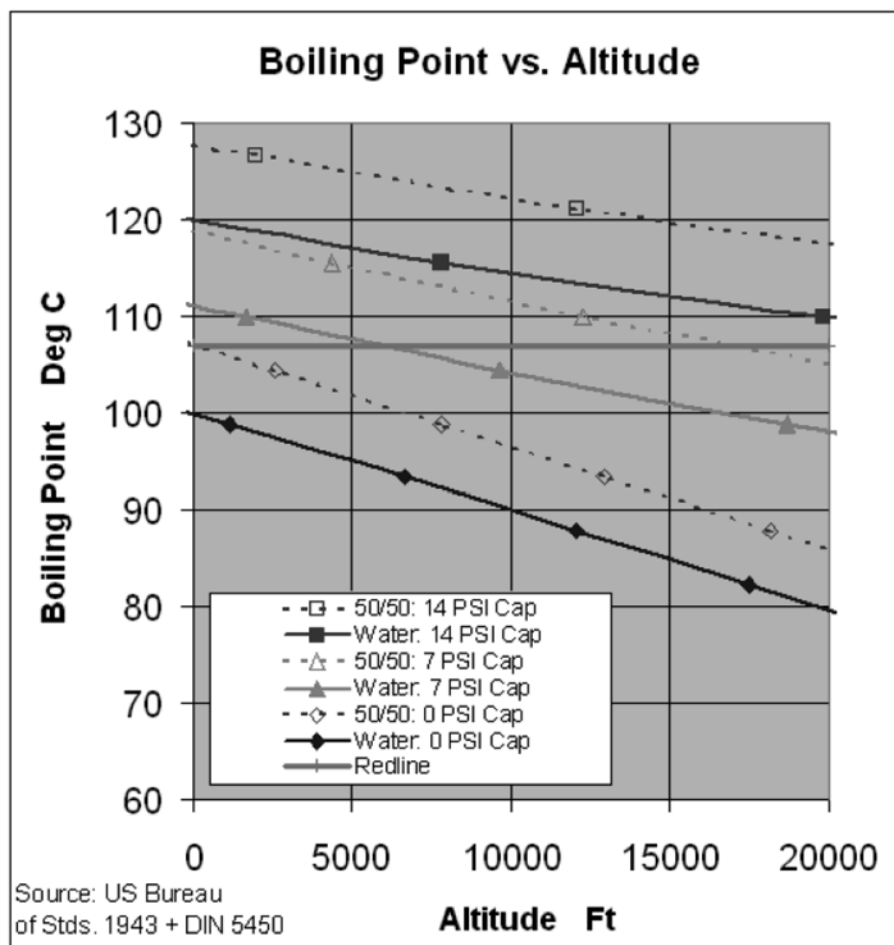


Figure 6.3

6.5.3 Lubricating Oil Temperatures

The engine oil temperature is directly related to coolant temperature through the use of a water-cooled engine-mounted oil cooler. It is also related to engine compartment temperature and airflow across the sump.

The normal maximum permissible lubricating oil temperature, measured in the main oil pressure rail or at the oil filter head, is 125°C. If the engine never operates at its maximum speed for more than one hour at a time, the maximum permissible oil temperature may be increased to 135°C. The correct oil temperature is essential to maintain a protective film on the bearing surfaces and ensure the engine's integrity.

For further information please refer to Chapter 9 — Lubrication Systems.

6.5.4 ATAAC System

In order to meet Tier 4 Interim emission standards all engines are now turbocharged and charge air-cooled. The purpose of an air-to-air aftercooler arrangement is to improve fuel consumption and lower emissions (NOx) to meet government regulations, and in some cases to facilitate increased horsepower.

The success of this cooling system arrangement is dependent on the level of reduction in compressor outlet temperatures and maintaining the boost pressure in the system.

Failure to meet the engine air inlet connection and/or system pressure restriction limits will result in emissions non-compliance and the installation cannot be approved by the applications engineering team.

It is necessary to reduce the temperature of the charge air under the most severe operating conditions to a temperature relatively close to ambient air (normally in the range of 25°C to 30°C above ambient). It is therefore essential that the supply of cooling air to the charge cooler is as close to ambient air temperatures as possible.

6.6 Cooling System Design Considerations

6.6.1 Coolant Filling, Venting, and Deaeration

A well designed cooling system will vent during fill, allow continuous deaeration of the coolant during operation and maintain a net positive suction head at the water pump inlet.

Filling

It is of primary importance that the system be designed to ensure that complete filling of the engine, radiator, and associated pipe work can be carried out without air being trapped at any point in the system.

Trapped air may result in localized boiling, damage to the water pump seal, reduced water pump flow, and in severe cases complete loss of coolant flow. Expansion of the air at working temperature can also result in excessive coolant loss.

Auxiliary circuits (e.g., cab heaters) should be designed to fill during routine filling of the total cooling system. This is helped by ensuring sufficient pressure differential across the circuit (supply to return line) and avoiding undulations and excessively long pipe runs.

Care should be taken to ensure that the engine is horizontal when it is being filled.

Deaeration

In addition to a satisfactory fill the system must incorporate features within the design, which will permit continuous deaeration, i.e., removal of entrained air, from the coolant while running. A poorly performing system will often have to go through one or more start-up and shutdown cycles to purge enough air from the coolant to achieve acceptable coolant flow.

High-mounted cab heaters or other system components are frequently problematic from both a fill and deaeration perspective. It is essential that the system be capable of deaerating quickly and completely during machine operation. If this is not possible, it may be necessary to provide a vent valve or plug at the highest point. Ideally the system should be designed to not need this valve, as there is no guarantee that it will be used in service.

Cause of Aeration

Aeration of the coolant may take place for the following reasons:

- It is difficult in practice to ensure that all air is expelled from the system during filling.
- In systems using an open (non-baffled) radiator top tank, the high velocity of the coolant entering the tank causes turbulence and a tendency for air to be drawn into the tubes together with the coolant. It is for this reason that this system will not be used for Tier 4 Interim engines. All radiator top tanks must be baffled.
- It is possible for combustion gases to become entrained in the coolant in the event of marginal cylinder head gasket sealing.

Effects of Aeration

Aeration of the coolant is likely to result in the following:

- Possibility of local boiling and high metal temperatures.
- Excessive coolant loss on hot shutdown.
- Rapid breakdown of the water pump seal leading to poor performance and increased leakage.
- Deterioration in water pump performance, resulting in a reduction in flow rate and an adverse effect on cooling. In severe cases, a complete breakdown in coolant flow may occur.

Various methods can be employed to provide system deaeration; the preferred method is to use an auxiliary header tank. This system along with some of the more commonly used alternatives is discussed in the Section 6.6.2.

6.6.2 Coolant System Arrangements

6.6.2.1 Auxiliary Header (Shunt)

An auxiliary header (shunt) tank provides positive deaeration and is the preferred cooling system arrangement.

The coolant tank is completely separate from the radiator and mounted independently above the engine. Approximately 5% of the total coolant flow is bypassed via the vent line to the tank, a relatively non-turbulent area, where the air separates from the coolant. Coolant is then returned via the fill line into the radiator bottom hose.

Unlike other arrangements this can be used for radiators mounted both above and below the engine as shown in the diagrams below:

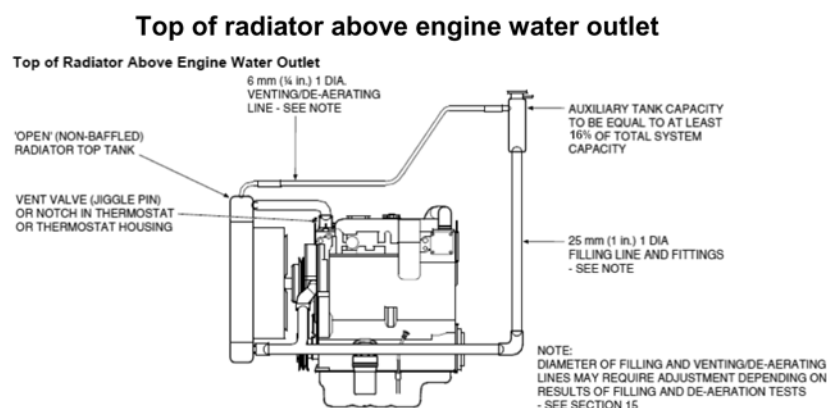


Figure 6.4

Venting

Air is vented from the engine (through the jiggle pins) and radiator through a single bleed line off the highest point of the radiator to the auxiliary tank.

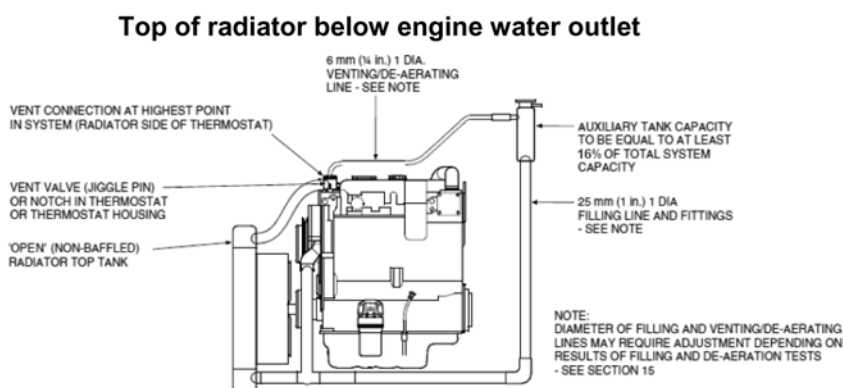


Figure 6.5

When designing the cooling system arrangement the following recommendations should be considered:

- The fill line connection should be located as close as possible to the water pump inlet to maximize water pump inlet pressure. The connection on the water pump inlet should be used where possible. Alternatively, the fill line should be routed directly into the radiator bottom hose.

Sometimes this tank can be positioned on top of or incorporated into the radiator design as shown below.

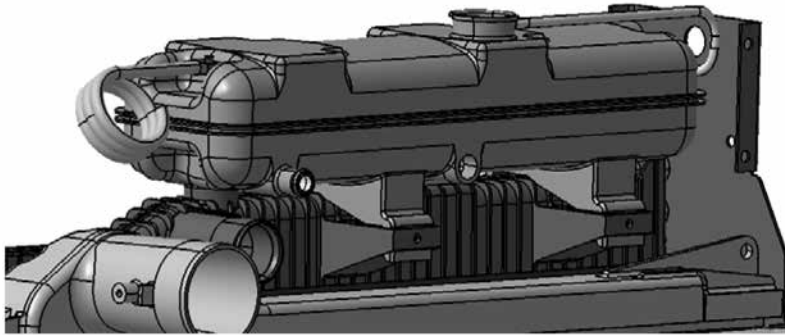


Figure 6.6

Advantages:

- Positive deaerating capability.
- Better net positive suction head at the water pump inlet
- Better gradeability
- Good drawdown capacity
- No risk of leakage from the tank into the core
- Reduced radiator height
- Can be positioned for good service access
- The use of composite tanks can provide for a visible coolant level indication

Disadvantages:

- Packaging requirements
- A separate fill line often involves complex routing, which can increase opportunities for trapped air. This can result in poor filling capability.
- Increased potential for leak paths

For this type of system to function successfully the design and position of the header tank, fill and vent lines needs to be considered very carefully. This is covered in the top tank design Section 6.6.3.

6.6.2.2 Integrated Radiator Top/Header Tank

Down-flow radiators are commonly specified with an integrated radiator top tank, particularly when tall, narrow cooling systems are required.

The radiator top tank serves as both the coolant reservoir and the deaeration space and, unlike a remote arrangement, the tank sees the full flow of coolant through it. Consequently, creating a quiescent area for deaeration can be difficult so incorporating design features to reduce flow velocity and minimize turbulence should be employed.

The best way to assist deaeration and prevent recirculation of entrained air is to incorporate a completely sealed horizontal baffle plate (see Figure 6.7). This essentially divides the header tank in two, the coolant flows into the lower half and a standpipe or vent line connects the lower to the upper half, which is used for expansion and deaeration. A separate fill line is used to feed coolant directly into the radiator bottom hose. The design requirements for this tank are very similar to those required for the auxiliary tank.

It is more common, however, for the radiator tank to incorporate a horizontal baffle that is not sealed and does not divide the tank into two separate compartments. (See Figure 6.7.) Again the coolant enters the tank below the baffle but this design allows a small proportion of coolant to flow around the sides of the baffle and through small holes within it, into a quiescent area to deaerate. As there is no permanent barrier between the radiator tubes and the deaeration space, this design is not as robust and more likely to re-circulate entrained air.

In some instances the tank design does not incorporate any baffles. As there are no positive deaerating features this design is non-preferred and not approved for use.

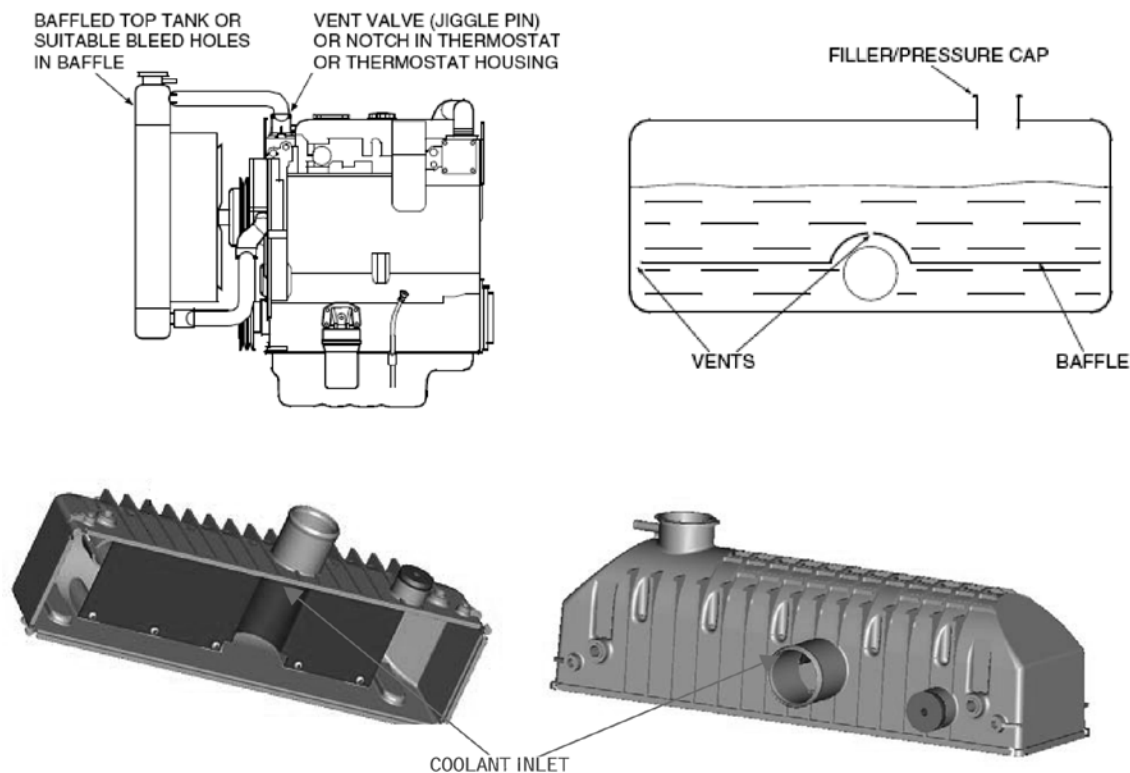


Figure 6.7

A radiator top tank should only be used where:

- The top tank is the highest point within the cooling system
- The bottom of the tank is higher than the engine water outlet

Advantages

- Simple system that is less restrictive during filling.
- There is no need for an external radiator vent.

Disadvantages

- Limited deaeration and expansion space
- Fails to deaerate properly
- Risk of recirculation of entrained air

6.6.2.3 Coolant Recovery System

Coolant recovery systems, also known as coolant overflow or “burp bottles” are not approved for use as they are not considered to provide a reliable and robust system for industrial/non-road equipment.

A coolant recovery system is often used when there is insufficient or no expansion volume in the radiator top tank.

As the coolant expands it is forced past a twin valve pressure cap via a tube to a remote overflow tank. As the coolant in the engine/radiator cools it contracts and creates a vacuum which draws the expelled coolant from the overflow tank back into the radiator. This cycle repeats each time the engine operates.

There are several significant disadvantages with this type of coolant system that render it unsuitable. This type of system is really only required where the design of the top tank/expansion tank is incorrect.

The advantages and disadvantages are listed below:

Advantages

- Allows a smaller radiator header tank if space is restricted.

Disadvantages

- The radiators used in such systems typically have little deaeration capability.
- The remote overflow tank can provide a false indication of coolant level as it bears no indication of actual coolant level in the radiator.
- Any leaks between the radiator core and coolant recovery system will render the system inoperable. As the coolant contracts and creates a vacuum, the presence of a leak will result in only air being drawn back into the radiator instead of coolant. These leaks are difficult to detect, as it is possible for the leak not to result in any coolant spillage.

6.6.3 Coolant Top Tank Design

It is essential that both the auxiliary header (shunt) tank and the radiator top tank should be of adequate capacity to ensure that a satisfactory coolant level will be maintained under all conditions and that sufficient header pressure is generated by compression of the air space.

The illustration in Figure 6.8 shows how the coolant tank should be sized with the percentage volume which should be allowed for deaeration, expansion, and working volume respectively along with critical design features that should be incorporated.

For mandatory design requirements for this tank please refer to Section 6.2.4.

Auxiliary Header (Shunt) Tank

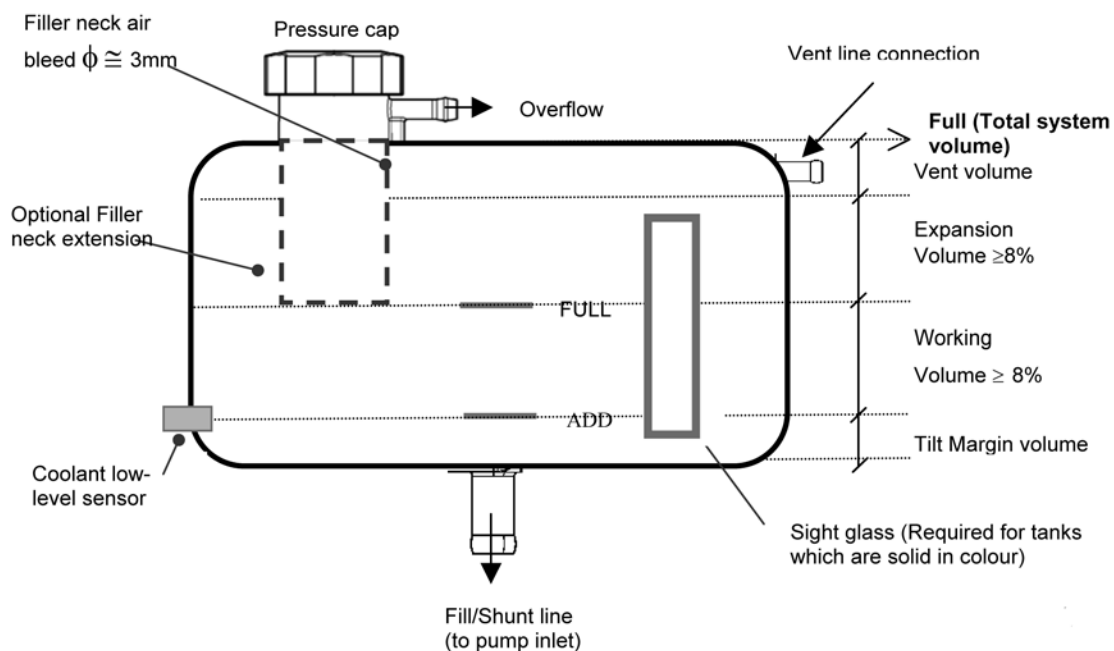


Figure 6.8

It is recommended that this tank is clear, or at least translucent, to provide a visible indication of the coolant level. If this is not possible, a slotted sight glass should be incorporated into the design. This should stretch from the low to the full level.

In all cases it is recommended that a low-level sensor is included to automatically indicate coolant loss to the operator.

If the tank capacity is too great then the pressure in the system will not build correctly and the water pump inlet pressure will not be maintained at a high enough level to pass the installation appraisal.

Total System Volume

The volume of coolant required to fill a completely drained system (engine, radiator, transmission, and other cooler cores, heater core, shunt/auxiliary tank, all coolant lines, etc.) to full.

Full

When the cooling system is completely full with the filler neck ready to overflow.

Tilt Margin Volume

The minimum volume of coolant required in the tank such that fill line is not exposed to air when the machine is tilted in application

Low Level

The tilt margin volume level when machine is on level ground defines the low level.

Sight Glass

The sight glass should be incorporated so that it provides a good indication of the coolant level in all conditions. It is recommended that a slotted sight glass, covering the maximum and minimum levels, be used. If only a small sight glass is used it can be hard to tell if it is coolant or air behind as no comparison in colouration can be made.

Working Volume

The volume between low-level mark and the high level should be 8% of the total system volume.

High Level or FULL Mark

This is defined by the working volume. The bottom of an extended filler neck or a line or mark on the tank normally indicates this level.

Expansion Volume

The volume above the high level mark should be 8% of total system volume. Plus an additional X% for venting volume (suggest 4% TBC).

Deaeration/Vent Volume

The volume above expanded volume until full. The vent line ports are located in this volume.

Fill Line

This should be designed to meet the mandatory requirements in Section 6.2.5. It is recommended that the fill line connection is taken from the bottom of the tank, not the side, to aid fill. It is best located near to the center of the tank to reduce the risk of air entering the shunt line under machine tilt/slew conditions. The fill line should be located as close as possible to the water pump inlet to maximize water pump inlet pressure. It is recommended that the connection on the water pump inlet is used or the fill line is routed directly into the radiator bottom hose.

Pressure Cap

The pressure cap should be designed/selected to match mandatory requirements in Section 6.2.1. The use of a separate filler and pressure cap is advised to reduce pressure cap degradation and maintain the integrity of the closed system.

Radiator Top Tanks

The design of the radiator header tank should follow the guidelines outlined in the auxiliary header tank design section above. In addition to this the following guidelines should be observed.

- The baffle should be placed a minimum of 32 mm above the top of the radiator tubes.
- The water inlet connection from the engine must be located below the baffle.

6.6.4 Charge Coolers

Air Return to the Engine

It is recommended that the cooled air be returned to the engine from the top of the cooler to prevent the risk of water entering the engine as a result of a condensation build-up. If this is not possible then a drain should be incorporated into the cooler design to allow periodic removal of any condensation.

Effect of the Induction System on Design

Any rise in induction temperature above ambient adds additional, unnecessary heat that needs to be reduced by the charge air cooler.

Maintaining any given inlet manifold temperature by cooling the charge air is made more difficult if the air entering the turbocharger is above the ambient temperature. Any increase in air temperature en-route to the turbocharger must be compensated by a corresponding increase in the temperature reduction through the charge cooler.

To eliminate or at least minimize this requirement the air cleaner must draw air from outside the engine compartment at a point away from any heated air such as that leaving the radiator or near the exhaust outlet. The air cleaner itself should be mounted away from and if necessary shielded from heat sources such as exhaust manifold, pipes or silencers, and ducting on both the intake and outlet of the air cleaner should be routed away from any heat source.

6.6.5 Cooling Airflow Arrangements

6.6.5.1 Parallel Charge Cooler and Radiator

As both the charge air cooler and coolant radiator are fed with the cool air available, this arrangement requires the lowest capacity coolant radiator possible, and potentially offers a lower-cost solution than the series arrangement. However this arrangement may require a higher total air throughput than the series type in order to maintain adequate cooling air velocity through the radiator matrices. If auxiliary coolers, for transmission or air conditioning are to be fitted they should not be mounted in front of the charge cooler for the reasons stated previously.

Care should be taken to avoid large restriction differences across the area covered by the fan. This can cause fan blade stresses being imbalanced and lead to catastrophic blade failures.

6.6.5.2 Series-Mounted Charge Cooler and Radiator

This arrangement is very useful when installing a charge cooler into a machine previously powered by a non-charge-cooled engine. A coolant radiator of similar cross section area is normally required, possibly with a reduced core thickness resulting from the reduced heat rejected to the coolant.

Note: In calculating the radiator requirements, the incoming air will be at a temperature significantly above the ambient as a result of being heated as it passes through the charge cooler matrix.

Experience has shown that the face area of the charge cooler needs to be the same as or smaller than that of the coolant radiator. If it is determined that a reduced core area is possible, care is required to ensure that the header tanks of the charge cooler do not obstruct the cooling air input to the coolant radiator. Suggested routes to avoid this problem include:

- Use of a down-flow configuration for one cooler and cross-flow for the other cooler so that the tanks of the radiator do not obstruct the core of the other cooler.
- Separating the total cores by a distance of area 100 mm, and possibly allowing some cooling air to enter the area between the cores, as it is a characteristic of some charge coolers that optimum efficiency is reached with a lower cooling air velocity than is required by a coolant radiator.

6.6.5.3 Direction of Airflow

Cooling airflow may be in either direction through the radiator cores, depending on the type of cooling fan used. It is important however that consideration should be given to the following factors when deciding on the most suitable flow direction for a particular installation:

When possible, the direction of flow should be such that air temperature at entry to the radiator is as close as possible to ambient temperature. In general, this requirement will be met most satisfactorily by the use of a “puller,” i.e., suction-type fan, since in the case of a “pusher” (blower)-type fan, pre-heating of the cooling air will take place due to passage over the engine surfaces. In mobile applications with significant forward velocity, the flow direction should be chosen to take advantage of the resulting “ram” effect.

Cooling fan efficiency and noise output is greatly affected by flow conditions at the fan inlet. In general, less obstructed flow conditions and improved inlet conditions will be achieved with a puller-type fan, since this is not subjected to the obstruction imposed by the engine in the case of a pusher fan installation.

Although the use of a puller (suction) fan will in general result in a more efficient cooling system, the following factors should be taken into account:

- In all cases the charge cooler should receive the coolest air
- In the case of enclosed installations, under hood/engine enclosure air temperature will be relatively high. For certain applications, e.g., earthmoving and construction machinery, operating in high sand/dust environments, the use of a puller fan may be unsuitable, due to the likelihood of radiator plugging and sand blasting.
- In a number of applications a puller fan is not suitable, since due to the layout of the machine, the operator would be subjected to high temperatures from the warm air leaving the radiator.
- In rear engine applications with significant forward speed, the ram effect due to forward motion may oppose the flow of cooling air from a puller fan (if the engine faces toward the rear), and careful ducting of the cooling air flow is necessary in order to prevent possible adverse effects.

6.6.5.4 Fan Cowls

In all installations, the use of an efficient fan cowl is essential, since this will enable the most effective use to be made of the available core area, and will also assist in the prevention of recirculation of cooling air.

The use of an efficient cowl will, in many cases, make it possible to use a lower cooling air flow rate, while still achieving satisfactory cooling, and so reduce the cooling fan power requirement and noise emission.

The various types of fan cowl are illustrated below.

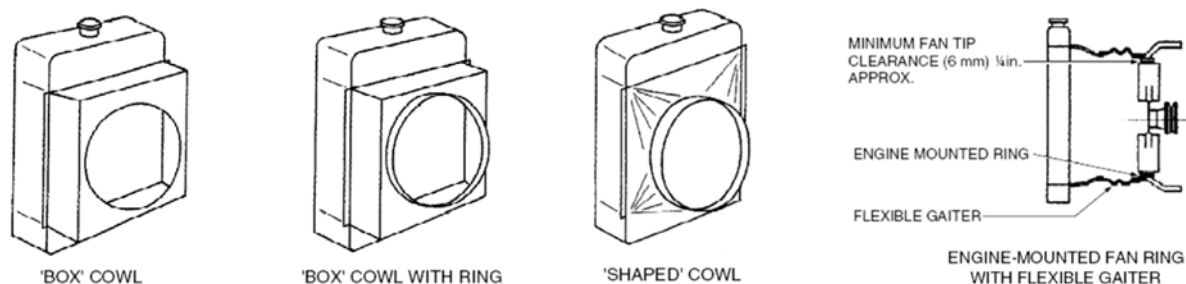


Figure 6.9

Type 1 — Box Cowl

This is the simplest, and least expensive type of cowl, and is suitable for general use in installations where the system restriction (and hence fan working pressure) is relatively low. Normally, this will apply to installations where radiator pressure drop is low, due to the use of a low number of tube rows and moderate cooling air flow rate.

Type 2 and 3 — Cowling with Ring Incorporated

In cases where the system pressure drop is higher, as in installations using radiator cores with a higher number of tube rows, and possibly also close fin spacing, greater efficiency will be achieved by the incorporation of a fan ring on the cowl, as shown. This assists in the prevention of air leakage at the fan tip and allows the fan to build up the required working pressure. The width of the ring should be equal to approximately half the projected fan blade width.

In general, optimum results will be obtained with the shaped cowl design (3) due to the improved flow distribution over the radiator core, but this type is more expensive to produce.

Type 4 — Flexible Gaiters

In installations where there is considerable relative movement between the fan and radiator cowl, as in the case of some flexibly mounted engines, arrangement 4 may be used, in order that fan tip clearance may be kept to a minimum (see Cooling Fan Tip Clearance in this section).

Fan/Cowl Relationship

The position of the cooling fan relative to the cowl has a considerable effect on efficiency. In many cases, the optimum position will be established by adjustment during cooling tests but in general, the relationships shown in the diagrams below have been found to give satisfactory results.

In cases where the overall airflow restriction is high, such as when the radiator is in series with other coolers it may be found that the fan adopts a radial as well as an axial flow. In such cases it may be advantageous to modify the relationship to encourage this. The fan manufacturer's advice should be sought.

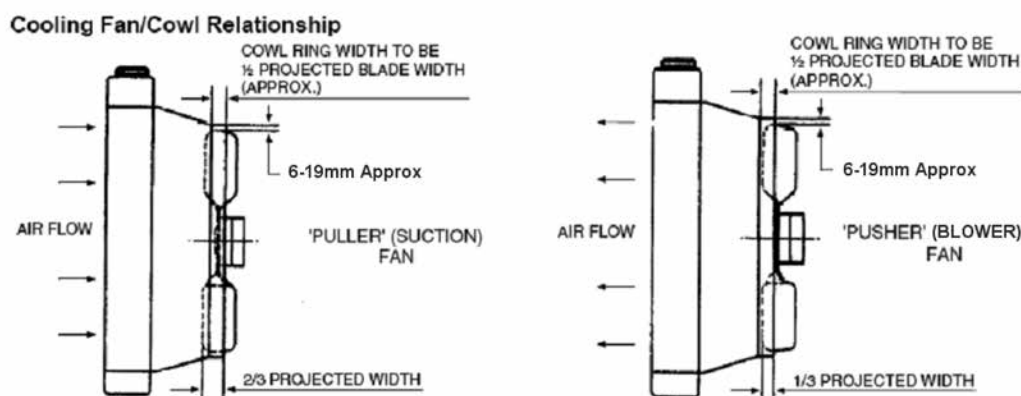


Figure 6.10

Cooling Fan Spacers/Distance Pieces

Spacers of various thicknesses are offered in the E.S.M. in order to enable the optimum fan/cowl relationship to be achieved. In all cases the maximum bending moment on the fan hub should not be exceeded; please refer to Chapter 12 for these mandatory requirements.

Cooling Fan Tip Clearance

It is very important, particularly when system restriction is relatively high, that the radial clearance between the fan blade tip and the fan cowl aperture or fan ring should be kept to a minimum. However, it is of paramount importance that the fan blade tips do not come into contact with the fan cowl under any operating conditions.

In general, clearance should not exceed 19 mm. Difficulties exist, however, in many flexibly mounted engine installations, where engine movement may take up this clearance. In such cases, for optimum results the engine-mounted fan ring arrangement Type 4 (reference Fan Cowls) should be used. This allows relative movement between the engine and radiator without affecting tip clearance.

Cooling Fan/Radiator Core Location

The cooling fan should be located centrally with respect to the radiator core, and it must be ensured that the fan does not overlap the sides of the radiator core, or the top and bottom tanks. Overlapping the sides of the core imposes fluctuating loadings on the fan blades, and can result in fan fatigue failure. For the same reason, care must be taken to ensure that support brackets, hoses, etc. are not located within the sweep of the fan blades.

There must be a clear area directly in front of and behind the fan; in general this should be a minimum of 25 mm or a clearance of at least one projected blade width; whichever is greater. Systems with clearance of less than one projected blade width should be tested to ensure no fan durability issues. In all cases it is recommended to consult your fan supplier.

Within the limitations of the space available the radiator should be located as far forward as possible from the fan. This enables the best distribution of cooling air over the radiator core. If, due to lack of space, the fan/core clearance must be minimized, the fan must not be positioned closer than 25 mm from the core, with the minimum clearance recommended being one projected fan blade width. This dimension must, of course, be increased if the movement of the engine and/or radiator on their individual flexible mountings will result in a reduction in clearance under operating conditions.

Prevention of Cooling Air Recirculation

When the engine and radiator are mounted inside an enclosure, it must be ensured that recirculation of the cooling air cannot take place. Suitable barrier and ducting arrangements are illustrated.

Figure 6.7 shows a suitable arrangement for an installation in which a puller (suction) fan is used. If a pusher (blower) fan is used, it is essential that the grill should extend over the whole of the front of the enclosure, in order to avoid turbulent air conditions inside the canopy at the cooling air exit from the radiator.

6.6.6 Coolant System Pipe Work

Hoses used in the cooling system must be of adequate duty to meet working conditions with respect to temperature, pressure, and resistance to anti-freeze and contamination by fuel and lubricating oils.

Only plain bore hose should be used. The internally convoluted flexible type of hose should not be used, since this is highly restrictive, and may result in excessive pressure drop.

Coolant hose lengths should be kept as short as possible with no dips or sags. With excessive hose length the hose expansion must be taken into consideration in calculation of expansion volumes.

Hose runs should be suitably supported/secured if necessary to prevent chafing. All radiator connections, remote header tank connections, oil cooler connections (waterside), and any other connections used in conjunction with hoses, should have beaded ends for improved sealing and security. The use of constant torque clamps is recommended with clamp positions marked on the hoses

Cab Heater Connections and Pipe Work

Tapings are provided on all engine types to take cab heater feed and return connections — the position of these is shown in the appropriate E.S.M. It is important that only the specified points should be used.

Hoses should be suitably secured to prevent the possibility of damage. Where the heater is positioned at a higher level than the rest of the system, a vent valve or plug should be fitted at the highest point in order to allow air to be expelled during filling.

6.6.7 Charge Cooler Pipe Work

- The charge air-cooling pipe work should be made of aluminized steel or aluminum.
- Pipes made from mild steel with a zinc electroplated corrosion resistance coating both inside and out may be acceptable, providing sufficient validation is carried out.
- Flexibility between the engine and machine chassis can be achieved by the use of flexible hoses either side of the rigid pipe work as indicated in Figure 6.11.
- The minimum diameter of pipe work should be no smaller than the compressor outlet diameter. An excessive volume can, however, have an adverse effect on response.
- The charge air pipe work should be as short and as direct as possible with as few changes in direction and section diameter as possible.
- The use of moulded elbows is not recommended, as they are prone to hose blow-off.
- Where 90° elbows are used it is also recommended that brackets are used to help restrain the ducting in the event of the hose blowing off.

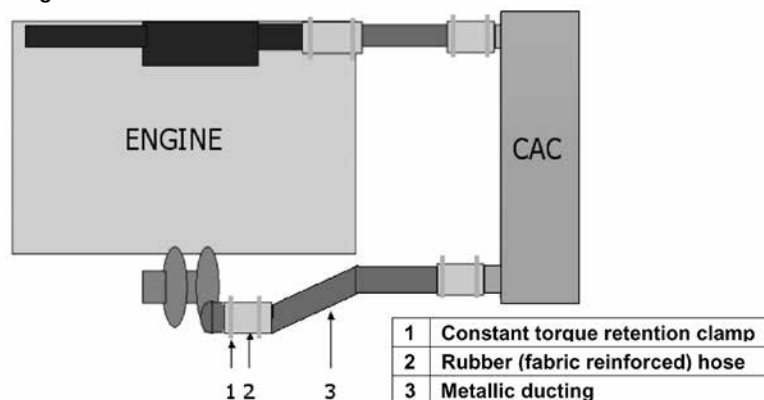


Figure 6.11

6.7 Cooling System Components

6.7.1 Coolant Radiators

The radiator cools the engine by exchanging heat between the engine coolant and air. The radiator has fan(s) to facilitate the heat exchange. Manufacturers offer various technological solutions to increase radiator efficiency, increase the radiator cooling capacity, reduce the radiator size, and improve the machine fuel economy by reducing the radiator weight and reducing fan consumption.

The functions of a radiator are as follows:

- Provide a heat transfer surface
- Serve as a pressure vessel to keep the coolant inside
- Serve as a reservoir to allow coolant to expand and contract and replenish fluid lost due to small leaks.
- Deaerate the coolant on initial fill and during machine operation.

The coolant entering the radiator may be dispersed through the matrix in either a down-flow or cross-flow direction.

Down-flow radiators are the traditional radiator design with the matrix attached to an upper header tank and lower collector tank. The header provides expansion space and reserve volume and the collector tank returns the cooled water to the bottom hose and water inlet.

Cross-flow radiators allow the radiator design to be low and wide to best utilize the available airflow. There are two coolant tanks down either side of the matrix, generally the inlet tank is down one side and the outlet down the other while a separate header tank is required to provide expansion space and reserve volume. These radiators are particularly good for installations where height is restricted, an increasingly common requirement as machine designs are optimized to improve “line of sight” for the operators.

In some cases, in order to achieve optimum cooling, a twin pass design (Figure 6.12) is required but care must be taken, as these radiators are generally more restrictive.

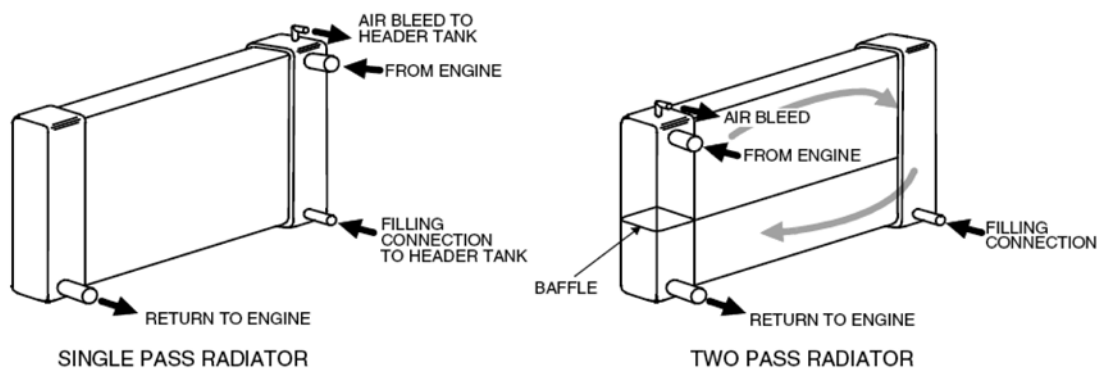


Figure 6.12

6.7.2 General Radiator Design

Coolant radiators and charge cooler radiators share many design features. This section outlines these common features.

Fins

Radiator fins should have good heat transfer performance and a reasonable resistance to bending. There are a variety of fin materials and thicknesses available. Material selection is based on cost, performance, and resistance to bending

Most radiator suppliers also provide fin designs with a performance enhancement. Enhancements may be bumps or ridges in the surface of the fin, or may be a punched hole, slit, or louvers. The benefit of these enhancements, however, may be at the expense of additional restriction.

Tubes

Tube design, like everything else in a radiator, is somewhat proprietary. They are frequently arranged in a number of different configurations as shown below.

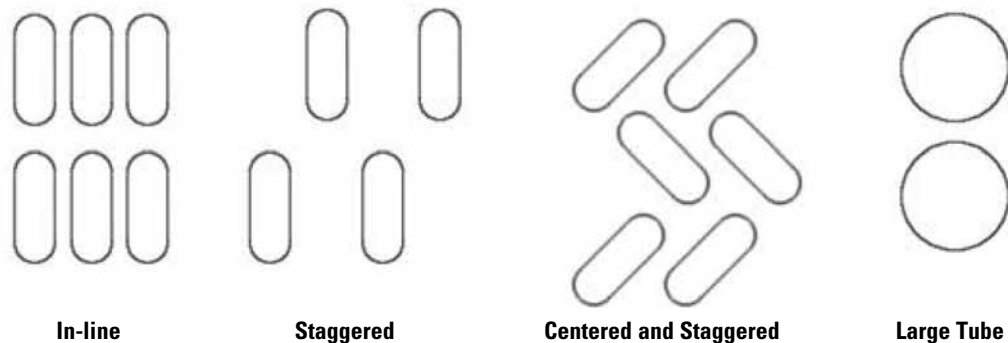


Figure 6.13

Core Construction

Radiator construction must be adequate to withstand the loadings and conditions that will be met in service. Special requirements also apply for machines operating in environments where there is a high sand or dust contamination of the cooling air, e.g., earth-moving equipment.

Typical methods of radiator core construction are illustrated below:

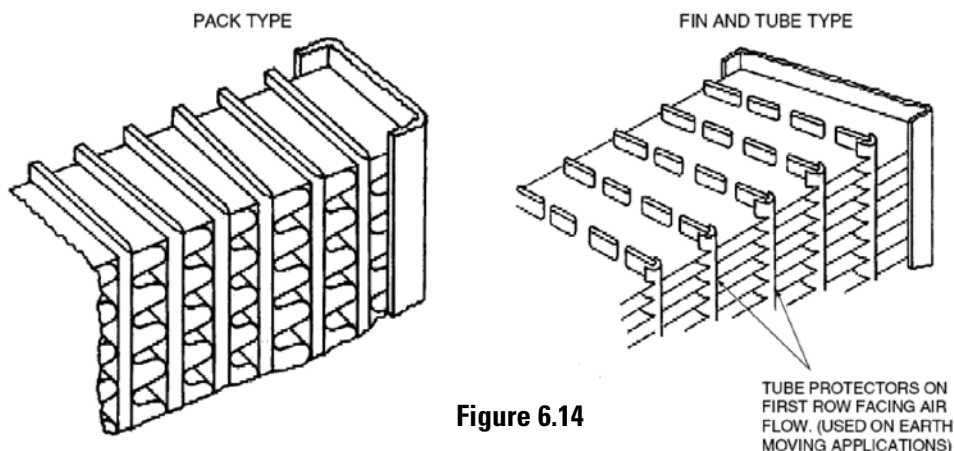


Figure 6.14

Pack-type Core

This type of core has advantages in manufacturing cost, coil, and heat transfer capabilities as the manufacturing process lends itself to a consistent bond between the fins and the tubes. However, radiators with this type of construction are manufactured for a wide variety of uses and care must be taken to select a unit correctly suited to the installation.

Units devised for operation in clean conditions (e.g., on-highway) often feature a fin pattern as shown below in Figure 6.15A. This construction gives a restricted area for airflow near the troughs of the fins and has a limited area of bonding between the fins and tubes.

Units designed specifically for off-highway applications feature a square fin construction as in Figure 6.15B. This is much less prone to clogging by dirt and has much-increased mechanical strength and improved heat transfer resulting from the increased bonding area.

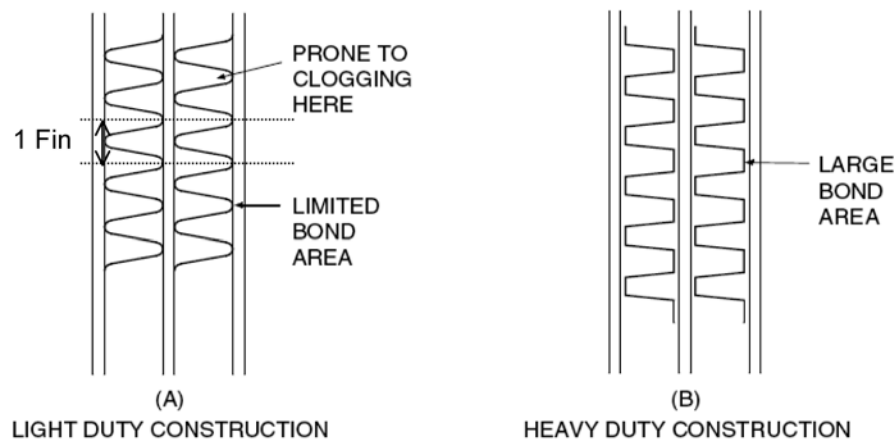


Figure 6.15 (A&B)

As an alternative to the type of radiator already noted, cores of welded aluminium construction are available. Due to the manufacturing methods used these cannot readily be classified as before; however, the functioning of the radiator depends on the same parameters of clear airflow without narrow sectors, and of good conductivity between the fins and the water tubes.

These radiators may include welded header tanks; alternatively, the tanks may be of plastic and attached by crimping using a suitable seal. Some suppliers of copper/brass radiators also use this arrangement. This type of construction has proven very rugged and satisfactory in service providing the design concept and detail and manufacturing quality are sound. The installer should satisfy himself on these points.

Fin and Tube Type Core

Fin and Tube construction is suitable for all application types.

Fin Density

Important restrictions apply with regard to the maximum density of fin spacing (i.e., closeness of fin pitch), which should be used to avoid plugging, the likelihood of which is application usage-dependant. Table 2 below give the recommended maximum fins per inch by application type.

Application-Type Fin Spacing

Application	Fin Pitch (mm)	Fins/inch
General Industrial	3.0	9
General Agricultural	3.0	9
Vehicle (off-highway)	3.0	9
Earth-Moving Machinery without Adequate Screening	4.0	6

Table 2

6.7.2.1 Operating in Severe Environments

When operating in severe environments the radiator should incorporate the following features:

- General construction should be heavy duty to withstand operational shock loadings.
- Radiator tube rows should preferably be in-line to assist in prevention of plugging. If staggered tube rows are used, the spacing between tubes and tube rows must be adequate to provide a free air passage through the core.
- In applications operating in extreme conditions of sand/dust concentration, the first row of tubes on the cooling air inlet side should be protected by a shield to prevent erosion due to sandblasting.
- Thickness of fins should not be less than 0.99 mm (.0035 in) and the edges of the fins facing the cooling airflow should be wrapped in order to increase strength (Figure 6.16).

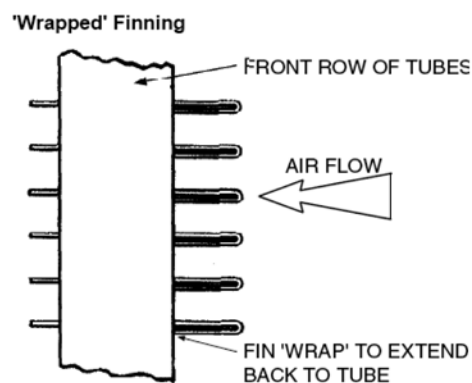


Figure 6.16

6.7.2.2 Radiator Draining

Engine Coolant Radiator

The use of a coolant radiator drain is recommended to aid servicing, allowing the attachment of a hose for the spent coolant to be collected and contained.

In addition to the radiator drain, draining from the RHS and LHS of the block and NRS cooler is required to completely drain the cooling system.

Sometimes machines require the use of a single drain point to allow all low points to be drained from one location. Typically a single point drain valve is mounted to the bottom of the radiator, and individual lines connect the drain valve to each of the system low points. Care must be taken with these systems to prevent the build-up of sediment in these lines and to prevent overcooling of the system by returning hot coolant too close to the bottom tank and allowing hot coolant to thermo-siphon into the radiator.

Charge Cooler

It is recommended, where possible, that the charge cooler design incorporate a drain point. This is required to enable any condensate to be drained out of the core and prevent the condensate entering the engine. The risk of condensate build-up is considered to be higher under the following circumstances:

- On engines with a twin (in-series) turbocharger arrangement – due to the higher boost pressure ratio
- In open installations where there is no canopy or machine body work.
- Where the air is not being returned from the highest point of the cooler
- If the cooler is mounted horizontally
- If the machine is operated in the following combination of conditions:
 - A high relative humidity
 - High duty factor
 - Highly transient work cycle
 - Little or no idle time

Radiator Pressure Caps

A mandatory level of pressurization is needed to maintain acceptable coolant boiling point at high altitudes. Radiator pressure cap and fill neck designs are covered in SAE J164 for small and medium caps. These standards cover the combination cap and relief valve design caps and fill necks built to this standard will ensure that the end user cannot readily install a low-pressure cap on a high-pressure system.

6.7.2.3 Radiator Mounting

In order to avoid possible failure of the radiator cores, it is important to protect them from excessive vibration and/or shock loading while maintaining sufficient flexibility to prevent overstressing of the core during normal frame deflections experienced in service.

Consideration should also be made for cleaning, particularly if the cores are mounted in series. Hinged designs or clean-out ports are sometimes employed to help access the space between the cores.

Typical flexible mounting arrangements are shown below. These are used in conjunction with bushed fixings at the side and/or flexible mounted stays at the top of the radiator.

Typical Radiator Mounting Arrangements

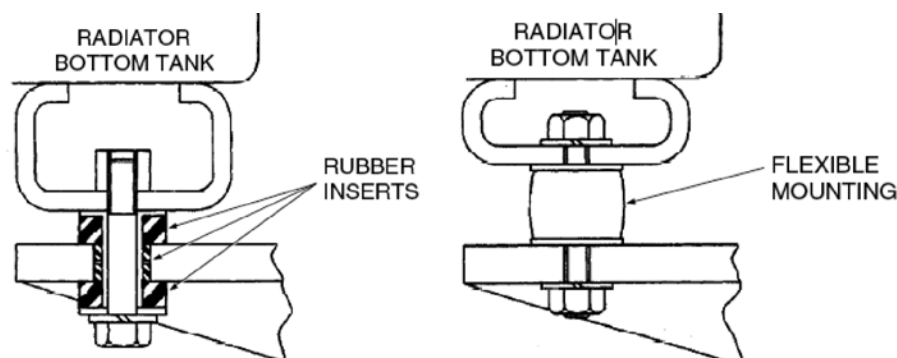


Figure 6.17

6.7.2.4 Coolant Radiator Selection

In most cases, the selection of a suitable radiator will be carried out in conjunction with the radiator manufacturer, who will have available information on stock radiator sizes and types, and the applicable radiator dissipation characteristics and other information. Initiating communication with the radiator supplier early in the design process is essential.

It is important, however, to appreciate that:

- The correct choice of cooling system package can have a considerable effect on noise emission and cooling system power requirement.
- In all cases, due to the effects of features of the cooling system layout, air flow conditions, duty cycle, etc., the actual cooling system clearance (i.e., the maximum ambient temperature for which the cooling system is suitable) can only be established by full cooling tests, as detailed in cooling system test procedure referenced in Chapter 16.

Selection Procedure

The following items must be considered during the selection procedure.

Application Type and Operating Environment

The application type and operating environment will determine the most suitable form of radiator core construction, and the maximum acceptable fin density and number of tube rows, in order to avoid the possibility of core plugging (see Radiator Construction and Mounting).

Ambient Temperature Clearance Requirement

Ambient temperature clearance requirements related to operating territory are covered in Chapter 16 — Installation and Audit Testing.

Total Heat Dissipation Requirement

Full load heat to coolant values for the current engine range, at the ratings applicable to the various application categories, is included in the Engine Sales Manuals (E.S.M.s).

To these values must be added any additional heat input to the cooling system, rejected from the transmission, hydraulic system, braking system, water-cooled exhaust manifolds, air conditioning systems etc., depending on the design details of the particular application type.

Transmission Converter Heat Load

Where heat is rejected to the cooling system from a transmission, determination of the additional heat load must be based on an estimate of the mean transmission efficiency over the duty cycle. Allowance must be made for an additional heat dissipation requirement equivalent to the power lost in the transmission.

In particular, torque converter transmissions can reject large amounts of heat to the cooling system.

Engine Coolant Flow Rate

Coolant flow rates for the engine range, with a fully open thermostat and typical system pressure drop [see Cooling System Pressure Drop (Waterside), to follow], are included in the E.S.M.s.

Cooling System Pressure Drop (Waterside)

Pressure drop incurred by the coolant in flowing through the total external cooling system, i.e., radiator, pipe work, in-line oil cooler if fitted should not exceed 35 kN/m² (5 lbf/in²) at maximum rating. This is an essential requirement in order to maintain adequate flow rate through the engine, and to prevent cavitation occurring at the water pump inlet.

Cavitation

Cavitation will occur if the pressure at the water pump inlet is reduced to the point when local boiling can take place, and will result in the following detrimental effects:

- Reduction in coolant flow rate. This in turn will lead to a higher coolant temperature, and further aggravate the situation.
- Damage to the water pump impeller and casing, and possibly also to the coolant passages in the engine water jacket.

6.7.2.5 Charge Cooler Selection

This process should be carried out in conjunction with the selection of the coolant radiator as in a conventional system the same fan is used to provide air for both systems.

The heat rejection and combustion air requirements for each engine life and rating are given in the E.S.M. and also on sheet 2 of the published power curves. This data can be used in conjunction with data supplied by the charge cooler supplier to determine the cooler specification. The calculations must be carried out for the maximum rated power of the engine, as it will be necessary to test the machine at this condition during the appraisal process.

A possible exception to this is for certain applications, normally stationary such as air compressors, where the engine selected has a higher power output than can be absorbed by the driven unit. (This occurs because in such cases it is necessary to have a reserve of power to allow the unit to operate satisfactorily where the engine power output is reduced by adverse operating conditions such as altitude, low-density fuel, high fuel temperatures, etc.) In such cases the match can be made at the power requirement of the driven unit. The relevant air temperature before the charge cooler, obtained from the engine performance data, must be used when calculating the corrected NRS inlet temperature and charge cooler efficiency.

6.7.3 Cooling Fans

6.7.3.1 Cooling Fan Selection

In all stationary applications, and in mobile applications where there is not significant ram air assistance due to forward motion, the cooling fan must deliver the total required air flow volume, as determined from the radiator dissipation characteristics.

When operating in very cold climates (-40°C), it should be noted that fan power absorption can increase by up to 25% until the engine warms up and the air temperature onto the fan stabilizes.

Fan Speed

In many cases, fan speed will be decided by the application design. This will be determined by the fan drive ratio.

In order to reduce noise emission, when a choice of fan drive ratio is available, the lowest practical fan speed should be used, compatible with airflow volume requirement and system restriction.

Earth-moving Machinery

The reduced air velocity through the core when a large, low-speed fan is used is particularly desirable in the case of machines working in high dust/sand environments, in order to reduce sand blasting of the core, and sand disturbance by the cooling air flow.

Fan Speed Limitations

When using a fan which was not specified by Caterpillar for the particular application and operating speed range, it is necessary to obtain the manufacturer's approval to avoid the possibility of failure.

Fan Diameter

In general, in order to achieve the best coverage of the radiator core, the fan diameter should match the dimensions of the core as closely as possible.

Care should be taken that the fan does not overlap the sides of the core, or the top and bottom tanks, in order to avoid fluctuating loading of the fan blades, which may lead to failure.

Types of Fan

A range of fans of puller and pusher types with varying blade angle (pitch) and blade widths as well as diameter are part of the product offering to match the air delivery requirements of the engine range. Please refer to the E.S.M.

Increased under hood temperatures for Tier 4 Interim engines mean that a pusher fan may no longer be viable and cooler air from outside of the engine compartment may need to be drawn onto the radiator to meet the cooling requirements.

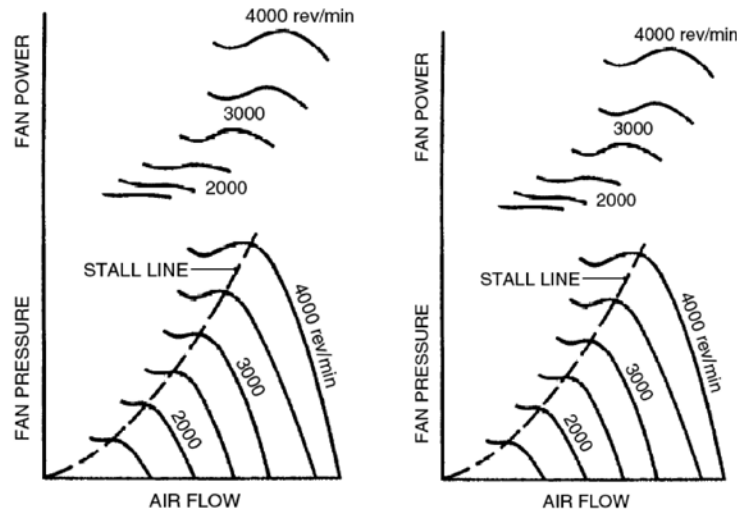
The standard ranges of fans are made of pressed steel, aluminium construction, or plastic construction.

Note: Care should be taken to ensure that the natural frequency of vibration of the fan blades cannot be excited by the blade-passing frequency, i.e., the frequency at which the blades pass obstructions in the airflow path, as this can lead to resonant vibration of the blades and hence fatigue failure.

Fan Selection Using Fan Performance Curves

Typical fan performance curves are illustrated below.

Fan Performance Curves — Fan and System Matching



These show air flow delivered against pressure head developed, at various fan speeds. Also shown is the corresponding fan power requirement.

Stall Line

For a given fan speed, if the fan working pressure is increased due to increased system restriction into the region to the left of the stall line, severe disturbance in flow conditions at the fan will occur, resulting in a major reduction in air flow and an increase in noise emission.

The fan must be selected using the performance curves to give the required cooling air flow against the total system restriction, without running into a stall condition. It should be noted that in addition to the restriction incurred across the radiator core, as determined from the radiator dissipation characteristics, the total system restriction includes any additional restriction incurred in the cooling air flow path. This varies widely according to the installation layout, type of radiator grill, inlet and outlet areas, etc., and is difficult to estimate.

As a general guide, in order to make allowance for the restriction incurred in the remainder of the system, the pressure drop incurred across the radiator should not account for more than 70% of the available working part of the fan characteristic.

This applies to systems with relatively unrestricted flow path. For more restrictive installations, this figure must be reduced accordingly.

Note: Fan performance curves as published by the manufacturers normally relate to test results obtained with the fan operating in an unobstructed tunnel or duct, with relatively low tip clearance. In the working conditions that will apply in service, fan performance is likely to be significantly lower than indicated by the curves. In addition, airflow is further reduced by the restriction of the engine component controls. In order to allow for this, the airflow requirement, as derived from the radiator dissipation characteristics, should be increased up to 100% before application to the fan performance curves.

6.7.3.2 Fan Drive Type

There are various methods of driving the fan, the selection of which is normally dependant on installation constraints and is usually a compromise between packaging, cost, and efficiency.

In all cases where a fan drive is not included in the factory build, please contact your applications engineer, so that the suitability of the drive and the possibility of additional loading of the crankshaft may be evaluated.

The main types of drive are discussed below.

Direct Drive Fan

A direct drive fan is mounted to and directly driven off the engine. It is engaged 100% of the time and its speed is directly proportional to the engine speed regardless of engine temperature or operating conditions.

A fan driven directly off the engine front end accessory drive is available as a standard option in the product offering with various fan heights and drive ratios, controlled by the crank and fan pulley diameters. Increased fan power requirements for Tier 4 Interim engines has also led to a heavy-duty offering with the ability to drive heavier and more powerful fans.

Crank-mounted fans are not approved, as they are subject to torsional vibrations, which is safety critical as it can ultimately lead to fan failures.

Hydrostatic Drives

A hydraulic fan drive uses an engine-driven pump to create hydraulic flow. This flow is then sent to a fan motor, which converts the pump's flow to rotation at the fan motor shaft.

A hydrostatic fan drive can either provide a fixed or variable fan speed; this is dependant on the pump type used.

A conventional hydraulic fan drive typically will have a fixed-displacement fan pump and fan motor, thereby creating a fixed gear ratio between engine speed and fan speed. Fan and engine speed continue to have a linear relationship until a pressure-based relief valve in parallel with the fan motor starts to allow flow to bypass the motor, thereby clipping fan speed so that it stays relatively constant as engine speed increases. This engine speed is typically referred to the cooling point, and above this engine speed the machine will operate at maximum fan speed and cooling airflow.

The use of a variable or fixed displacement, pressure compensated pump with a fixed displacement motor can provide a tremendous amount of flexibility in the speed control of the fan. Depending on the system selected these designs can lose significant fan speed at high oil temperatures.

Electric Fan Drive

This is not normally a realistic option to drive the primary cooling fan in construction and industrial equipment due to high power requirements.

Electric fan drives can either be "on/off" or "variable speed."

Mechanical Viscous Fan Drive

Viscous fan drives are used to reduce the fan load when cooling is not required, and thereby lessen power requirements and related fuel demands. A viscous fan drive offers an improvement in efficiency over direct drive fan cooling. This hub-mounted, fluid-coupled device contains a hydraulic turbine using a viscous silicone fluid to transfer energy from driving element to driven element.

Typically, a bi-metallic element on the front of the viscous drive senses the temperature of air passing through the radiator and operates a valve to control the silicone transfer fluid, affecting fan engagement and disengagement. The fan drive is not controlled directly by engine temperature but indirectly by sensing the temperature of cooling air passing through the radiator.

The hydraulic nature of a viscous drive prevents it from achieving fully on or fully off operation. Consequently, in the disengaged mode, the fan continues to operate at speeds as high as 45 percent of the fully engaged rate. The partial engagement or parasitic drag of a viscous drive can contribute to engine overcooling, resulting in unnecessary fuel consumption. The physical properties of the hydraulic fluid in a viscous fan drive may also change over time, and lead to decreased performance and further degradation in cooling performance.

The use of viscous fan drives is non-preferred as the relationship between the air-on temperature sensed by the bimetallic strip and the temperature of the cooled air returning into the engine is not linear and can be affected by many external influences. It can, therefore, be difficult to ensure that the engine inlet charge air temperature is maintained within the required certification limits. For approval, control of this intake temperature must be demonstrated as outlined in the appropriate test procedure ref TPD1746.

The response time to transient load conditions may also be cause for concern and the specification of the drive must be carefully considered to ensure that the cut in temperature and speed is appropriate for all operating conditions.

This type of fan drive is not suitable for pusher (blower) fan configurations as the airflow over the bimetallic sensor has not passed through the radiator core.

6.7.3.3 Electronic Operation and Control

There are various methods for controlling the operation of a fan. This is becoming increasingly important, as the benefits can be substantial. Minimizing the use of the fan can make a significant contribution to reducing fuel consumption, improving engine performance, adhering to regulatory noise requirements, and can even help increase radiator and belt life.

Some of the methods of fan operation and control are discussed below:

Variable Speed/Demand Fans

An electronically controlled demand fan sensing the engine air inlet temperature and engine coolant temperature, as a minimum, is the preferred variable speed fan option for Tier 4 Interim engine installations.

This type of fan has all the benefits of the mechanical viscous fan drive arrangement but allows for a more accurate control of the engine inlet air temperature which is required to meet the stringent legislative requirements. The use of multiple inputs can also be incorporated into the control strategy, i.e., transmission and hydraulic oil temperatures.

This type of control strategy is compatible with the following types of customer fitted fan drives:
Electronically controlled hydraulic fans

Electronically Controlled Viscous Fan Drives

If demand fans are to be used the following advice should be noted

- A plugged tapping in the engine air inlet spigot is provided for a charge air temperature sensor on all products.
- The Electrical and Electronic Application and Installation Manual — LEBH0005 outlines the demand fan control software strategy; please refer to Chapter 11 for more details.

On-off Control Fans

An on/off fan drive responds to changing operating conditions and controls the radiator fan accordingly. This fan is either completely off, essentially disengaged, or completely on and engaged at full engine speed. It is able to respond directly to engine sensors or input from the engine ECU that reflects actual engine conditions, and can control the engine temperature within a narrow range. Consequently, the control unit is able to engage the fan clutch only when cooling is required.

These types of fan are available with either pneumatic or electric actuation.

This type of control is not recommended for the primary drive in industrial or construction equipment but is ideal for auxiliary electric cooling fans which may be considered necessary in the event of additional heat loads associated with Tier 4 Interim engines.

Reversible Fans

Variable pitch fans, which allow the blade profile to be changed to create maximum airflow, can be operated in reverse to clean plugged cores. If allowed to operate in the neutral plane they can regulate flow/noise and reduce SFC.

6.7.4 Additional Cooling Cores

There are a number of other cooling cores that may be incorporated into a cooling pack for the machine. The mounting method and position in relation to the airflow through the charge cooler and coolant radiator must be considered carefully. These commonly include the following:

Transmission Coolers

Torque converters operate under varying conditions of slip and torque multiplication, and in extreme cases this efficiency can be as low as 70% averaged over a machine working cycle. In this case, 30% of the engine power is rejected as heat, and even under less severe conditions between 5% and 25% of engine output is rejected.

To dissipate this heat it is common practice to use the engine cooling circuit. Either an oil-to-water heat exchanger is placed into the engine coolant circuit (normally in the engine coolant inlet hose) or an oil/air radiator is installed in front of the coolant radiator, raising the air temperature entering the latter components.

In either case this extra heat must be considered in the selection of coolant radiator and cooling air fan, and test procedures must consider operation with the most severe torque converter heat rejection.

6.7.4.1 Hydraulic Coolers

The hydrostatic transmission consists of an engine-driven, variable delivery pump which provides hydraulic fluid to drive one, or several, fixed displacement hydraulic motors. The motors can therefore be mounted remotely from the pump, the hydraulic fluid being transmitted through flexible pipes. This allows great flexibility when designing the transmission layout.

As with torque converter transmissions, provision must be made to deal with heat rejected by the hydraulic circuit to the engine cooling system. Due to the much higher efficiencies (normally 90% +), the magnitude of this effect is much smaller.

6.7.4.2 Fuel Coolers

Fuel coolers are frequently required to lower the fuel temperature to within the limits of the engine low-pressure fuel system and material limits of the composite fuel tanks, connections and lines. Please refer to Chapter 8 for more details.

Again the fuel cooler is an additional core that must be considered in the layout of the cooling cores.

6.7.4.3 Air Conditioning Condensers

If air-conditioned operator cabs are an option, a condenser will be required. This is commonly incorporated into the cooling pack along with the other required cooling cores.

6.7.5 Components Requiring Cooling Feed

Cab Heaters

It is essential that only the cab heater ports and connections identified and supplied with the engine are used. This is to ensure sufficient pressure differential across the engine to provide the necessary flow requirements. It also ensures that the engine coolant flow is not adversely affected, which could lead to long-term engine damage.

Cab heaters must be selected to ensure that they are capable of sustaining the maximum coolant pressure without deformation or failure.

Cab heater hoses should be to hose specification SAE 20R1 TBC and not exceed the maximum internal diameters specified in Section 6.2.

Remote Block Heaters

There are ports identified on the engine for the use of a block heater. Please refer to the E.S.M. for details of their locations and thread specifications.

Emersion block heaters must use the suitable ports identified in the engine specification manual. Not all block heaters are compatible with Tier 4 Interim engines. Please contact your applications engineer for further advice.

Coolant Level Sensors

The engine supports the use of an electronic coolant level sensor, although this is not part of the product offering. Please refer to the Electrical and Electronic Application and Installation Manual LEBH0005 for further information.

Compressors

The coolant supply for airbrake compressors must be taken off the cab heater ports using the connections supplied with the engine or alternatively tee'd into the cab heater hoses.

Aftertreatment Module

The aftertreatment module requires an engine coolant feed. Please refer to Chapter 5 — Aftertreatment and Exhaust Systems, for further details on this requirement.

7.0 Under Hood Thermal Management

7.1 Introduction

Under hood temperature management requires an increased focus at Tier 4. This is due to the addition of aftertreatment components into the engine compartment that can both add radiated heat and restrict airflow, along with an increased number of control systems whose temperature limits must be adhered to.

For separate air systems (engine compartment separate from the cooling package), higher temperatures will melt the components and/or reduce the effective life of the components. For integrated systems, where the engine and aftertreatment are in the same compartment, besides the component failure issues, higher under hood temperature may also increase the temperature of the air entering the cooling cores, affecting the air-to-core (ATC) rise.

Table 7.1 indicates the temperature capabilities for the engine and supplied components. You should aim not to exceed these general limits. Some local temperature limits will, however, be lower or higher and are defined in the mandatory requirements Table 7.2.

Tier 4 Under-hood Temperatures			
Ambient Temp in Engine bay (°C)	Engine state	Percentage of engine life	Max time at Max Ambient temp
120	Stopped, but must be startable (heat soak)	2	20mins
105	Running	13	3 hours
85	Running	85	Indefinite

Table 7.1

7.2 Thermal Management Mandatory Requirements

All emission-related installation instructions are highlighted by the **EM** symbol.

Failing to follow these instructions when installing a certified engine in a piece of nonroad equipment violates federal law (40 CFR 1068.105(b)), subject to fines or other penalties as described in the Clean Air Act.

- **EM** Adequate cooling for all engine components must be provided within the enclosure design to ensure they do not exceed their maximum temperature limit for all conditions or exceed the maximum intermittent temperature limit in worst case operating conditions (hot shutdown).
 - Table 7.2 outlines the localized allowable operating temperatures of the on-engine components for all 4- and 6-cylinder products.
- **EM** Where extremely high local temperatures are measured, additional cooling methods must be used to control the component temperatures.
- **EM** The use of thermal insulation (for example thermal lagging or wrapping):
 - Is not permitted on any engine component including: the exhaust manifold, turbocharger/s, turbocharger inter-stage ducting (twin turbo arrangements), NRS pipe work and exhaust backpressure valve (BPV).
 - Is not permitted on the flexible section (bellows) of the engine to aftertreatment connection.
 - Requires Caterpillar approval if used on any other engine or engine system component including the aftertreatment itself or parts within the engine-to-aftertreatment interconnecting pipe work (excluding the bellows). Refer to Section 7.4.6 Reducing Heat Transfer — Lagging and Wrapping.

Component	Min °C	Max °C	Max intermittent °C	Surface	Ambient	Notes
Rotating Electrics						
Remy 13 & 18si (rear cover)		246	280	x		Rear cover surface temperature
Remy 13 & 18si		125			x	Alternator ambient air inlet (May be ducted)
LD Denso 115QI		125			x	
Heavy Duty-Denso HDB		93			x	
Heavy Duty-Denso HDB SC		105			x	
Heavy Duty-Remy36SI		125			x	
Batteries		52			x	
Battery Cables		80			x	
starter motors?		120			x	
Top of engine Components						
Inlet Throttle Valve		140			x	
NRS Valve		140			x	
CCV Separator		175	200		x	
CCV Hose		120	130		x	
Valve cover/Top cover		175	200		x	
Controls System Items						
Harness - Convolute		120			x	
Harness Connector - Deutsch	-55	125			x	
Harness Connector - ampseal		125			x	
Harness Covers (J1/J2)		120			x	
Harness - fir-trees		120			x	
Pressure Sensors	-40	125			x	
Temp sensors	-40	120			x	
Aftertreatment Soot Sensor Box		85			x	
Aftertreatment Soot Sensor Harness		200			x	
ECM		110		x		Surface of ECM on hot spot
Other						
Aftertreatment Cans		250		x		Average Skin Temperatures (Hotspots are expected)
Crankshaft Damper		85			x	
Back Pressure Valve		140			x	localised cooling strategy may be needed
Electric transfer pump (ETP)		93			x	
FEAD components	-40	85	105 (3 hours max, 13% of life)		x	Also 120°C for 20mins (hots oak)
Fuel lines (convolute)		140		x		
Fuel lines (metal)		200		x		
Turbo waste gate		180		x		
Smart waste gate		125		x		
Ether Cylinders		90			x	
Engine Mounts - Natural Rubber		82			x	
Engine Mounts - Synthetic Rubber		107			x	
Air Cleaner restriction indicator		88			x	
Air filter elements		110			x	

EM Table 7.2

Please Note:

- Items in green are supplied components
- Items in orange are generic and temperatures are given as an indication. Please contact your supplier for exact values.
- In all cases refer to Chapter 16 — Test Procedures, for details of how the above limits will be measured. Unless stated otherwise, intermittent limits refer to periods not exceeding 20 minutes and 5% of the machine life.

7.3 System Overview

Before under hood temperature concerns can be addressed the mechanisms of under hood heat transfer must be understood. The fundamental modes of heat transfer are conduction, convection, and radiation; and the temperature of the engine compartment air or any component involves a balance of these modes.

Many of the areas of concern for under hood temperature involve components that are not directly attached to the engine and the relevant modes of heat transfer are convection and radiation. Either or both of these modes may be important depending on the magnitude of the airflow through the compartment and the magnitude of the temperatures of the hot components that act as heat sources.

Radiation is proportional to the difference of the temperatures to the fourth power, so temperatures above 300°C become an important source of radiation in typical ambient conditions.

Forced convection is roughly proportional to the air velocity and the temperature difference to the first power, so engine compartments with flow velocities above 3 m/s will have significant convective heat transfer. Free or natural convection can have an impact when velocities are significantly lower and the temperature difference between the air and the surface is high, but typically radiation becomes the dominant mode of heat transfer in these situations.

A significant new source of heat radiation and/or conduction in Tier 4 installations is the aftertreatment. The regeneration process is the cause for the high temperatures seen from this emissions-critical component and cannot be avoided.

The most appropriate method for mitigating high under hood temperatures should be used. There is no one solution; it is application/installation-specific. The method best used is dependent on the available packaging space, cooling fan system being used, and the positioning of sensitive or hot components.

7.4 Thermal Management Design Considerations

7.4.1 Airflow Requirements

Airflow requirements are sensitive and dependant on the machine design and component layout. The key to meeting the temperature requirements is to encourage even airflow around the engine compartment; with the aim being to eliminate dead zones and hot spots.

Increasing the fan's airflow will not always provide the solution, as unless the airflow across the critical components is significantly increased it is an inefficient use of power.

If the layout is poor, the air may be going directly in and out of the engine compartment through the shortest route, bypassing the sensitive components completely.

Theoretical modelling is a good tool to fully understand the airflow and heat transfer characteristics of the installation. It is understood that this is not a tool that is commonly available and in all cases there is no substitute for development test work.

To ensure that the temperature of all the critical components is maintained within limits, it is suggested that a minimum airflow of 9 m³/min is achieved across them.

7.4.2 Location of Heat Sources

The careful positioning of the more extreme heat sources, such as the aftertreatment module and exhaust pipe routing, is a first step toward meeting the temperature limits of critical engine and aftertreatment components.

These items should not be positioned, if possible, close to the critical components. Ideally, the heat sources should be downstream of the airflow from the main fan to avoid additional convection of heat over the engine.

When the positioning of hot items cannot be further improved, alternative actions must be taken to meet the temperature limits for the critical components. Suggestions for these are detailed in the rest of this chapter.

7.4.3 Predicted Aftertreatment Temperatures

The aftertreatment skin temperature and the gas temperature are difficult to measure and/or simulate and are dependent upon the location of the engine and aftertreatment within the application. Therefore, the potential temperatures are provided as a guideline for safe design of the vehicle even under conditions of unexpected engine and/or aftertreatment failure; and proper precaution should be taken to ensure that the aftertreatment device is properly shielded and not mounted in close proximity to surrounding components that may be damaged by heat.

Normal operating temperatures can reach up to 550°C at peak torque for all engine families. Therefore, thermal protection on the surface of the main exhaust piping may be required. Proper precaution should be taken to ensure that the aftertreatment is not mounted in close proximity to components that may be damaged by heat.

The temperature of the exhaust gas and the temperature of the exhaust system components can reach up to 650°C during active regeneration.

Installing a module in an enclosure without airflow will not be possible due to the temperature limitation of the control systems components.

7.4.4 Lowering Risk of Debris Build-up

In harsh environments, debris can quickly build up on engine components if the operator does not regularly inspect and clear debris from inside the engine compartment. This build-up of debris (chaff, straw, dirt, dust, etc.) may lead to engine components either:

- Overheating, causing temporary or permanent damage, as the debris acts to insulate the component as well as limiting the cold airflow over its surface. This is mainly a concern for engine electronics.
- In the worst case, causing a fire as the debris reaches a temperature high enough to cause it to combust (i.e., chaff on exhaust manifolds). This is a concern for hot engine components, such as the CEM, Turbo, and manifold.

To combat this the following installation design considerations should be taken into account:

- Fine grills in front of all air inlet features on the enclosure design. The mesh should be a compromise between being so fine as to become clogged on a frequent basis and so large that it does not do a sufficient job of reducing build-up on engine components. If this outer mesh becomes blocked it will more visible to the operator; this is preferable to debris build-up in unseen areas of the engine compartment.
- When designing protective shields for engine components, consider the effect on the likelihood of debris build-up. If the shields are poorly designed they can capture debris that would otherwise pass through the engine compartment, in a manner that increases the temperature of the component being protected.

In all cases the operator's maintenance manual should request that debris build-up is cleared from the engine compartment on a regular basis.

7.4.5 Increasing Airflow

Additional Fans — Electric

- Where aftertreatment or engine components are separated from the engine compartment, additional electric fans can be used to increase airflow.
- They can also be used to force cool air to, or extract hot air from, components sitting in dead zones of the engine compartment, where there is limited natural or forced airflow from the existing fan configuration.
- This may require additional air intakes or vents on the exterior of the engine enclosure.

Ducting of Cooler Air

- Metallic or polymer (convolute) ducting can be used to take cool air directly to critical components.
- The air can be ducted from the ambient air outside or from a cooler area of the engine compartment (with or without the assistance of an electric fan).
- This method is particularly useful for applications where the at-risk component is tightly packaged and in very close proximity to hot components.
- Often this approach requires the component to have ducting built into its design to ensure the cool air hits the critical parts of its assembly (i.e., alternator rear-cover ducting).

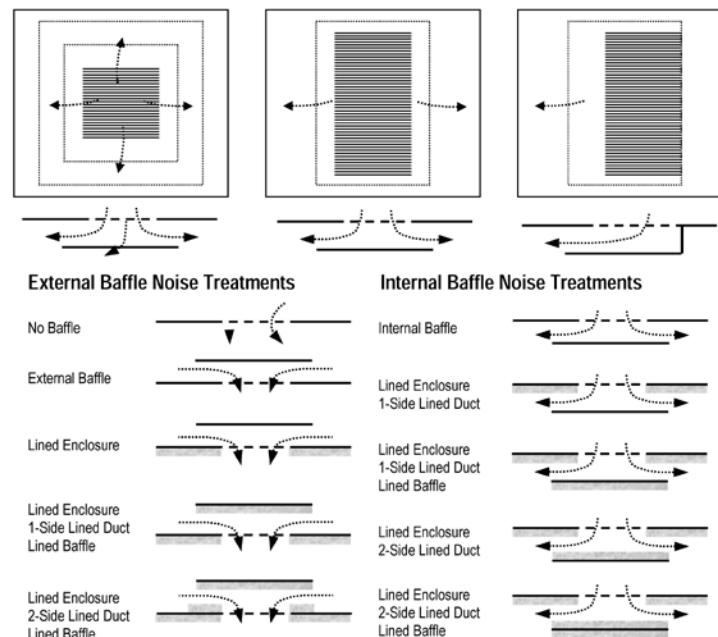
Increasing Under Hood Volume

- Increasing the under hood volume can have a positive effect on the amount of airflow through the engine compartment.
- Creating clear routes for air to flow around the engine is vital to ensure that areas of static air are minimized where localized hot spots may occur.

Perforations in Sheet Metal/Enclosure Walls

- A range of baffle/perforation designs can be used to help increase the airflow to the engine.
- The additional open area allows the opportunity for increased airflow. The same openings will allow additional sound to escape

The size and shape of the perforations should be selected with safety and plugging/debris ingestion considered.



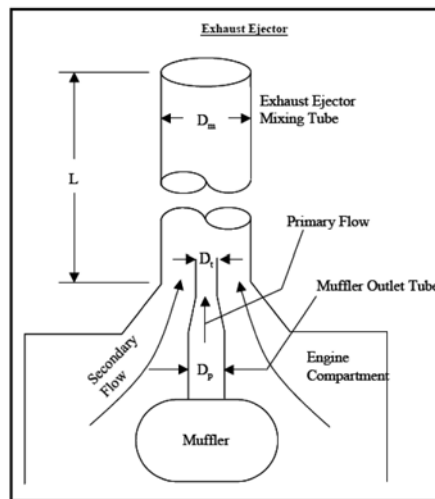
Exhaust Ejectors (Sealed Engine Compartments Only)

These can also be known as exhaust venturi systems. They work on the principle of the pressure differential between the exhaust flow and the pressure in the engine compartment drawing warm air out and mixing with the exhaust gases.

This approach requires understanding of the pressure levels within the engine compartment and drives the need for good quality control over sealing, ducting, or sheet metal perforations.

If the pressure within the engine compartment is too low it can lead to the exhaust gasses being drawn back into the engine compartment. This can occur at low engine speeds as the exhaust flow levels drop, meaning the compartment pressure can drop lower than the exhaust flow (particularly if additional fans are being used).

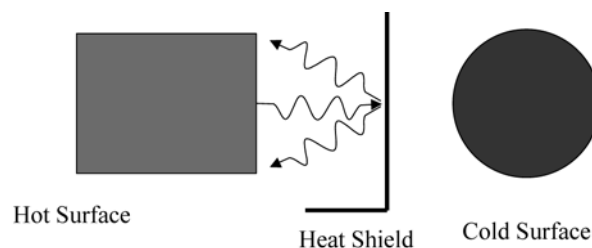
Balancing the pressures requires careful design and testing to optimize the system performance. Critical design parameters include the diameter of the stack, the height of the stack and the insertion of the muffler outlet pipe into the ejector stack.



7.4.6 Reducing Heat Transfer

Heat Shielding

- Heat shields work by reflecting the heat back toward the source component.
- The surface that faces the hot component must have a low emissive value (reflective surface).
- Heat shields are generally thin, externally metallic, components composed of one or more layers.
- They are typically mounted with an air-gap to the component being shielded.
- They can be mounted either on the source of the heat or the component which has become the sink.
- Care should be taken not to exceed the hot components maximum temperature limit as the heat reflected back increases its temperature further.



Lagging/Wrapping

Modifications made to the engine in the course of installing or using lagging could result in the EU type approval being invalidated for that engine.

Wrapping of the aftertreatment is not recommended, as the insulation can cause local hot spots that may exceed the material temperature limits. However, it is understood that, in some installations, insulation of the aftertreatment will be necessary when heat shield is not a satisfactory solution. When insulation is used it is necessary to confirm that the material temperature limits are not exceeded and that the temperature limits of components close to the DPF are not exceeded in areas where it is not practical to completely insulate, for example, around sensor connections. Additional temperature measurements will be required to allow an installation sign-off.

Wrapping of the engine-to-aftertreatment interconnecting pipe work may also be required in certain circumstances but this must not under any circumstances come into contact with the bellows section, as this would lead to reduced movement capability.

In General:

- Wraps are generally thicker than heat shields and work to minimize the amount of heat that can be radiated from a component's surface.
- The wrap is normally made from a material with low thermal conductivity and must have sufficient thickness to achieve the temperature reduction required.
- A construction with a low emissivity internal surface can help reduce heat transferred into the wrap.
- They can only be used on the heat source component.
- Ensure that the wrap will not increase the source component's temperature above its limit.

7.5 Summary of Thermal Management Tools

Cooling by Convection	Minimizing Radiated Heat	Minimizing Conducted Heat	Other
Optimizing the Location of the Aftertreatment Module			
Internal Ducts/baffles	Heat Shielding	Insulation	Fluid Cooling
Increasing Under-hood Volume		Careful Selection of Material Properties	Heat Sinks
Additional Electric Fans			Reduce Debris Build-up
Exhaust Ejectors			
Hood Perforations			

7.6 Summary of Recommendations

It is recommended that all customers make a study of under hood temperatures around all critical components in normal and worst case operating conditions.

- It is essential that temperature limits of engine and aftertreatment components are not exceeded.
- Heat shielding can be used to protect sensitive components, but it must be carefully installed so it does not act as a heat sink for other components. Resulting in heat being conducted onto the component being shielded.
- Lagging should be used with caution. If used inappropriately it can lead to the lagged component exceeding its own temperature limits.
- When using heat shields care must be taken not to provide a short circuit path for heat transfer, particularly when dealing with materials that have high conductivity. Proper sealing of air leaks around the cooling pack is essential to help minimize the recirculation of hot air onto the cooling pack and/or engine compartment.

8.0 Fuel Systems

8.1 Introduction

The fuel system is a critical engine system, and plays a vital role in delivering not only engine performance, but also compliance with emission standards.

In order for a diesel engine to function correctly it must be supplied with an adequate supply of fuel. The fuel must meet the recommended specification and be free from air, water, and solid matter. The fuel system must be installed correctly and must adhere to installation instructions, cleanliness standards, and be subject to regular maintenance following correct practices and procedures.

8.1.1 Fuel System Safety Requirements

Due to the high pressures generated by the common rail fuel system, the following safety requirements *must* be adhered to when working on the engine.

Failure to follow the correct inspection, maintenance, and service instructions may cause personal injury or death.

- After the engine has stopped, the fuel pressure must be dissipated from the high-pressure (HP) fuel lines before any service or repair is performed on the fuel system. To do this, please follow the service guidelines detailed in the OMM.
- Contact with high-pressure fuel may cause fluid penetration and burn hazards. HP fuel spray will cause a fire hazard.
- It is strongly recommended that an engine cover be fitted over the HP fuel system in applications where the OEM or installer does not provide a machine enclosure to provide protection to a third party.
- Inspection of the fuel lines, hoses, filters, and system components should be undertaken to check for wear and deterioration and to ensure there are no foul conditions. Correct fitment of clamps and heat shield should also be ensured.
- Correct practices and procedures should be followed as outlined in the following appropriate service manuals:
 - Operation and Maintenance Manual (OMM)
 - System Operation Test and Adjust (SOTA)
 - Specifications (Specs)
 - Disassembly and Assembly (D&A)

8.2 Fuel System Mandatory Installation Requirements

All emission-related installation instructions are highlighted by the **EM** symbol.

Failing to follow these instructions when installing a certified engine in a piece of nonroad equipment violates federal law (40 CFR 1068.105(b)), subject to fines or other penalties as described in the Clean Air Act.

8.2.1 General Requirements

- No electrically powered engine cranking is allowable without both the ECU powered up and the HP fuel pump electrically connected. However, manually turning the engine over by hand, where the engine speed can never exceed 15 rev/min, is acceptable. Refer to the Electrical and Electronic A&I manual for further information.
- The engine must be equipped and operated with the filters supplied with the engine.
- Under no circumstances is it acceptable to modify the fuel system components or replace/customize sections of the fuel system that were supplied with the engine (as delivered).
- It is not acceptable to disturb or alter the fuel system lines, mounts, clips, or common rail assembly.
- During fast fill the pressure build-up must not exceed 400 kPa at the electric transfer pump inlet when the engine is not running and 20 kPa if the engine is running. It is recommended that fast fill is not conducted during engine running unless the fuel tank is designed to minimize aeration of the fuel.
- It is not permitted to prime the fuel system by using compressed air.

8.2.2 Cleanliness

- All components installed before the secondary filter including lines and fittings must meet the cleanliness specification detailed in Table 8.1.
- The fuel supply prior to the suction screen must meet cleanliness standard ISO 4406: 1999 level 18/16/13.
- The fuel system components post secondary filter must not be disturbed unless approval has been given by Caterpillar for a remote secondary filter.
- If the fuel lines post secondary filter are disturbed, the fuel entering the FIP must meet cleanliness standard ISO 4406: 1999 level 15/12/9. Controls and procedures must be in place to ensure this.

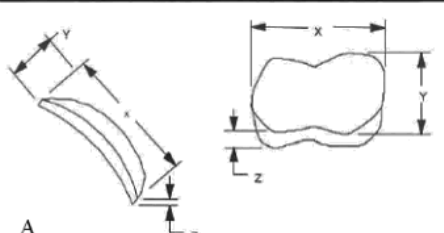
Cat Common Rail OEM Component Cleanliness Standard For components pre secondary filter - (i.e. Fuel tanks and sender units)								
This specification defines cleanliness levels applicable to finished engine components and assemblies.								
All cleanliness standards are based on flushing the specified area with solvent filtering the flushed solvent onto a membrane filter patch, measuring particle dimensions with a microscope and measuring total particle mass with an analytical balance.								
The specified cleanliness must be met at the time of assembly								
Particle to be measured for size are metallic, rust (either free or loosely attached), slag, sand, and other abrasives. If particles are fragile and break up with gentle probing (gentle probing will not tear a membrane filter patch), only the remaining solid pieces are to be measured for specification performance.								
Largest Particle Allowed, in microns (A)			Maximum No. Particles allowed per given particle length, In Microns (a)		Maximum mass allowed (B)		Abrasive (Oxide) restricted (B)	
X	Y	Z	#	X	mg/m2	mg	40	mg
1200	500	150	4	500-1200	170	10	No (D)	1.2
			(B) Per passage (D) For fuel system components only, No more than 10 abrasives greater than 40 microns in size per cleanliness patch # = Number of particles					
Based on 1E2500A								

Table 8.1

8.2.3 Fuel Specification

- The fuel used must meet the specification requirements detailed in the engine OMM. The minimum specification is detailed below.
- Ultra low sulphur diesel with a sulphur content ≤ 15 ppm (required by U.S. law). In Europe this may be marketed as sulphur free fuel and the maximum sulphur content will normally be ≤ 10 ppm, though in certain member states this fuel may contain up to 20 ppm sulphur at point of final delivery to user.
 - Minimum viscosity 1.4 cSt at 40°C
 - Maximum viscosity 4.5 cSt at 40°C
 - Maximum water content in fuel supply is 0.1% (ASTM 1744)
- Lubricity:
 - Maximum wear scar 520 micrometers with no fuel additive.
 - Maximum wear scar 520 micrometers with Perkins recommended fuel additive (see OMM for detail)

8.2.4 Pressure and Temperature Limits

Please refer to Table 8.3 for the process limits of the fuel system.

8.2.5 Fuel Tank Requirements

- The fuel tank must meet cleanliness specification detailed in Table 8.1.
- The fuel tank must be vented and the vent filtered to a maximum of 4 microns.
- The vent must be serviceable and an appropriate maintenance instruction included in the machine manual.
- The tank material must be capable of withstanding the maximum temperature requirements, withstand the fuel types required for use, and must not contain any materials listed within Table 8.2 prohibited materials.
- The use of non-serviceable fuel tank inlet filter (filler neck) is not permitted.

8.2.6 Fuel Line Requirements

- Fuel lines (tank to engine) must meet an SAEJ30R7 minimum requirement and SAEJ30R9 as modified by the manufacturer for specific bio-diesel levels.
- Fuel lines between the Cat Regeneration System pump to aftertreatment must meet the following requirements:
 - 2068 kPa (300 psi) working pressure
 - 4-121°C operating temperature range
- Fuel lines must be adequately supported, as short and direct as possible, with no dips, sags, or kinks. They should be kept away from heat sources and be clear of all fouls with other components.
- Shut-off valves must not be used in either the supply or return line unless an electrical interlock is employed to prevent the engine cranking with the valves closed. It should be noted that cranking/running with the supply/return valves(s) closed can cause damage to the electric fuel pump, Cat Regeneration System pump or common rail pump.
- If the fuel supply tank is above the fuel filters, a non-return or isolation valve with an electrical interlock should be fitted in main return line after the fuel cooler to prevent fuel system drain-back.

Fuel Supply Line

- The main engine fuel supply line must be a minimum of 150 mm away from the fuel return line or lines, at their point of termination inside the fuel tank.
- The fuel supply line must not become uncovered under any operating conditions (machine pitching/slewing, gradeability etc.).
- If a gauze filter is fitted on the fuel supply line it must be accessible for service and diagnostic purposes.
- The C7.1 ACERT engine must have a separate fuel supply line to the Cat Regeneration System taken from the clean side of the primary filter head using the connectors supplied.

Fuel Return Line

- The fuel return line/s must terminate below the minimum fuel level within the fuel tank.
- A non-return valve may be fitted in the RTT line/s, provided the system restriction limits in Table 8.3 are not exceeded.
- If the regulator return line is joined to the main fuel return line:
 - The backpressure in the regulator return line must not exceed the limit in Table 8.3.
 - The join must be after the fuel cooler.
- The fuel return line from engine to fuel cooler must be capable of withstanding a maximum temperature of 140°C.
- The C7.1 ACERT engine must have a separate return line from the Cat Regeneration System to the secondary filter head. The return from the Cat Regeneration System pump must not be returned directly to the tank.

8.2.7 Fuel Filter Requirements

- Only Caterpillar supplied filters may be used within the fuel supply system.

Primary (Pre-filter)

- The primary filter must be placed in a position that is clearly visible and allow sufficient access for servicing safely without damage to other components.
- The primary filter must be mounted vertically within a tolerance of $\pm 5^\circ$.
- The primary filter must be mounted in a location that is isolated from excessive vibration to prevent the emulsification of water in fuel.
- The primary filter must not be subject to G loading in excess of:
 - 10 g vertical low cycle acceleration
- If supplied with a water-in-fuel switch, this must be connected directly to the machine harness.

Secondary (Main Engine) Filter

If approval has been given for a remote secondary filter then the following additional requirements must be adhered to:

- The ECU to secondary filter fuel line must meet material standard SAE J30R9.
- The ECU to secondary filter fuel line must have an internal bore no less than 8 mm.
- The secondary filter must be placed in a position that is clearly visible and may be easily serviced, safely, without damage to other components.
- The secondary filter should be mounted vertically with a tolerance of $\pm 5^\circ$.

- The secondary filter must not be subject to G loading in excess of:
 - 10 g vertical low cycle acceleration
- It is not permitted to remove the quick fit connectors on the secondary filter head during installation or for routine maintenance.
- If a male quick fit is damaged the filter head must be replaced.
- An air vent line must be fitted from the secondary filter to the main fuel return line prior to the fuel cooler.

8.2.8 Inlet Suction Screen

- The inlet screen must be placed in the fuel line prior to the ETP.
- The inlet screen must be located in a position that is easily accessible for service.
- Vibration exposure should not exceed 10 g in any direction.
- The ambient temperature surrounding the inlet screen must not exceed 93°C.
- The fuel inlet connection should point downward and take into account frequent operating conditions.

8.2.9 Electric Transfer Pump (ETP)

- The ETP must not be operated without a fuel supply.
- The ETP must be used with the supplied inlet screen.
- Vibration exposure must not exceed 5 to 800 Hz: 10 g peak in any direction.
- The ETP inlet connection must always be facing downward under all operating conditions.
- The chassis mount ETP must not be disassembled from the supplied mounting plate and is not serviceable.
- The engine mounted (4-cylinder) ETP will be removable from its bracket for servicing.
- The ETP must not operate submerged in water or any other fluid.
- Direct jet washing is prohibited.
- The ambient temperature surrounding the ETP must not exceed 93°C.

8.2.10 Cat Regeneration System C7.1 ACERT Only

- The Cat Regeneration System pump must be mounted off-engine.
- The Cat Regeneration System pump must not be mounted with the manifold pointing downward (reference Figure 8.1).

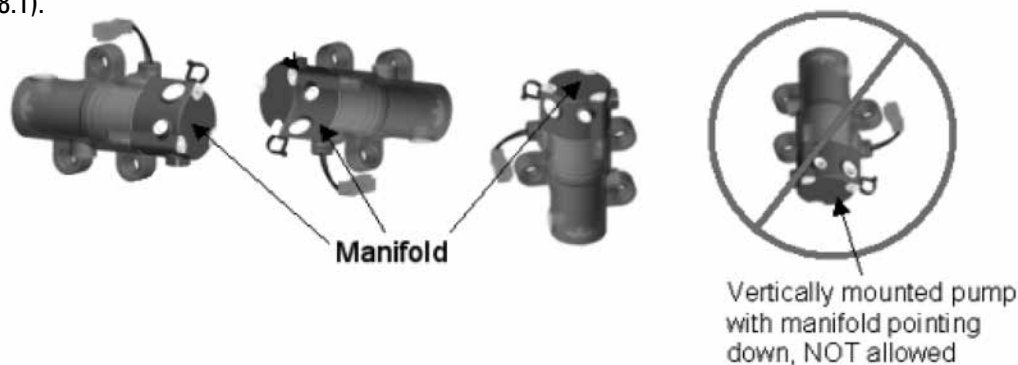


Figure 8.1

- The correct isolation mounts detailed in Figure 8.2 must be used on all 3 mounting points.
 - 3 bolts of diameter M8 or 5/16" must be supplied by the customer.
 - All other components are supplied with the pump.

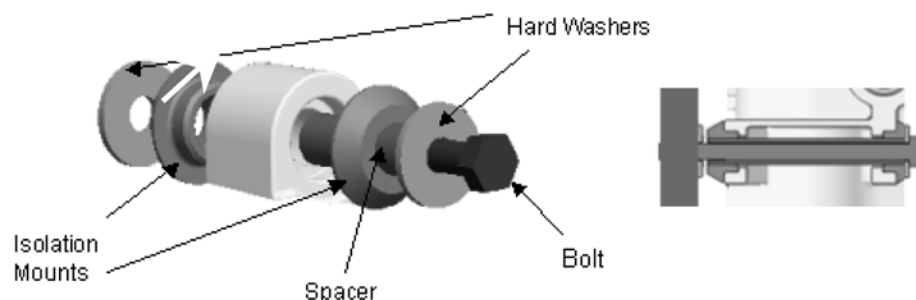


Figure 8.2

- The vibration must not exceed 4 g rms.
- Flexible plumbing is required.
- The ambient temperature surrounding the pump must not exceed 120°C under all operating and shutdown conditions.
- The fuel line restriction limits must not exceed those detailed in Section 8.5.7.
- Do not mount where the Cat Regeneration System pump will be subjected to external forces such as underbrush, etc.

8.2.11 Fuel Connectors

Both the primary and secondary filters are supplied with quick fit connectors on the filter head. The correct mating part must be employed when connecting fuel lines. For all fuel system connection sizes please refer to the relevant E.S.M. It is recommended that you consult your application engineer before design and or resource is initiated.

8.2.12 Prohibited Materials

Table 8.2 contains a list of prohibited materials that must not be used within the fuel system. These should be taken into consideration when selecting and designing any fuel system components such as the fuel tank or fuel cooler. Particular care should be taken with the application of any plating and/or coatings that are used.

Use of these materials may contaminate the fuel leading to coking of the injector nozzle.

Prohibited Material	Symbol
Lead	Pb
Sodium	Na
Calcium	Ca
Zinc or Zinc Plating	Zn
Copper	Cu

Table 8.2

We recommend only the following zinc plates as being acceptable:

- Zinc Phosphate: ASTM B117, D609
- Zinc Chromate/Trivalent plates: ASTM 4042

These materials along with chemical compounds may also be present in fuel and certain fuel additives, e.g. corrosion inhibitors, the presence of which can cause Internal Diesel Injector Deposits (IDID). These deposits may affect the proper functioning of the fuel injectors.

In order to prevent this, fuel additives that have measurable levels of any of the following listed substances should not be used:

- Acids e.g. dimmer and fatty (oleic, stearic and linoleic), including DDS (Diamino Diphenyl Sulfone)
- Alkali metals e.g. sodium, calcium, potassium, etc. including compounds, e.g. sodium chloride, sodium hydroxide, sodium nitrate, etc.

- Carboxylates
- Organic amides

If in doubt please consult your application engineer for further guidance.

8.3 Fuel System Operating Parameters

8.3.1 Fuel Specifications

Please refer to mandatory Installation requirements for details of fuel specifications, quality, and cleanliness requirements.

Ultra Low Sulphur Diesel (ULSD)

ULSD with a maximum fuel sulphur level of either 15 or 20 ppm¹ is required in all diesel applications using a diesel particulate filter (DPF and DOC). Fuel sulphur levels in excess of 20 ppm will rapidly damage the DPF and DOC, likely resulting in the need to replace the aftertreatment unit. Damage to the DPF and/or DOC may impact emissions.

For cleaning and replacement of the DPF please contact your service dealer.

¹EPA regulations require ULSD to be ≤ 15 ppm sulphur content. In the EU, the sulphur content in ULSD for non-road applications varies and may legally be as high as 20 ppm.

Bio-diesel

Bio-diesel fuel may be used up to B20 (80% standard ULSD with 20% bio-fuel dilution by volume), provided an appropriate approved additive is used, refer to OMM for the acceptable specification. Use of higher concentrations will affect performance, durability, and warranty conditions.

As bio-fuel is chemically more reactive than the mineral oil used in diesel fuel, it is imperative to consider the effects of this fuel on all components that it may come into contact with.

Advice should be sought from the applications department if the use of bio-diesel is required.

8.3.2 Temperature and Viscosity

The fuel system compensates for both fuel temperature and viscosity. Provided the fuel temperature is below the maximum limits, the effect of increased fuel temperature and decreased viscosity should not affect the performance and durability of the engine.

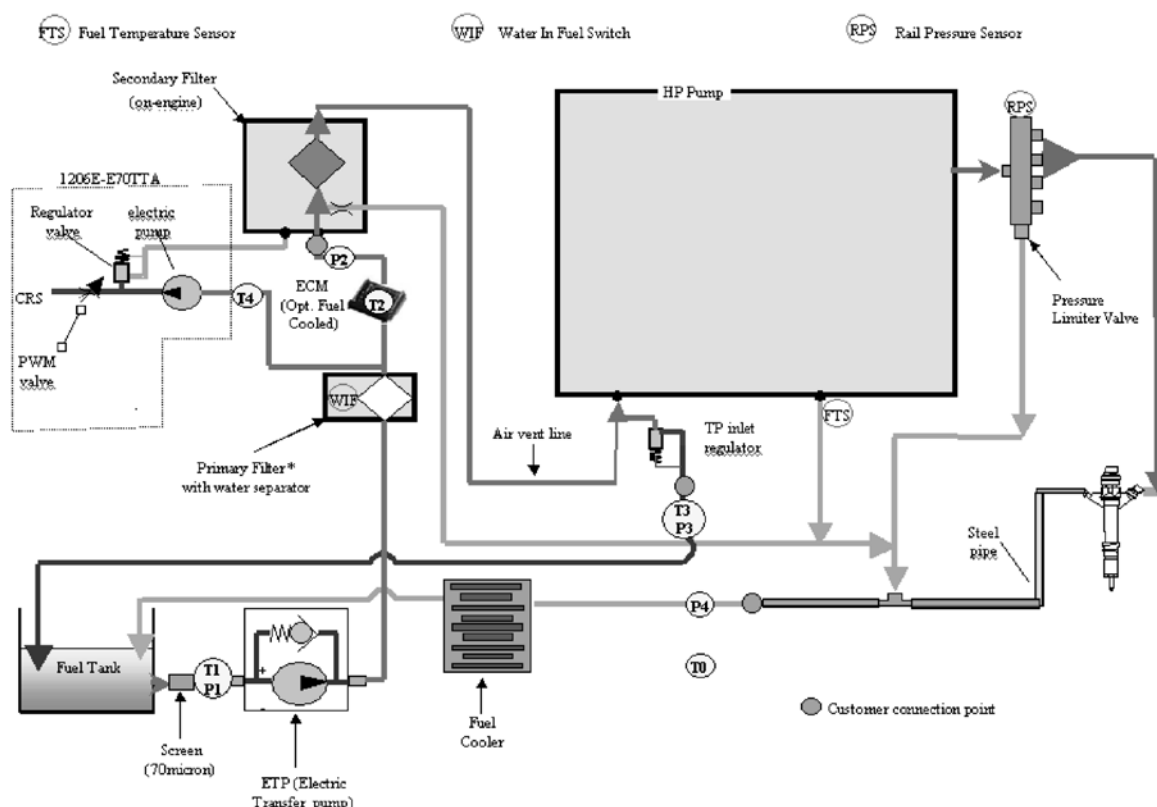
8.4 Fuel System Overview

The C4.4 ACERT-C7.1 ACERT Cat engines use an electronically controlled common rail fuel system. The Electric Transfer Pump (ETP) draws fuel from the tank through a suction screen (which removes any coarse particles from the fuel) to the primary filter where water is separated from the fuel and any primary filtration occurs. The fuel is then used to cool the ECU (unless an air-cooled ECU has been approved for the installation) prior to secondary filtration, where finer contaminants are removed before entering the high-pressure pump. The high-pressure pump supplies fuel at up to 200 MPa to the common rail where it is distributed to the injectors.

Excess fuel is returned from the secondary filter and high-pressure pump, combining with the excess fuel from the common rail limiter valve (not in normal operation) and injector leak-off before returning to the fuel tank. There is also an additional return to tank line at the low-pressure fuel circuit regulator valve; this is required to control the fuel pressure into the high-pressure pump.

For the C7.1 ACERT an additional fuel supply line is required for the Cat Regeneration System, this fuel is taken from the main engine fuel supply after the primary filter and returned into the secondary filter inlet. The connection of this fuel line is the responsibility of the OEM.

8.4.1 Fuel System Schematic



For the 4-cylinder engine the position of the primary filter may change dependant on option selection. For example when a remote secondary filter is selected with an on-engine ETP, a fuel line is supplied directly from the ETP to the ECU. This means the primary filter needs to be fitted after the ECU before the secondary filter. It is acceptable to fit the primary filter before or after the ECU but the integrity of the pipe work supplied with the engine must not be disturbed.

Refer to the Fuel System Test Procedures in TPD1746 for signoff testing requirements.

Component		Min (limit)	Max (limit)
Electric Transfer Pump inlet	P1	-15kPa	+15kPa
	T1*	n/a	93°C
Pipe - ETP to primary Filter		n/a	Recommended 20kpa
Pipe - Primary Filter to ECM (if customer supplied)		n/a	Recommended 15kpa
Pipe – ECM to secondary Filter (if customer supplied)		n/a	Recommended 15kpa
Secondary filter inlet pressure	P2**	(80 +P3) kpa	(120+P3) kpa
LP Regulator return connection	P3	n/a	+15kpa
	T3	n/a	75°C
RTT Line Pre fuel cooler	P4	0	+20kpa
ARD pump inlet	T4	n/a	79°C

Table 8.3

*This is a component temperature limit for the ETP. The system should be designed to ensure that the temperature at T1 is low enough to ensure the maximum temperature at T3 can be achieved.

**P2 needs to be measured to ensure the pressure into the HP pump is within specification. The limit is dependant on the pressure in the TP regulator return line (P3) as this pressure affects the operation of the TP inlet regulator, which controls the HP inlet pressure.

8.4.2 HP Fuel System

The high-pressure pump is a 2 (4-cylinder) or 3 (6-cylinder) plunger pump that is driven at engine speed by the gear train. The pump is inlet metered by a Suction Control Valve (SCV) and is lubricated by fuel oil.

No assisted engine rotation is allowable with the pump electrics unplugged, or without the ECU powered up. It is acceptable to hand crank the engine as long as engine rotational speed does not exceed 15 rpm. The Tier 4 Interim pump differs from the Tier 3 pump, i.e.:

Emissions	Solenoid	Solenoid Valve	Fuel Delivered
Tier 3	De-energized	Closed	Maximum
Tier 4	Fully energized	Closed	Minimum
Tier 4	De-energized	Open	Maximum

If the engine is cranked without powering up the ECU with no power to the pump or injectors, maximum fuel will be delivered to the fuel rail while the injectors draw no fuel from the rail. There will be a consequential build up of pressure in the rail. Although this may activate the pressure relief valve it will have an adverse effect on its durability and it will also risk damage to the pump itself.

8.4.3 LP Fuel System

The low-pressure fuel system consists of an inlet suction screen, ETP, then a two-filter, filtration system as standard with a heavy-duty twin secondary filter arrangement as an option.

A Caterpillar supplied inlet screen, primary and secondary filter is mandatory on all applications. The primary filter includes a water separator and is supplied with water in fuel switch. It can be supplied mounted or as a loose fit option for remote mounting onto the application.

Priming of the low-pressure fuel system is achieved by energizing the ETP during service. This can be achieved by ignition key operation (refer to OMM). Please note that the ETP should not be energized for longer than two minutes without a fuel supply, or ETP damage may result. Nor should it be energized when the fuel supply is shut off; there is a mandatory requirement for an electrical interlock on any shut-off valves in the supply or return lines.

The system is self-venting; therefore, you must not loosen the LP or HP pump, rail, or injector pipes during priming of the system.

8.4.4 Fuel System Components

8.4.4.1 LP — Suction Screen

The supplied inlet suction screen must be fitted in the fuel line prior to the ETP. This screen is a stainless steel mesh strainer and is required to protect the ETP from the ingestion of debris, which may cause internal plugging of the screen within the transfer pump itself. Operation of the ETP without the use of the inlet screen can lead to a reduction of fuel flow and overheating of the pump which can subsequently result in component failure and possible rail pressure derates.

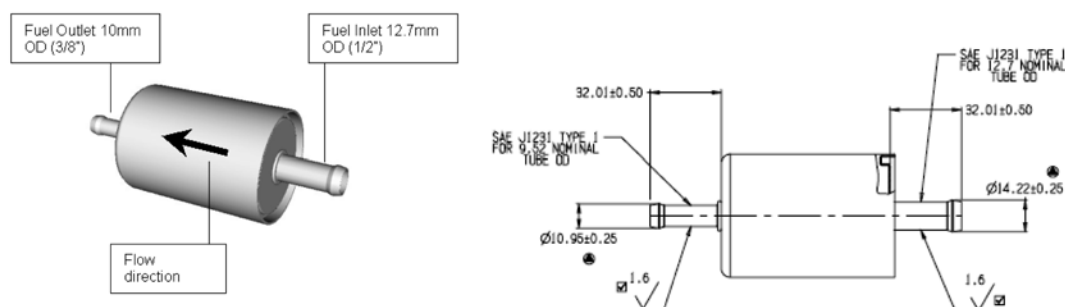


Figure 8.3

8.4.4.2 LP — Electric Transfer Pump (ETP)

The electric transfer pump (ETP) is a roller cell pump that uses brushless motor technology to provide fuel pressure and flow to the low-pressure fuel circuit.

It is supplied as a loose assembly for the OEM to mount to the machine chassis with an additional engine-fitted option on the 4-cylinder product. The assembly is supplied fitted to a manifold, for the chassis-mounted option, which not only provides the mounting surface for pump installation but also houses the fuel outlet connection. The on-engine version uses a cast iron bracket and is fitted by Caterpillar during engine build.

There are two voltage types offered to cater for 12VDC and 24VDC systems.

Control of the ETP is achieved through the engine ECU which energizes the ETP via a machine OEM-supplied relay. The maximum time the pump can be energized (engine not running) for priming is 120 seconds.

For details of the required electrical connections and requirements please refer to the Electrical and Electronic A&I manual LEBH0005.

ETP relay is controlled by a pin on the J1 connector (see pin table in Electrical & Electronic A&I manual). The machine supplied ETP relay suggested part numbers are:

- **115-1615** Mechanical “ice cube” relay, 12V, 85°C temperature limit.
- **3E-5239** Mechanical “ice cube” relay, 24V, 85°C temperature limit.

The ETP electrical specifications are:

- 12VDC – 10A max static current
- 24VDC – 5A max static current

ETP Assembly (chassis mount):

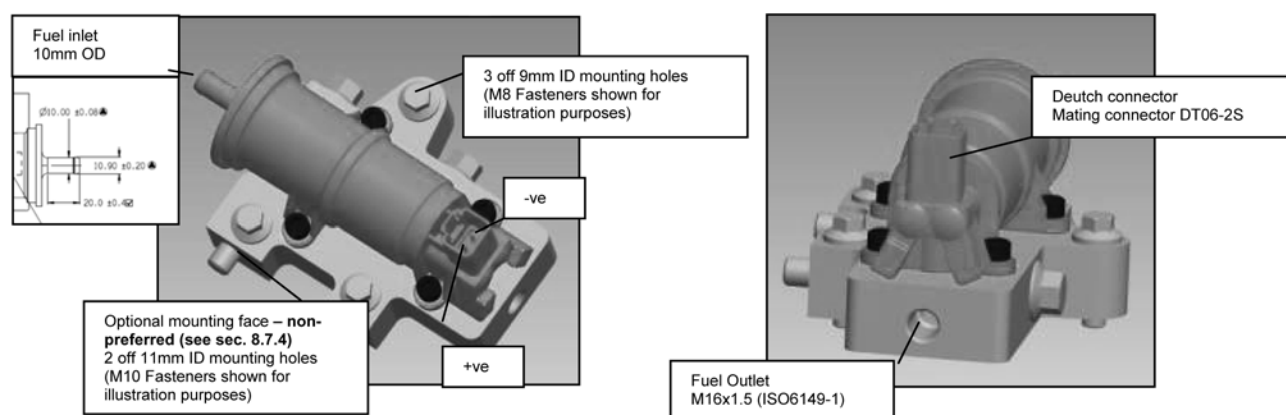


Figure 8.4

8.4.4.3 Cat Regeneration System Fuel Pump

The regeneration system requires the use of ULSD to operate properly during DPF regeneration events. The Cat Regeneration System pump is an electric pump, which is used to supply regulated fuel to the Cat Regeneration System combustion head. It takes its fuel from the main engine fuel supply after the engine primary fuel filter and returns excess flow to the secondary filter head. An additional, non-serviceable, final filter is pre-installed at the Cat Regeneration System fuel manifold inlet to ensure the stringent fuel cleanliness requirements are met.

8.4.4.4 LP — Primary Filters

Primary (Pre) filters are considered the first filter in the engine fuel system and provides a 10-micron filtration level. They also feature a water separator bowl, which must be drained manually.

The primary filters can either be engine-mounted or supplied loose from the factory.

- All primary filters will be supplied with suitable male connectors for customer fitment of fuel lines.
- It is permissible, although not preferred, for these male connectors to be removed and replaced with a preferred connection type, provided it meets the mandatory material specification requirements.

The primary filters can be supplied fitted with water-in-fuel switch as an option. If fitted the switch must be connected directly to the machine harness.

8.4.4.5 LP — Secondary Filters

Secondary filters offer a higher filtration level (4 microns), than the primary filters and are the last serviceable filter before the fuel enters the high pressure pump and consequently, the fuel rail and injectors.

For this reason, it is mandatory that the secondary filter is not modified in any way and is serviced regularly with official OE parts. Although a remote secondary filter option is available it is highly recommended that the standard fitted option is selected and that the remote option is only taken when there are no other available alternatives. If a remote secondary filter option is selected, the mandatory requirements Section 8.2.7 must be adhered to.

8.4.4.6 LP — Heavy-Duty Secondary Filters

Heavy-duty filters are recommended where the machine environment is extremely dusty (mines, etc.) and/or when the fuel supply is likely to be contaminated with particulate. The heavy-duty system features a twin filter arrangement for even greater filtration efficiency.

It is recommended that the heavy-duty filter arrangement be used for machines in dirty environments; or where fuels supplied are known to be of low quality.

8.4.4.7 Additional Fuel System Components

WIF Switch

The WIF switch is an option on the primary filter. It provides a signal to the engine/machine control indicating when the water bowl needs draining, which is useful if access/visibility of the primary filter is limited.

8.4.4.8 Components Requiring a Fuel Feed

Cat Regeneration System Fuel Pump

Refer to Section 8.5.5.

ECU

In order to prevent overheating of sensitive components and capacitors on the electrical circuit board, ECU cooling is provided by a fuel passage, integral to the ECU body. Pipe work to the ECU is provided from the primary filter head as standard, but for the 4-cylinder engine it may also be supplied from the ETP, depending on option selection.

An air-cooled ECU is an option for installations that have good air flow around the ECU and have successfully passed the required testing for approval. Ref TPD1746.

8.5 Fuel System Design Considerations

8.5.1 Fuel System Pipe Work

- All fuel lines should be designed to be as short and direct as possible with no dips, sags, or kinks. They should be kept away from heat sources and be clear of all fouls with other components.
- Pipe work must be to the material specifications outlined in this document. It is recommended that the fuel supply line have a minimum internal diameter of 10 mm.
- The use of shut-off valves must not be used in either the supply or return line unless an electrical interlock is employed. This is to prevent the engine cranking with the valves closed. It should be noted that cranking/running with the supply/return valve(s) closed can cause electric fuel pump or engine damage.
- The fuel return line(s) must terminate below the minimum fuel level within the fuel tank. This is to prevent jetting (aeration of the fuel) and prevent drain-down of the fuel system when the engine is not running.

8.5.2 Fuel System Connectors

- All quick fit connectors used on the supplied system are to SAE standard J2044. It is advised, where possible, that these are used on all machine interfaces with the engine fuel system (excludes RTT connection).

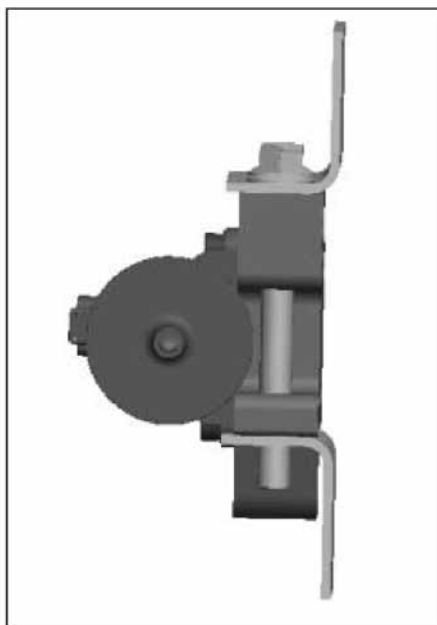
8.5.3 Fuel Inlet Screen

- The fuel inlet screen must be fitted in the fuel line prior to the ETP. All connections must be clean, tight, and leak-free and the screen itself must be adequately supported to prevent any vibration or transmission through the fuel lines, which may cause consequential damage. Fuel lines should also be clipped and adequately supported within 100 mm of the screen interfaces.
- Mounting of the screen can be achieved using P-clips or saddle clamps but care must be taken to ensure that the screen housing is not deformed. Vibration exposure should not exceed the maximum limit in the mandatory Section 8.2.8 and isolation mounting must be used if required. If this is thought necessary, however, then it is recommended that the A&I engineer is consulted before any design is pursued. The preferred screen orientation is vertical with the inlet connection pointing downward, taking gradeability of the machine and frequent operating conditions into consideration.
- The inlet screen requires servicing and must be serviced in accordance with the requirements in the OMM. It must, therefore, be located in a position that is easily accessible for service. Areas that are exposed to collision, operator, or service damage should be avoided as well as positions that are in close proximity to any source of heat. Ideally the screen should be placed in a location with good airflow to ensure that the temperature under all conditions remains below the maximum listed in the mandatory requirements Section 8.2.8.

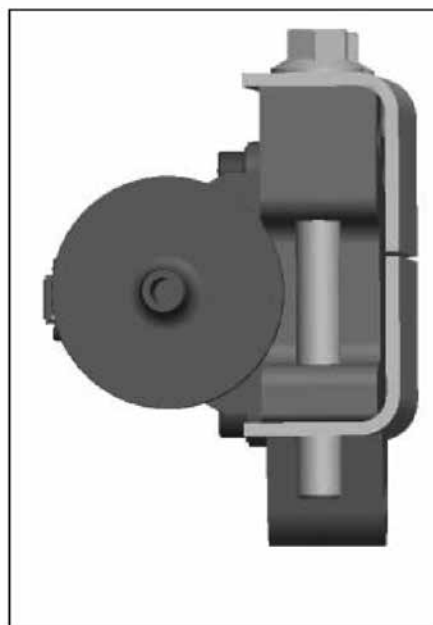
8.5.4 Electric Transfer Pump (ETP)

- The ETP should be located as close to the machine fuel tank as possible, prior to the primary fuel filter, with sufficient space made available to install and service the suction screen. The supplied suction screen must be used to maintain the performance of the pump, without which, the performance may degrade and premature failure may occur.
- If the machine has a wading requirement then the ETP should be installed no less than 100 mm above the fording line to ensure that the ETP is not submerged during machine/ETP operation. If considered possible or likely then the pump should also be protected against direct jet washing.
- To prevent damage to the ETP, the correct voltage ETP must be selected for the machine — a 12VDC pump should not be used on a 24VDC machine. There must also be a continuous, uninterrupted fuel supply to the pump to prevent premature failure of the pump or motor.
- When mounting the ETP to the machine careful consideration needs to be given to the suitability of the mounting location. Areas that are exposed to collision, operator, or service damage should be avoided as well as positions that are in close proximity to any source of heat where the ambient temperature could exceed the maximum limit (with the ETP operational). Please refer to mandatory requirement 8.2.9. Fuel tank surfaces are also not considered ideal as they may promote noise radiation.
- The mounting area itself should be flat and should, ideally, be paint-free. If mounting on a painted surface, it is recommended that the paint thickness should not exceed 20 microns in order to reduce the risk of vibration that may propagate over time. Vibration exposure should not exceed the maximum limit in the mandatory requirements 8.2.9 and isolation mounting should be considered if thought necessary. It is recommended, however, to consult your A&I engineer before proceeding with any design.
- All connections to the ETP must be clean, tight, and leak-free. Fuel lines should be clipped and adequately supported within 100 mm of the ETP interfaces. The ETP should only be painted after the fuel connections have been masked and with the electrical connection made (connector in place).
- The ETP should never be mounted with the inlet connection uppermost as this can lead to air lock formation. The preferred orientation is with the pump vertical and the inlet connection pointing downward (machine gradeability must also be taken into account).

- When mounting the ETP using the optional mounting face (2-bolt fixing), one of the two suggested mounting schemes detailed below should be used to ensure that the pump is adequately supported.
- The correct torque values for all fasteners must be applied and controlled.



Scheme 1



Scheme 2

8.5.5 Cat Regeneration System Fuel Pump

- The Cat Regeneration System fuel pump must be mounted off engine to minimize the exposure to vibration. Every effort should be made to mount the pump in the location with the least vibration possible. Assistance can be provided where required. On inspection of the final design, any installation of the pump deemed unsuitable will be required to undergo a vibration assessment. Further assessment details will be provided if required.
- In order to isolate the pump and reduce vibration load into it, it is recommended that isolation mounts be used on all three mounting points of the electric pump.
- Flexible plumbing is also required to help prevent vibration transmission. Fuel inlet and return lines should be sized in order to minimize inlet restriction to the pump to within the acceptable limits detailed in Section 8.5.7.
- The location of the pump should be carefully considered; it must meet the mandatory installation requirements but must also be accessible for service with a minimum of 32 mm clearance from the regulator valve, not subject to damage or excessive heat and must meet the maximum height restrictions.
- For electrical connection details of the pump, please refer to the Electrical and Electronic Installation Manual.

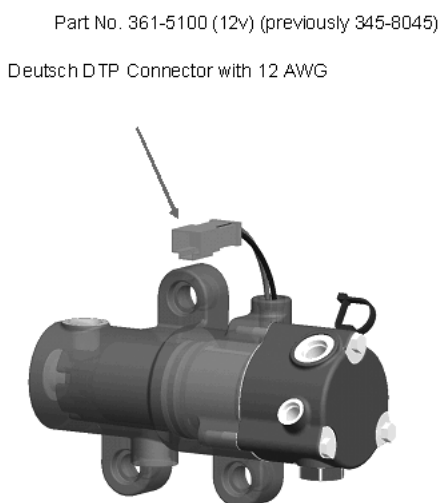
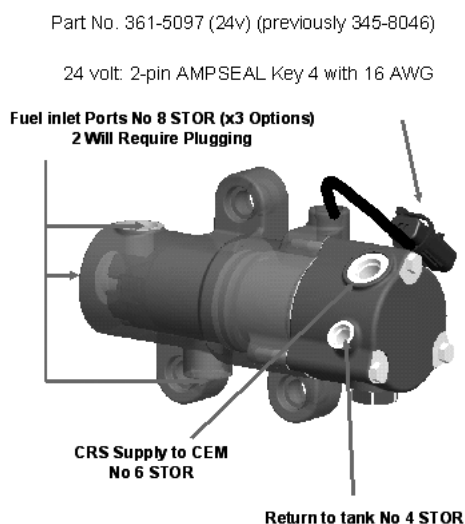
8.5.6 Cat Regeneration System Fuel Line Connection Points

Table 8.4 provides the connection points for the Cat Regeneration System fuel system.

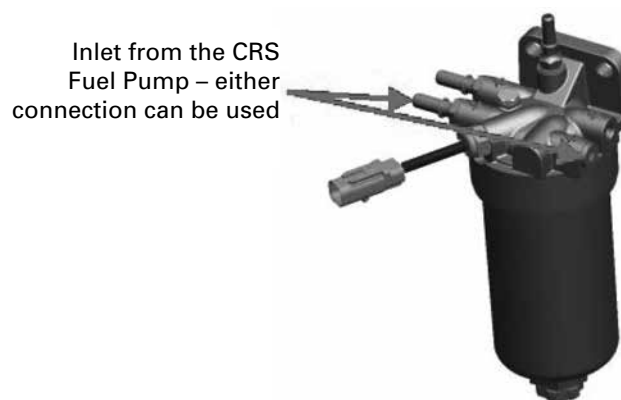
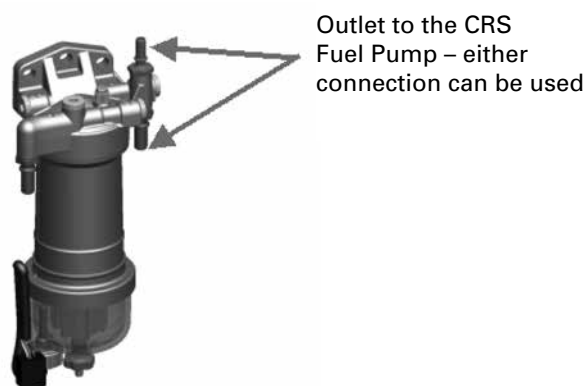
Connection Point	Description	Fitting Type	Application
Cat Regeneration System Fuel Pump Inlet	Fuel Line from Fuel Source	No. 8 STOR	C7.1 ACERT
Cat Regeneration System Pump Discharge	Fuel Line from Cat Regeneration System Fuel Pump to AT	No. 6 STOR	
Aftertreatment Module Fuel Inlet	Fuel Line from Cat Regeneration System Fuel Pump to AT Fuel Inlet	11/16 ORFS	
Cat Regeneration System Pump Return	Fuel Line Return to Secondary Filter	No. 4 STOR	

Table 8.4

Cat Regeneration System Fuel Pump Connections



Primary fuel filter connection points for Cat Regeneration System fuel pump feed (C7.1 ACERT only).



Secondary fuel filter connection points for Cat Regeneration System fuel pump feed (C7.1 ACERT only).

Figure 8.5

8.5.7 Cat Regeneration System Fuel Line Restriction

The fuel lines need to be routed and sized to meet flow restriction specifications for the Cat Regeneration System fuel system lines. Flow restriction of a line is the pressure loss across the line when fuel flows through it. The flow and maximum restriction (pressure drop) requirements of Cat Regeneration System fuel lines are specified in Table 8.5.

Cat Regeneration System Fuel Line	Restriction Allowable @ Pump
Cat Regeneration System Pump Discharge to AT Inlet Manifold	20 kPa Max @ 1 LPM
Cat Regeneration System Pump Inlet Line from Primary Fuel Filter Out	27 kPa @ 1.5 LPM
Cat Regeneration System Pump Return to Secondary Fuel Filter Head	20 kPa Max @ 1 LPM

Table 8.5

The table below shows pressure drop for different horizontal line lengths, ID size and 45° and 90° bends. Use this chart to validate intended fuel line installation design to ensure the pressure drops fall within the allowable at pump pressures specified in Table 8.5 above. Elevation head pressure contributes approximately 2 kPa per 0.3 m of elevation when aftertreatment is located above pump regardless of line size.

Flow Rate L/Min	Line ID	Line & Elbow Restriction (kPa)								
		Line Length in mm							45° Elbow	90° Elbow
		200	500	1000	2000	3000	4000	5000		
1	6.2	0.21	0.42	0.84	1.68	2.52	3.36	4.20	0.30	0.45
	7.9	0.08	0.16	0.32	0.64	0.96	1.28	1.60	0.20	0.27
	10.3	0.03	0.06	0.12	0.24	0.36	0.48	0.60	0.10	0.15

8.5.8 Fuel Cooling

There is an increase in fuel return temperatures on all the Cat C4.4 ACERT-C7.1 ACERT Tier 4 Interim products. Higher fuel rail pressures leading to increased injector leak-off temperatures have largely driven this, combined with an anticipated increase in under hood temperatures.

It is, therefore, even more pertinent to assess the need for fuel cooling to ensure that not only is the maximum fuel temperature not exceeded, but the fuel returning to the tank does not exceed the material capabilities of the tank and fuel lines. This must be considered for all conditions of operation including the minimum level of fuel in the tank.

The factors affecting fuel cooling are complex and dependant largely on the installation and duty cycle of the machine.

The following factors have been found to have a significant influence on the temperature of the fuel:

- Fuel tank location — positioned near an additional heat source, i.e., hydraulic tank, subject to good air flow
- Fuel Tank material and cross sectional area — ability to dissipate heat
- Under hood temperatures — ability of components to dissipate heat
- Fan — pusher/puller airflow across the fuel tank, filters, and pipe work along with its location
- Material and routing of fuel lines
- Reserve volume of fuel in the tank

If a fuel cooler is required it is the OEMs responsibility to provide and install the fuel cooler while adhering to the cleanliness, pressure, and temperature requirements.

It is recommended that the fuel cooler be fitted on the fuel-return-to-tank line; although the flow rate is lower than at the supply line, the higher temperatures should provide a more efficient cooling solution.

8.5.8.1 Fuel Cooler Specifications

Contact your applications engineer for guidance on fuel cooler sizing/selection.

- Flow range, inlet temperature objectives etc must be stabilized and below the tank maximum material temperature limit.

8.5.9 Fuel Tank Design and Installation

The fuel tank must be located to ensure that the maximum fuel pressure head, fuel supply and fuel return restrictions are not exceeded.

The tank must be designed to include the following features:

- Expansion space
- Sediment space (required to prevent suction screen plugging)
- Drainage
- *Tank vent and filter – see mandatory requirements
- Serviceable large particle filter, within tank filler neck

Tank baffling should be considered, particularly where machines can experience extreme or frequent changes in gradient. It is essential to ensure that under all achievable gradient conditions there is sufficient fuel level to cover the fuel supply line; this is to prevent unnecessary machine stoppages or reduced ETP pressure/flow and hence engine performance. Minimum tank volume of 5% or more.

Care should be taken not to exceed the maximum high-pressure pump inlet pressure specified in the E.S.M. when applying fast fill procedures during machine assembly; adequate venting during filling should control this.

*The tank vent must be serviceable and sized to achieve a 500-hour service interval, taking into consideration the environment where the machine is operating, particularly if high levels of airborne debris are likely.

Material Specifications

- The fuel tank material should be matched to the calculated return-to-tank fuel temperatures as stated in the mandatory requirements. This should include the fuel temperatures seen in all operating conditions and under all tank fuel levels.
- The tank should not contain any of those materials on the prohibited materials list see Table 8.2.
- Care should be taken to ensure that any fluid-borne contamination does not contaminate the fuel system. The use of chemicals in the fuel tank manufacturing processes and the use of vapour corrosion inhibitors increase the risk and particular care to be taken to ensure rigorous flushing processes are employed.
- If the use of bio-fuels is likely then care should be taken that the material selected is resistant to the solvent effects and their associated degradation, which may adversely affect some tank paints and surface coatings. The tank should not be translucent, as light can cause photo-degradation of bio-fuels.

8.5.10 Serviceability

All filters and screens must be located in positions which are easily accessible for service with sufficient space allowed for filter removal and access to the water drain. Consideration should be made for the addition of a hose on the water drain which may be required to help capture the water when draining. Care must be taken to ensure that filters are not placed directly above any rotating electrics or hot surfaces which would be at risk from any fuel leaks and spillages during normal operating practices.

In addition to the fuel filters the fuel tank vent location must also be accessible for service and the filter media easily removed and replaced as part of a routine maintenance schedule for the machine.

If a gauze filter is fitted on the fuel supply line it must be accessible for service and diagnostic purposes.

9.0 Lubrication Systems

9.1 Introduction

It is important to ensure that the lubrication system is compatible with the particular application and operating conditions to which the engine will be subjected.

Factors that should be taken into consideration include:

- Lubricating oil specifications
- Lubricating oil temperatures
- Oil sump capacity and gradeability (tilt)
- Pressure losses in any external systems
- Protection from dirt contamination
- Reference should also be made to Chapter 6 — Cooling Systems, in relation to lubricating oil cooling.

9.2 Lubrication System Mandatory Requirements

All emission-related installation instructions are highlighted by the **EM** symbol.

Failing to follow these instructions when installing a certified engine in a piece of nonroad equipment violates federal law (40 CFR 1068.105(b)), subject to fines or other penalties as described in the Clean Air Act.

9.2.1 General Requirements

- Maximum operating temperature not to exceed 125°C continuous and 135°C intermittent* (measured at main oil gallery or filter head).
- The oil pan must be matched to meet the machine's maximum gradeability (tilt).
 - This must include installed engine angle plus the maximum machine tilt in operation.
- The maximum oil change is 500 hours, with Caterpillar specified oil. This period may need to be reduced in severe operating conditions, e.g., heavy dust or elevated operating temperatures.

* Intermittent is defined as when the maximum sustained temperature is limited to 10% of the total machine operation or no more than 1 hour in every continuous operating period.

9.2.2 Remote Filter Installation Requirements

- Remote oil filter systems must be approved by Caterpillar.

9.2.2.1 System Pressure

- Nominal operating delivery pressure 400-480 kPa at normal operating temperature at rated speed.
- Max operating pressure: 1400 kPa.
- Burst pressure for filter assembly: 1900 kPa
- Filter assembly integrity: 1400 ± 35 kPa: 10 million cycles

9.2.2.2 System Pressure Drop

- Max system restriction of 50 kPa (clean filter) with 50 L/min oil flow at 100°C. Measured between engine-out and return-to-engine (including all pipe work and filter), with the standard 15W/40 oil grade.

9.2.2.3 Working Temperature Capability

- If any elastomeric sealing ring or adhesive is incorporated in the design it must be functional through the temperature range -40 to +150°C.

9.2.2.4 Hose Specification

- Hose assemblies must be capable of withstanding the test requirements as specified in Cat TD104 part II class L. Please contact your applications engineer for further information.

9.2.2.5 Cleanliness

- Maximum dirt levels within oil filter head: 5 mg according to Cat TD292. Please contact your applications engineer for further information.
- Maximum dirt levels within fluid handling hoses and pipe work: 6 mg/m length.
- Maximum particle size within fluid handling hoses and pipe work: non-rubber particle size to be 125 microns MAX, rubber particle size to be 600 microns MAX.

9.2.3 Summary of Remote System Recommendations

- Pressure tight screw connections should be used for lubricating oil pipes.
- When arranging the pipe work, enough flexibility should be allowed to accommodate any relative movement of components, but it is important that the pipe is positioned so that it cannot be rubbed or damaged during any operating condition.
- Additional clamping may be used on all pipes except on the braided part of those pipes with external metal braiding.

9.3 Lubrication System Design Considerations

9.3.1 Oil Temperature

Working within the maximum oil temperature limits specified in the mandatory requirements helps to:

- Protect bearings, oil seals, and all wearing surfaces of the engine, as well as avoiding excessively high oil consumption
- Control viscosity
- Ensure that oil condition is managed satisfactorily up to the specified oil change periods

The engine oil temperature is directly related to coolant temperature through the use of a water-cooled engine-mounted oil cooler. In order to help maintain oil temperature within the mandatory limits, the installation should be designed to provide good airflow across the engine, particularly around the sump (oil pan) area where hot air can frequently stagnate.

Remote Filters

On certain engine types, when the standard oil filter positions are not accessible in the installation, a remote-mounted filter may be used. Remote oil filters systems must be approved by Caterpillar. See also 9.2.2.

9.4 Serviceability

- To achieve satisfactory engine service life, it is essential to adhere to the oil and filter cartridge change periods recommended in the OMM.
- To facilitate oil changes and filter cartridge removal, it is essential for these and the dipstick to be positioned in a readily accessible position and to be protected from possible damage.
- Whenever possible it should not be necessary to remove the engine in order to remove the oil sump (oil pan).
- It should be recognized that the oil cooler can hold significant quantities of oil, which may not be fully drained and changed in the course of routine engine oil changes.

9.4.1 Approved Oils

It is important to use only lubricating oil that conforms to an approved specification to suit a particular engine type. The engine E.S.M. gives approved oil specifications. Information is also given on viscosity ranges recommended for operation within various ambient temperature ranges.

9.5 System Components

9.5.1 Lubricating Oil Filters

- The engines are supplied with full-flow lubricating oil filters as standard equipment.
- These filters are designed specifically for use on diesel engines to adequately handle the flow, temperature, and pressure involved, and provide the required filtration capacity.
- It is not recommended that any filter type other than that supplied with the engine should be used.

9.5.2 Oil Cooler

All Tier 4, 6-cylinder engines are fitted with:

- Below 130 kW = 12-plate oil coolers
- 130 to 205 kW = 15-plate oil coolers
- 205 kW or greater = 16-plate oil coolers

All Tier 4, 4-cylinder, engines are fitted with 6-plate oil coolers.

The technology used to meet Tier 4 emissions requirements has led to greater heat being rejected to oil, and this increase has been accommodated by improvements to the oil cooler and cooling system.

The flange head fixings retaining the cover of the lubricating oil cooler must not be removed (unless for service) or have any form of brackets attached to them, to ensure that the integrity of the joint is maintained.

9.5.3 Oil Sampling Valve

The oil-sampling valve is an optional component fitted in the oil filter head. It is a non-return check valve for oil sampling purposes only and is supplied with a fitted dust cap.

9.5.4 Auxiliary Components Requiring Lubricating Oil

Auxiliary driven equipment, such as hydraulic pump drives, will require lubricating oil feed and returns. These oil feeds and returns are available, as at Tier 3, on the LHS of the block.

Pipe work can be supplied fitted for these options if included in the engine specification. This pipe work will be steel tubing with compression fittings at the compressor and engine cylinder block interfaces.

10.0 Crankcase Ventilation Systems

10.1 Introduction

Unlike previous emissions regulations, Tier 4 regulations require all crankcase emissions to be included in the total system emission values. It is, therefore, essential to ensure that the crankcase ventilation system and any of its associated components are correctly installed to provide a robust and durable system that ensures compliance throughout the life of the product.

The correct Installation of the crankcase ventilation system is mandatory to enable installation approval.

10.2 Crankcase Ventilation System Mandatory Requirements

All emission-related installation instructions are highlighted by the **EM** symbol.

Failing to follow these instructions when installing a certified engine in a piece of nonroad equipment violates federal law (40 CFR 1068.105(b)), subject to fines or other penalties as described in the Clean Air Act.

10.2.1 General Requirements

- **EM** During sustained continuous operation the pressure in the crankcase ventilation system must not exceed 3 kPa. For transient intermittent conditions the system must not exceed 5 kPa regardless of conditions.
- **EM** Gases in the breather canister outlet pipe must be kept above 5°C at all sustained operating conditions. Please refer to Chapter 14 — Cold Weather Operation, for further details.
- **EM** Crankcase ventilation systems component operating temperature limits must not be exceeded. Please refer to Chapter 7 — Under Hood Thermal Management, for these temperature limits.

10.2.2 Open Crankcase Ventilation (OCV) — H0300

- **EM** If extension of the vent hose is required, the hose connector provided must be used. (This is fitted to the exit point at sump joint level.)
- **EM** The hose clamp used to secure this extension to the connector must be tightened to 5 N•m +/-1 N•m.
- **EM** The extension must not have any dips or sags.
- **EM** The maximum unsupported mass that can be suspended from the vent hose connector is 300 grams.

10.2.3 Closed Crankcase Ventilation (CCV)

- **EM** Engines built into machines sold into EPA territories must not be converted to CCV as a factory-fit option.
 - Aftermarket fitment following the machine's final title transfer to the end user is acceptable provided a reasonable basis exists for knowing that such use will not adversely affect compliance with emissions standards.
- For non-EPA territories the crankcase ventilation system may be converted to a closed system.
- In all cases the following installation requirements must be met:
 - Filtered crankcase gases must be returned into the induction system between the air filter and the turbo air inlet.
 - The breather canister-to-induction pipe restriction must not exceed 0.5 kPa at a gas flow rate of 200 L/min.
 - The hose must not have any dips or sags.

10.2.4 Material Specifications

All customer-supplied hoses, used within the crankcase ventilation system, must meet the following requirements:

- Must not allow the permeation of oil; materials considered to be acceptable include the following:
 - Silicone pipe with a fluoro elastomer lining is used to meet this specification.
 - SAE 517 type 100R6 hydraulic pipe (BS EN 854 type R6 and ISO 4079-1 type R6 are equivalents).
 - Extruded Polyamide tube
- Must have a minimum nominal internal diameter of:
 - 25 mm for breather pipe (6-cylinder)
 - 19 mm for breather pipe (4-cylinder)

10.3 Crankcase Ventilation Fundamentals

Crankcase ventilation systems are designed to control the balance of air pressure between the engine crankcase and the atmosphere while processing the accompanying fumes.

Crankcase pressures that are excessively above or below atmospheric pressure can have negative affects on component life, the lubricating oil system and overall engine emissions.

10.3.1 Crankcase Emissions

Crankcase emissions result from combustion by-products and/or exhaust fumes escaping around the piston rings, turbochargers, valve stem seals, and auxiliary driven equipment into the crankcase. These escaping fumes are commonly called blow-by. If not controlled, it can pressurize the crankcase, possibly leading to an oil leak.

The overall volume of blow-by varies due to cylinder pressure, piston ring pressure, and component wear. Venting the emissions to the atmosphere is a simple solution to release the pressure and trapped fumes. The need to manage these emissions to meet Tier 4 regulatory requirements adds complexity to crankcase ventilation systems.

Elements found in blow-by can include wear particles, oil, fuel, gas, and air. The specific composition of the elements varies due to fuel type, engine type, engine speed, load, and maintenance history. Typically, blow-by is made up of hydrocarbons (HC), carbon monoxide (CO), carbon dioxide (CO₂), and nitrogen oxides (NO_x).

10.3.2 Crankcase Ventilation

Crankcase ventilation systems can be classified as either Open Crankcase Ventilation (OCV), or Closed Crankcase Ventilation (CCV). An open system vents blow-by to the atmosphere. A closed system vents the blow-by into the intake air stream where it returns to the combustion process.

C4.4 ACERT-C7.1 ACERT engines are all supplied with open systems featuring a high efficiency coalescing filter, which separates the filtered oil vapor from the blow-by gases and drains it back to the cylinder block. These filters are not optional and must be serviced at predefined service intervals. Please refer to the engine OMM.

Maximum pressure restriction limits on the system exist to minimize the risk of excessive crankcase pressure build up, which can lead to the damage of oil seals, resulting in engine oil leaks.

10.3.3 System Arrangements

OCV

In open systems the filtered crankcase emissions are vented to the atmosphere. As shown in Figure 10.1, any gas or vapors that exit the filter are routed through a pipe to below sump joint height where it terminates (clipped back to the cylinder block).

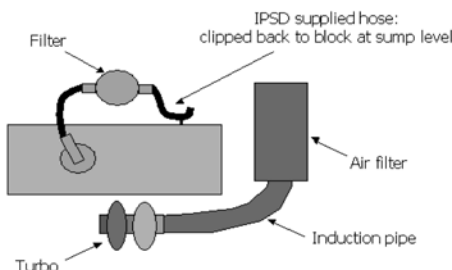


Figure 10.1

CCV

CCV systems must route any crankcase emissions into the intake air stream.

A low pressure CCV system involves piping the crankcase emissions into the low-pressure side of the turbocharger. As shown in Figure 10.2, the blow-by gases flow from the crankcase, through the coalescing filter and are then routed to the induction pipe and into the turbocharger. They then pass through the charge cooler and back into the inlet manifold until they reach the combustion chamber.

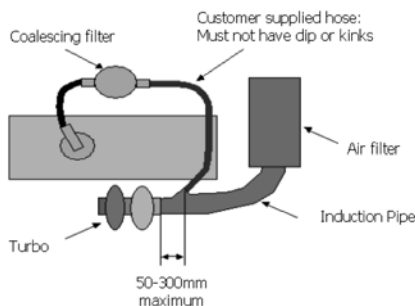


Figure 10.2

10.4 Crankcase Ventilation System Design Considerations

10.4.1 General System Considerations

The type of crankcase ventilation system needs to be carefully considered based on the territory and operating environment of the machine.

The OCV system fitted on all C4.4 ACERT-C7.1 ACERT engines has a high-efficiency filter; however, condensate, mainly sooty water, and occasionally condensed oil vapor, will be discharged from outlet pipe. In some territories this type of discharge is unacceptable, therefore a CCV system or catch tank may be considered.

OCV System

For an OCV system there is no requirement for additional components to be added unless an alternative termination point for the pipe is needed. In this instance an extension of the pipe length will be allowable, provided the mandatory OCV installation requirements have been met. If the vent hose is extended, there should be a continual fall with no dips or sags in the pipe.

CCV System

For a CCV system additional parts are required to close the system. These components are not available within the engine offering and are the sole responsibility of the customer.

Closing an open breather relies on the high efficiency of the coalescing filter to prevent significant amounts of vapor or particulate reaching the turbo inlet. It is therefore essential to ensure that the correct guidelines and service procedures are followed. Please refer to the relevant engine OMM for further information.

If connecting directly onto the breather canister, care should be taken to ensure that the connector selected is robust and can support the type of hose selected. Standard quick-fit connectors are generally only suitable for lightweight hoses i.e., polyamide 11/12 and heavy-duty quick-fit connectors are normally required for anything more substantial.

Note: CCV may only be used if the mandatory requirements in Section 10.2.4 are met.

For all systems the following recommendations should be considered:

- Ensure adequate support is provided for all fitted pipes.
- Pipe lengths should be kept as short as possible.
- Pipes should be clear of any foul conditions and not be crushed or deformed.
- It is recommended to run all pipes as close to the engine as possible and away from any cold air streams to help meet the temperature requirements.

10.4.2 Operation in Cold Ambient Conditions

Crankcase ventilation gases contain a large quantity of water vapor. This water can freeze in cold ambient conditions and block or damage parts of the crankcase ventilation system. The extent of vulnerability is highly dependant on the application. For this reason, lagged or heated pipes may be required in cold conditions to comply with the minimum gas temperature detailed in the mandatory requirements Section 10.2.1. Refer to Chapter 14 — Cold Weather Operation, for further details.

10.4.3 Serviceability

The following serviceability items pertaining to the crankcase ventilation system should be considered when designing the engine installation:

- 200 mm of vertical clearance is recommended for removal of the filter element (top or bottom for the 6-cylinder, top only for the 4-cylinder product).
- Running pipe work in front of/over serviceable components should be avoided where possible.

10.4.4 In-use Testing of OCV System (H0300)

Tier 4 emissions regulations include in-use testing of applications. If using an OCV system, the exit pipe emissions must be measured during in-use testing. Please refer to Chapter 5 — Aftertreatment and Exhaust Systems, for further information.

The design of the installation must, therefore, be able to accommodate this requirement by allowing the fitment of any necessary testing and measuring equipment with minimal modification.

Further details of the requirements and recommendations will be provided once EPA has promulgated regulations governing in-use testing.

10.5 System Components

10.5.1 Primary Separator

The primary separator, on the engine top cover, is essential for efficient removal of liquid oil by impaction. The primary separator design has been modified at Tier 4 to include the following new features:

- Optimized geometry to maximize oil removal
- Single-piece design to reduce joint interfaces
- Increased outlet size to decrease pressure drop improving oil drainage from the coalescing filter
- Quick fit connection to pipe with o-ring sealing

10.5.2 Coalescing Filter

For Tier 4, the breather canister contains a high efficiency oil coalescing filter element. This incorporates significant changes both internally and externally to the filters used on earlier generations of Cat engines. For this reason they are not interchangeable. Using a Tier 3 breather canister or element on a Tier 4 engine is not permissible because it will result in noncompliance with Tier 4 emission standards.

A filter element must always be in the breather canister when the engine is running. Running without an element will cause emissions non-compliance and potential induction system fouling (CCV only), with engine performance reduction.

- Features a tool-free top and bottom service on the 6-cylinder product and tool-free top servicing on the 4-cylinder product.
- Quick fit connector stubs are featured on all connections to and from the canister.
- Tier 4 regulations increase the service interval to 1500 hours.

10.5.3 Breather Pipes

All Caterpillar supplied pipes are made from convoluted Polyamide (PA11 or PA12) plastic with quick fit connectors.

10.5.4 Non-return Valve

The drain from the oil coalescing filter features a non-return valve at the interface with the block to prevent bypass of the filter.

10.5.5 Quick Fit Connectors

The crankcase ventilation system features quick fit connectors throughout for all pipe connections.

11.0 Starting and Charging Systems

11.1 Introduction

The detailed installation requirements for all electrical starting and charging systems are contained within the Tier 4 Interim Rotating Electrics Manual obtained from your applications engineer.

Listed below are the mandatory requirements for this system, however, Tier 4 Interim Rotating Electrics Manual obtained from your applications engineer should be reviewed thoroughly before any design work is conducted. This document provides a detailed explanation of the mandatory requirements, provides specific electrical product information, and gives general recommendations and good practice guidelines. Additional information may also be found in the Tier 4a Electrical and Electrical Installation manual LEBH0005.

11.2 Starting and Charging Mandatory Requirements

All emission-related installation instructions are highlighted by the **EM** symbol.

Failing to follow these instructions when installing a certified engine in a piece of nonroad equipment violates federal law (40 CFR 1068.105(b)), subject to fines or other penalties as described in the Clean Air Act.

Refer to Tier 4 Interim Rotating Electrics Manual obtained from your applications engineer for exact values not detailed below.

11.2.1 Starting Motor

The starter motor selected must be suitable for the working environment of the machine.

The starter motor must be selected to ensure that:

- Minimum cranking speed over TDC > 60 rpm.
- The minimum mean cranking speed must be > 100 rpm.
- The starter motor must be located so that the starter is protected from fluid spills, debris and extreme environmental conditions.
- The maximum temperature of the starter motor must not be exceeded.
- The following minimum clearances must be maintained between the starter and engine components:
 - Exhaust manifold $\geq$ 50 mm
 - Engine parts (including brackets attached to the engine) $\geq$ 4 mm
 - Body parts $\geq$ 30 mm
 - Wiring harness/application wiring — no interference
- The starter drain must not be restricted so fluids can drain out easily.
- Starter motors must be operated within the following parameters:
 - The maximum time for continuous crank must not exceed 30 seconds, following which the starter should be allowed to cool for 2 minutes before further cranking. This sequence should not be repeated more than 3 times. If this is required, a further 30 minutes cooling time is required before the further cranking is allowed.

11.2.2 Starter Circuit

- The main battery-to-starter motor cable size and length must be selected to ensure that the total starter circuit resistance does not exceed the maximum value for the selected starter motor.
- The current, resistance, and fuse requirements must meet the requirements for the selected starter motor. Refer to Tier 4 Interim Rotating Electrics Manual obtained from your applications engineer.
- The positive and negative connections to the starter must be fed directly from the battery.

- The starter motor T31 terminal must be grounded directly to the primary earthing point on the machine or back to the battery, not to the engine block.
- Strain relief or an anchor point must be provided at the starter motor main supply and ground terminals and cables should be supported a minimum of 600 mm thereafter.

11.2.3 Alternator and Charging Circuit

- The alternator must be correctly specified to ensure that:
 - the application and battery needs are met across all speed and temperature ranges.
 - the maximum electrical load of the application does not exceed the alternator capability under all operating conditions.
- The alternator selected must be suitable for the working environment of the machine.
- The alternator must be protected from fluid spills, airborne dust, debris, and extreme environmental conditions.
- The alternator air inlet temperatures must not exceed the maximum allowable for the selected alternator.
- The following minimum clearances must be maintained between the alternator and engine components:
 - Exhaust manifold ≥ 50 mm
 - Engine parts (including brackets attached to the engine) ≥ 3 mm
 - Body parts ≥ 35 mm
 - Wiring harness/application wiring — no interference
- Maximum allowable alternator circuit voltage drop should not exceed the following:
 - 12V starter system: 0.5V
 - 24V starter system: 1V
- Cables leading to and from the alternator must be fed from below the body of the alternator.
- Wires must not be stretched tight or excessively loose and must be clamped near the alternator terminals for support.
- For Cat medium-duty alternators the D +/I terminal is designed to have a lamp or resistor in series to the ignition source for fault indication (current sink). If used this must:
 - not be connected directly to a battery or ignition source.
 - not be directly (or via a diode) connected to a B+ source
 - not have a load on the terminal that is greater than 1 amp
- For Cat heavy-duty alternators the B- terminal must be connected to ground. The strap must be correctly sized to carry the maximum cold current of the alternator.
- Under no circumstances should the case or rear nuts of the alternator be removed and used as a ground connection.

11.2.4 Battery

- The CCA rating of the battery must not exceed the maximum CCA rating of the starter motor.
- The battery voltage must not drop below 6.0V at first crank then 7.3V for the duration of the cranking.

11.2.5 General

- All connections must be correctly insulated and supported.
- All connections must be free from paint and corrosion.
- An insulated return path must be used for wet back-end applications.
- The ECU must be fed directly from the battery and not via the starter motor terminals.

12.0 Driven Equipment

12.1 Introduction

Tier 4 Cat engines fitted with a front-end belt drive arrangement option will feature poly-vee belts with auto-tensioners. The standard arrangement contains an 8-rib belt. A 12-rib heavy-duty version with heavy-duty fan drive will also be available as an option for the 6-cylinder engines. PTO devices can be driven from the Front End Accessory Drive (FEAD) system if required.

PTO adaptors and PTO devices can also be mounted on the rear face of the timing case. Adaptor options have been provisioned for to allow both SAE A and B pumps to be mounted to timing cases. Please refer to the E.S.M. for options and compatibilities.

12.2 Driven Equipment Mandatory Requirements

All emission-related installation instructions are highlighted by the **EM** symbol.

Failing to follow these instructions when installing a certified engine in a piece of nonroad equipment violates federal law (40 CFR 1068.105(b)), subject to fines or other penalties as described in the Clean Air Act.

12.2.1 Front-End Accessory Drive (FEAD)

12.2.1.1 General

- The maximum simultaneous power/load of the driven equipment (fan, alternator, air conditioning) must not exceed the maximum capability of the front-end drive arrangement. See Sections 12.2.1.2 and 12.2.1.3 for details.
- The minimum distance of any component from the inside or outside face of the belt must not be less than $\pm 5\%$ of the unsupported span length and no less than 6 mm from the edge of the belt. See Figure 12.1.

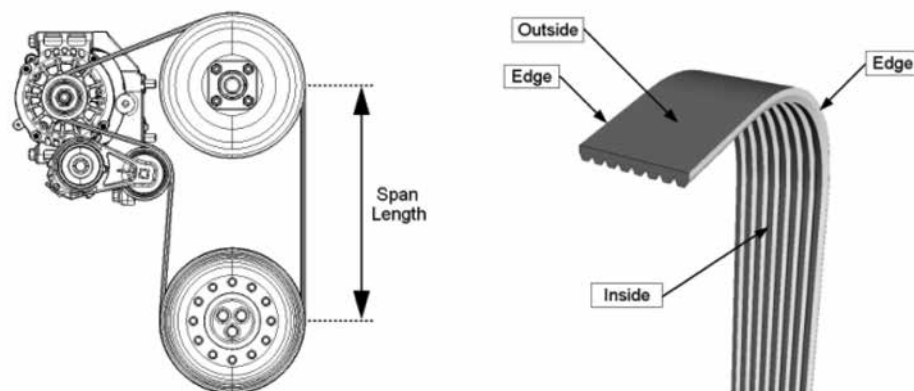


Figure 12.1

- Tier 4 fan drives should not be used in applications where the following gyroscopic conditions will be exceeded:
 - Engine rotation from rest, through 140° , in less than 3 seconds.
 - Fan center of mass is greater than 1.9 m from the rotational axis of the machine.
 - Fan inertia exceeds 1.01 kg.m^2 .

(This may be an issue in applications such as 360° hydraulic excavator.)

12.2.1.2 Standard Configured Front-end Arrangements

- Standard configured front-end arrangements should not be modified and should require no adjustment outside of normal service intervals.
- For the standard duty drive arrangement (8-rib belt):
 - The total system power absorption must not exceed 21.5 kW.
 - The maximum mass on the fan hub must not exceed 7 kg in total.
 - The combined center of mass of components attached to the extension (e.g., fan, fan clutch, spreader plate) must not exceed 127 mm (5") from the extension/fan pulley interface.
 - The combined fan, fan clutch, and fan extension inertia must not exceed 0.1 kg.m².
- For the heavy-duty drive arrangement (12-rib belt, 6 cylinder engine option):
 - The total system power absorption must not exceed 34 kW.
 - The fan power must not exceed 30 kW.
 - The maximum mass on the fan hub must not exceed 26 kg total.
 - The combined center of mass of components attached to the extension (e.g., fan, fan clutch, spreader plate) must not exceed 127 mm (5") from the extension/fan pulley interface.
 - The combined fan, fan clutch, and fan extension inertia must not exceed TBC kg.m².

12.2.1.3 Customer-Supplied Front-end Arrangements

For customer-supplied front-end arrangements the customer is responsible for the design and durability of the FEAD and supplied components. Where this design impacts on standard supplied engine components, a full analysis and validation must be conducted for approval before use. Approval in this case does not, however, imply or assume responsibility for this arrangement. The responsibility will remain solely with the customer.

- A drive analysis must be conducted on all customer-supplied front-end arrangements and have Caterpillar approval.
- The maximum crank hub side load must not exceed that which is shown on the polar moment diagram in the E.S.M.
- The maximum alternator hub load must not exceed the component limits. Please contact your applications engineer for further information.
- Misalignment — The maximum entry angle of the belt to the pulley must not exceed 0.5°. (Alignment of components must be within acceptable limits to prevent excessive wear). This includes consideration of crank end float service limits.
- Painting — Any over-spraying operation that is conducted must adhere to strict masking guidelines and procedures, which must be controlled and repeatable. Please contact your application engineer for further information.

12.2.1.4 Customer-supplied Fans

- Please refer to Chapter 6 — Cooling Systems, for mandatory requirements for Caterpillar supplied fans.

12.2.1.5 Servicing Requirements

- The multi-v belt tensioner must be accessible for servicing of the belt. This is only possible from the front or RHS of the engine depending on installation design.

12.2.2 Mandatory Installation Requirements — Power Take Off (PTO)

12.2.2.1 Timing Case (Gear-driven) PTO

- The maximum bending moment at the rear of the timing case must not exceed the maximum bending moment for your timing case option as specified in the relevant E.S.M.
 - Where the unsupported mass exceeds the limit, an adequate support bracket must be fitted.
- The maximum torque taken off the drive must not exceed the maximum limit specified for the timing case option selected in the technical data section of the relevant E.S.M.
 - A maximum instantaneous 10% overshoot is allowed, at the point of the load being applied (not continuous).
 - For hydraulic pumps the maximum rate of pressure rise must be less than 4000 bar/sec.
- Where a compressor through-drive is being used to drive a hydraulic pump, the torque limit of the compressor itself must not be exceeded. The compressor through-drive torque limits are given in the relevant E.S.M.
- All twin cylinder compressor use requires approval from your applications engineer. Please contact your applications engineer for further information.
- Any customer-supplied PTO gear requires Caterpillar approval.

12.2.2.2 Crankshaft (Axial) PTO

- The maximum permissible rear crankshaft thrust loads must not exceed those specified in the relevant E.S.M.
- Maximum front crankshaft overhung load must not exceed that shown on the polar moment diagram in the relevant E.S.M.
- Any rear crankshaft overhung loading must be approved by Caterpillar, (process TBA).
- Customer power-take-off (axial or belt-driven) is not permissible from standard crankshaft pulley options. Customers must select a PTO pulley option if power-take-off is required.
- The maximum power-take-off (front) with HD crank pulley is as specified in the relevant E.S.M.
 - All axial PTO usage requires Caterpillar approval. This may include torsional vibration analysis TBC.
- Crank-mounted fans are not approved.

12.2.2.3 Caterpillar Supplied FEAD Driven AC Compressors

- The maximum ambient temperature at the AC compressor should not exceed 95°C.

12.3 Driven Equipment Fundamentals

Accessories such as compressors, steering pumps, etc., can be driven from various PTO positions on the engine. These positions will vary, depending on engine type, but generally accessories can be:

- Mounted on the engine, and belt-driven from a PTO groove on the crankshaft pulley.
- Mounted on the back of the timing case, and gear-driven from the timing gears.
- Mounted on the engine frame, and driven axially through a coupling from the front of the crankshaft.
- Driven directly off other equipment, e.g. from a gear-driven compressor.
- Driven from a FEAD system.

The amount of power available from a crank-driven PTO belt depends on the distance of the PTO pulley from the face of the cylinder block, and the direction of the resultant loads acting on the pulley. It will also depend on the pulley material and the type of drive from the crankshaft. Various crank pulleys are available and some accept a bolt-on PTO pulley.

12.4 Driven Equipment Design Considerations

It is recommended a standard configured and approved front-end arrangement be selected. If a customer-specific FEAD is to be used, analysis of the front-end drive is required to ensure that the engine components are not excessively loaded and their durability reduced.

To aid design of any front-end arrangements the following recommendations are considered to be good practice and should be considered as a guide to help meet the requirements for approval.

The standard engine components (adaptors, pulleys, dampers, etc.) must not be removed or modified without approval from the applications engineering team. A change of front-end pulley in some cases may introduce a torsional vibration problem (see Torsional Vibration 12.4.2). Any PTO auxiliary pulley manufactured by customers must be approved by the applications engineering team. The inertia of the customer pulley is very important, as excessive inertia can cause torsional vibration issues. See the E.S.M. for guidance on maximum permissible inertia.

12.4.1 Crankshaft Side Loadings

The allowable side loadings on the crankshaft depend on the engine type, operating speed, and the machine application. Please refer to the relevant E.S.M. for these limits.

The engine can usually accept a greater side loading below the crankshaft than above. Where this is the case the belt drive should be arranged, if possible, so that the driven equipment is below the crankshaft center line. Where two or more belt drives are required and can be arranged in opposite directions, this is preferable to help balance the loadings.

12.4.2 Torsional Vibration

The diesel engine, plus its driven equipment (driven from either front or rear) is made up of rotating masses connected by a series of shafts. This forms a torsional mass-elastic system, which will vibrate at its own natural frequency when acted upon by an exciting torque.

A resonant condition will occur when the frequency of the exciting torque is equal to the natural frequency of the system, or one of its harmonics. This condition will result in high vibratory stress, which can lead to damage of the crankshaft or any driven shafting. It is therefore necessary to ensure that the characteristics of the total system, i.e., engine and driven machinery (including front end PTO if fitted), are such that excessive torsional vibration stresses will not occur.

The size and position of the PTO pulley or coupling are important because of their effects on torsional vibration characteristics of the system. Crankshaft pulley loosening can result if these characteristics are not tuned to match the operating conditions of the installation.

The necessary tuning can be achieved by changing the inertia or stiffness of the system, by altering the rubber mix of a flexible coupling, or by using a special damper on the crankshaft pulley. As a general guide, all axially driven inertia should be as low as possible in order to minimize the effects of vibratory torque. Driven equipment that introduces damping into the system (e.g., hydraulic pumps) will have a beneficial effect on the torsional vibration characteristics. The use of a flexible coupling in the system will have a similar beneficial effect, and coupling manufacturers are usually able to give guidance in this respect.

12.4.3 Belts and Pulleys

The correct tension must be applied to any PTO belt-driving arrangement, as insufficient installation tension can cause belt slippage at high powers and high speeds, reducing belt life, etc. With a PTO drive from the crankshaft, excessive belt tension will result in higher side loadings than necessary, which could result in crankshaft failure.

The supplier of the fan belt/PTO belt will be able to supply the calculated belt tension, which can then be used to determine if crankshaft side loads are within the engine's limitations.

It is recommended that necessary guarding or safety provision is made to prevent human intervention to all exposed front-end drives or other rotating components. It is the responsibility of the OEM to ensure that the relevant directive and/or legislation, dependant on application and operating territory, is adhered to.

If a FEAD guard is deployed, care must be taken that the design of this guard does not prevent airflow, as that could result in overheating, and that it does not allow the build-up of excessive dust, dirt, or water that may affect the durability of the belt.

Any customer-designed/supplied pulleys should be made from cast iron or steel.

To help ensure satisfactory belt life the following should be taken into consideration:

- Standard available belt drive arrangements have been designed to withstand a continuous temperature of 85°C.
- As a rough guide, for every 1°C increase in ambient temperature the belt life will be reduced by 50%.
- Belt alignment also has a direct effect on the life of the belt. Misalignment can lead to a significant reduction in the belt life, leading to premature failure. This must be taken into consideration when designing mounting pads for auxiliary components and during manufacture.
- Care should be taken to ensure that the minimum bend radius of the belt is not exceeded. This can be done by limiting the minimum pulley diameter to 60 mm.
- Care should be taken to prevent the contamination of pulley grooves during storage, manufacture, and operation. Problems are commonly caused by corrosion during storage and ineffective masking during over-spraying.
- The maximum belt span should not exceed 300 mm without incorporating an idler pulley, as excessive belt flap can lead to slippage during operation.
- Idler pulleys used for tensioning multi-vee belts should be positioned on the slack side of the belt, and should not be smaller than the minimum diameter recommended by the manufacturer for a particular belt.
- A suitable automatic tensioner is preferable to one that is adjusted and clamped, as it can enable the correct installation tension to be used. This is increasingly important with larger PTO values, as more installation tension is required to avoid slippage, resulting in a higher side loading/bending moment on the crankshaft.
- An automatic tensioner is also very important where there could be relative movement between a flexibly mounted engine, and driven equipment mounted on a separate chassis (not a recommended arrangement).

12.4.4 Timing Case PTO Recommendations

For both engine platforms, a heavy-duty timing case is available. The overhung weight of some equipment may require that this heavier duty timing case be fitted if suitable. It is recommended that a support be provided for pumps and compressors driven from the front-end gears to minimize the bending moment on the rear of the timing case and minimize misalignment of the PTO drive gear.

12.4.5 Hydraulic Pump Drive Recommendations

A wide variety of hydraulic pumps are available, with a range of flange and drive shaft connection types; commonly SAE-A or B flanges with splined or tapered shafts.

These pumps are customer-supplied and fitted. It is necessary to select the correct adaptor and mating gear to suit the engine timing case and gears; please refer to the mandatory requirements.

The following points must be considered to enable satisfactory performance:

Power and Torque Limits

The maximum power and torque available from different PTO positions on each engine type is given in the relevant E.S.M. Depending on engine speed, either power or torque may be the limiting factor. Neither limit must be exceeded under any operating conditions.

The power and torque of the pump can be calculated to ensure these values are not exceeded, see Section 12.4.5.1.

Alignment and Clearance

Correct support and alignment of the pump must be ensured to prevent excessive axial and/or radial loads being imposed. The pump must not foul any part of the installation under operating conditions, i.e., with a fully equipped engine installed in chassis.

Cooling

Caterpillar approval is required to use engine oil or coolant to cool any auxiliary equipment. Approved connection points must be used and these are shown in the relevant E.S.M. Consideration should be given to the size, length, and routing of these lines, with respect to flow rates, restriction levels, and any external heat sources.

Where auxiliary equipment is not cooled by engine fluids, consideration should still be given to the positioning of its cooling core; as it can directly impact engine cooling pack performance.

Oil Leakage

Industry standard joints and seals must be provided between the engine and pump to prevent oil leakage. Hoses and pipe work must be capable of withstanding the pressures and temperatures to which the installation will be subjected.

Manufacturers' Recommendations

The respective hydraulic pump manufacturers' installation, operating, and maintenance instructions must be followed, also their recommendations regarding the type of oil to be used in the system.

12.4.5.1 Calculating Hydraulic Pump Requirements

$$\text{Power (kW)} = \frac{\text{Flow (l/min)} \times \text{Pressure (bar)}}{600 \times 0.9 \text{ (efficiency*)}}$$

$$\text{Torque (N•m)} = \frac{\Delta \text{ Pressure (bar)} \times \text{Displacement (cc/revolution)}}{20 \pi \times 0.9 \text{ (efficiency*)}}$$

*0.9 is a generic value at the time of printing. Actual pump efficiency may vary with pump type, and your pump manufacturer should supply the value for accurate calculation of power and torque requirements.

12.4.6 Air Compressor Recommendations

A customer-supplied air compressor must meet the mandatory requirements. Below are some additional points that must be taken into consideration. In all cases supplier recommendations should be followed for any equipment supplied with compressed air.

Ascertain that the instantaneous torque loadings are within the capacity of the PTO drive system and that the compressor weight is not excessive.

Air Cooling of Belt-driven Air Compressors

Compressors should be situated in a cooling air stream to provide good airflow over its cylinder head when the machine is both stationary and moving. It should, if possible, be positioned where it will not be substantially affected by radiated heat from the engine exhaust system. If insufficient airflow is available, a water-cooled compressor should be used.

Water Cooling of Gear-driven Air Compressors

Water-cooled compressors require an adequate water flow rate to ensure efficient cooling under all operating conditions, i.e., the air outlet temperature is kept below 220°C.

Caterpillar approval is required to use the engine coolant to cool the air compressor. Approved connections points must be used and these are shown in the relevant E.S.M. Consideration should be given to the size, length, and routing of these lines, with respect to flow rates, restriction levels and any external heat sources.

Lubrication

Oil feeds must be provided for gear-driven compressors. Caterpillar approval is required and the approved connections points must be used. These are shown in the relevant E.S.M.

Air Supply

If the compressor has an integral air filter, it must be adequate for all intended operating environments. Integral air filters tend to be neglected during engine servicing, so it must be ensured that the filter is accessible and serviced at the required intervals.

If the compressor has a separate air filter, it must be adequately supported and the induction port must not be restricted.

When intake air is taken from the engine induction system, it should be downstream of the air filter and must not be from the inlet manifold.

Suction Pipe Work

Suction pipe work should be selected to provide an acceptable depression at the compressor inlet of not more than 7 kPa. Depressions greater than 7 kPa can increase oil carry-over to an unacceptable level, and also reduce compressor-operating efficiency.

Under no circumstances should the inlet to the compressor be taken from a positive pressure source; the air supply should be at atmospheric pressure.

Delivery Pipe Work

Compressor delivery pipe length must be adequate to ensure that the temperature of the air at the rubber hose does not exceed 100°C; usually a minimum length of 2 m of steel tubing should be used from the delivery port, and situated in a cooling air stream whenever possible. Sharp bends and restrictions will increase the compressor working pressure, resulting in a rise in operating temperature.

12.4.7 Caterpillar Supplied AC Compressor Recommendations

A hi/low pressure switch is required at the discharge side of the compressor. This is to ensure the compressor shuts off prior to high discharge pressure relief and prevents running the compressor in low temperature conditions that do not or would not allow proper circulation of refrigerant.

The oil circulation rate in the system at low idle should be at or slightly above 3.3%. The suction-side pressure switch is typically at 5 psig and is there to give indication there is not enough suction pressure for proper continuous operation. If they have a system to detect low refrigerant charge, it would be a plus.

The compressor should be properly balanced with the cab or heat load for reliability and durability reasons. This includes examining machine operation and compressor speeds to match the heat loads.

13.0 Noise Control

13.1 Introduction

Pressures are increasing throughout the world for reduction in the noise of everyday life. Noise is a matter which affects not merely the convenience and comfort of the end-user, but the health and welfare of the whole community. Exposure to high noise levels for extended periods of time can cause damage to hearing, and, as the level of noise increases, the ability of the human ear to withstand injury falls away sharply. In consequence, it is becoming the pattern in legislation to impose on suppliers of products, an obligation, at each point in the chain of manufacture or sale, to ensure that those products will not generate noise levels which induce hearing loss.

For many years, Caterpillar has played a leading part in the field of noise control of both engines and total installations. The aim of this section is to give guidance on ways in which quiet installations may be achieved, based on experience gained on a wide variety of application types.

It is for each manufacturer who installs the engine to ensure that the noise levels produced by the equipment are compatible with the welfare of those who come within the operating environment. This section is intended to help equipment manufacturers understand noise terminology and techniques that may help in reducing the overall noise levels of their machines and the individual noise contributions.

For more detailed information on topics discussed in the following pages, and for specific advice on particular installation problems, OEMs are invited to contact their nearest Caterpillar area representative. These offices have available to them the full resources of the application engineering department, Peterborough.

There are no legislative noise requirements directed at the engine itself. Despite this we recognize that it is a significant contributor to overall machine noise and as such have developed the engine to the lowest practical noise level within economical and technological constraints.

Noise reduction features are incorporated into the design of every engine and are part of the standard offering. External features such as an isolated oil pan and damped timing case cover are used. Other features that help noise are designed into the engine itself and include good control over piston dynamics, an optimized fuel system and good control of clearances within the gear train.

13.2 Noise Control Mandatory Requirements

There are no legislative noise requirements directed at the engine itself.

13.3 Noise Fundamentals

13.3.1 Definition of Noise

Noise is generally defined as unwanted sound. Sound itself consists of small pressure variations in the air, the source of which may be either a vibrating structure or a pulsating gas flow.

The criteria by which noise is judged are its level (or intensity) and its frequency composition, which determines its subjective characteristics. The human ear in good condition can detect noise over the approximate frequency range 20 to 16,000 Hz (1 Hz = 1 cycle per second), but is particularly sensitive to noise within the frequency range 500 to 4,000 Hz

Sound is commonly referred to in terms of sound pressure and sound power. These terms are frequently confused but are fundamentally different. Sound Power Levels (SWL or LW) and Sound Pressure Levels (SPL or Lp) are both used to describe the noise levels of engines and machines and are both quoted as decibel numbers (dB), but they are not the same quantities and are used for different reasons.

- SWL should be used to describe the overall noise level of a noise source such as an engine or machine. The main reason for using it is for understanding the requirements of machine legislation and how individual components contribute to this.
- SPL should be used to describe the noise level at particular points such as, at an operator's ear in his normal working location. Sound pressure levels describe how sound is experienced by a human being.

The technical differences between sound pressure and sound power are described in the Table 13.1.

Sound Power Levels, dB reference 1 pico-Watt	Sound Pressure Levels dB reference 20 micro-Pascal
SWL quantifies the overall sound energy being radiated by a sound source and as such is an absolute value .	SPL quantifies the pressure fluctuations in the air at a particular point in space and as such is a relative value .
SWL cannot be measured directly. It is calculated from average SPL measured in accordance with a valid procedure; there are several valid procedures. Different procedures will involve different average SPL values being calculated but they should all result in the same value of SWL being obtained.	SPL is measured directly using a microphone. The average of SPL values from different locations is calculated on a sound power (or energy) basis.
SWL allows for simple direct comparison of the strength of different sound sources. It is the only reliable way of comparing the noise levels of engines or machines made by different manufacturers.	SPL can only be used for simple direct comparison of the strength of different sound sources if the same microphone positions were used for each set of measurements.
The overall SWL value for several individual noise sources can easily be calculated by summing the individual SWL values.	Summing the SPL associated with several sources is difficult and not normally done in the context of engines and machines where measurement distances are relatively small.
SWL is not a direct indicator of the noise level being experienced by an operator. An estimate can be made if the distance from the source to the operator is known.	SPL can be a direct indicator of the noise level being experienced by an operator, providing measurements are made at the appropriate locations.
SWL is used to assess machine overall exterior noise for legislation purposes.	SPL is used to assess operator exposure to noise for legislation purposes.

Table 13.1

13.3.2 Units of Measurement

There are two units of measurement for sound. These are the Watts (W) for sound power and Pascals (Pa) for sound pressure. For convenience both are expressed in decibel numbers (dB), which expresses, on a logarithmic scale, the ratio between the sound being measured, and a reference sound level.

The reference for sound power is 1 pW (pico Watt) and the reference level for sound pressure is 20 micro Pa which is known as the threshold of hearing and is approximately the minimum sound audible to a person with very good hearing (It should be noted that, as the decibel is a logarithmic unit, an increase of 3 dB actually represents a doubling in sound intensity — or energy. However, the response of the average human ear is such that an increase of approximately 10 dB is necessary for a doubling in subjective loudness to be perceived).

Both sound power and sound pressure levels are commonly A-weighted as indicated by dBA. This approximately simulates the frequency response of the human ear to noise, by suppression of noise components at very low and very high frequencies, and amplification of those in the middle frequency range.

Most commercially available noise meters incorporate electrical weighting networks which enable dBA levels to be read directly.

13.3.3 Addition and Subtraction of Decibels

In noise analysis and reduction work it is often necessary to calculate the effects of combining or eliminating noise sources. However, decibels CANNOT be added, subtracted or averaged arithmetically, since the decibel is a logarithmic unit — in fact, 80 dB + 80 dB = 83 dB, and not 160 dB. (Thus, an increase of 3 dB represents a doubling of sound intensity).

Subtracting, adding, and averaging can be done from first principles, using the equations shown in the calculation method below. Alternately, charts are available for this purpose. A simple chart is illustrated, together with instructions for its use in Figure 13.1.

Calculation Method

First, all decibel values that are to be used in any calculation must be the same type. Do not mix sound power levels and sound pressure levels. Do not mix A-weighted values and un-weighted values.

Second, it is necessary to return to standard quantities, or more simply the sound quantity ratios (X).

$X = 10^{(dB/10)}$ (these will be large numerical values)

Although it is not necessary, the sound quantities can be converted to normal engineering units by using the appropriate equation for the original values (i.e., power or pressure):

Sound Power = $X * (1 \times 10^{-12})$ Watt

Sound Pressure = $[X]^{0.5} * (2 \times 10^{-5})$ Pascal

$$dB_{sum} = 10 \log_{10} (X_1 + X_2 + X_3 + \dots)$$

$$dB_{average} = 10 \log_{10} \{ (X_1 + X_2 + X_3 + \dots + X_n) / n \}$$

$$dB_{diff} = 10 \log_{10} (X_1 - X_2) \quad (X_1 > X_2)$$

Examples Using Sound Power Values

Addition

0.01 Watt + 0.01 Watt = 0.02 Watt

100 dB + 100 dB = 103 dB

$X_1 = 1 \times 10^{10}$; $X_2 = 1 \times 10^{10}$; $(X_1 + X_2) = 2 \times 10^{10}$

Average

0.10 Watt and 0.01 Watt = 0.055 Watt

110 dB and 100 dB = 107.4 dB

$X_1 = 1 \times 10^{11}$; $X_2 = 1 \times 10^{10}$; $(X_1 + X_2)/2 = 5.5 \times 10^{10}$

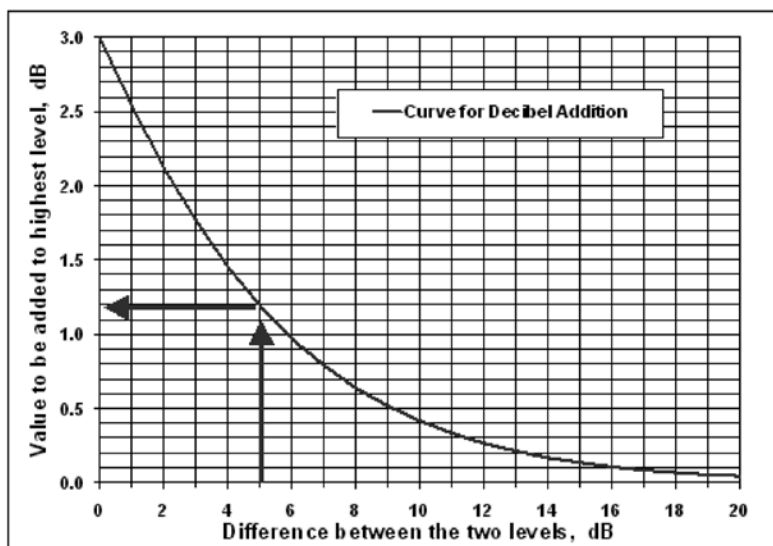
Subtraction

0.10 Watt - 0.01 Watt = 0.09 Watt

110 dB - 100 dB = 109.5 dB

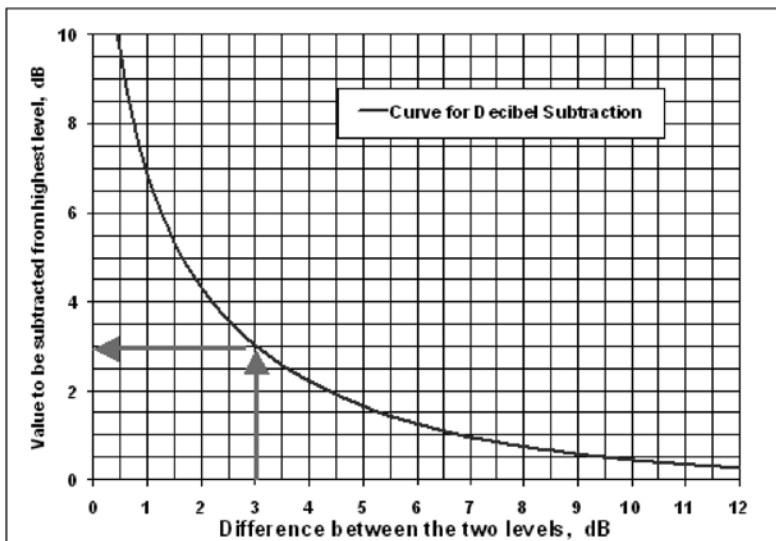
$X_1 = 1 \times 10^{11}$; $X_2 = 1 \times 10^{10}$; $(X_1 - X_2) = 9 \times 10^{10}$

Sound Level Addition and Subtraction Charts



Example of Decibel Addition

- 100 dB + 105 dB = 106.2 dB
- Difference between two values = 5 dB
- Addition value = 1.2 dB
- Result = highest value + addition value
- Result = (105 + 1.2) dB



Example of Decibel Subtraction

- 104 dB - 101 dB = 101.0 dB
- Difference between two values = 3 dB
- Subtraction value = 3.0 dB
- Result = highest value - subtraction value
- Result = (104 - 3.0) dB

Figure 13.1

13.3.4 Basic Noise Reduction Techniques

Listed below are six basic techniques, each of which performs a basic noise reduction function. These techniques may be used simply or in combination, depending on the characteristics of the noise (for example, whether airborne and/or structure-borne, frequency content, amount of reduction required).

1. Insulation

Insulation enables a large reduction in noise to be achieved by imposing a substantial barrier or shield between the noise source and the observer. The degree of noise reduction achieved is a function of the mass of the barrier material used; therefore, such materials as steel plate, lead sheet, and heavy rubber sheet are particularly effective. Complete sealing of all gaps and apertures is absolutely essential if the full potential benefit of insulation is to be achieved.

2. Absorption

In contrast to insulation, the material used for acoustic absorption is porous (for example, polythane foam, fiberglass blanket, etc.), and is usually placed inside the area where the noise source is situated, in order to prevent internal reflection and build-up (or reverberation) of noise.

On its own, absorption material does not stop the transmission of noise. It requires a supplementary layer of non-porous material to act as a barrier, such as the main body panels of an engine compartment. This barrier helps to contain the noise energy while the absorption material absorbs and reduces this energy.

For example, in a machine, a firewall protects (insulates) the operator from the operating noises of the equipment. This firewall simply deflects the external noises in another direction, so the noise and energy needs to be contained and reduced. The noise from the engine is usually contained within the engine compartment, encouraging the build-up of energy, which can then be absorbed by the use of absorption material. This can frequently be seen on the underside of the machine hood, for example.

3. Damping

This technique is used to reduce the vibration of noise radiating surfaces; for example, flat unsupported panels. Damping can be provided either by the application of a surface treatment or by making the panel from a material which is inherently well-damped. Damping constrains the flexural bending of the panel and absorbs energy as the material is alternately put into tension and compression. Where the mass of the damping layer is significant in relation to the mass of the panel, the vibration frequency response characteristics of the panel may be modified with beneficial effect.

4. Stiffness

Vibration amplitudes can sometimes be reduced by stiffening (for example, by swaging of sheet metal body panels), usually as a design feature. However, the effect on complex structures, such as engine crankcases, is less predictable, as the effects on the vibration amplitude/frequency characteristics of the increased mass may outweigh the benefits of the increased stiffness.

5. Isolation

The principle is to isolate sources of vibration from any surfaces which could generate sound waves. All anti-vibration mountings come into this category, an obvious example being engine mountings, which are covered in Section 3 of this manual.

It is also possible acoustically to de-couple one surface from another using a rubber compound so that the vibration of the de-coupled surface is out of phase, and of much lower frequency than that of the exciting force.

6. Separation

Machines legislation requires you to measure the sound power level of the whole machine; therefore, unlike on highway vehicles, the repositioning of individual sound sources usually provides no additional benefit.

13.4 Minimization of Total Installation Noise

13.4.1 Legislative and Marketing Considerations

These are usually the main factors influencing noise reduction requirements. Sometimes legislation sets specific limits upon maximum noise levels, which may not be exceeded. Sometimes it is framed in general terms so as to leave the manufacturer responsible for establishing and implementing noise safety levels in respect of his product. Such legislation tends to be supported or supplemented by marketing considerations, which grow increasingly important as operators become noise-conscious.

Noise measurements are carried out to both customer's own product objectives and to ensure compliance with legislative limits. These are of two types:

- External or bystander noise (sound power values)
- Internal or operator noise (sound pressure values)

The test procedure required is selected by the OEM in accordance with the type of machine/vehicle as, invariably, legislation applies to the machine and not directly to the engine. This may be with the machine stationary, moving at a constant defined speed, or carrying out a defined test cycle. There may be a requirement for tests at various conditions to enable the prediction of the time of exposure to specified noise levels.

Because of the variation in the above requirements for the wide variety of machines available and differences in the requirements between territories, it is vital that the OEM sets out what exactly is required for his products. Caterpillar is obviously able to overview this in relation to similar products from our broad customer base and knowledge of legislation, but advice made resulting from this should only be used to draw the attention of the customer and not to make final decisions on the objectives.

In order to avoid problems at a later date, it is important to consider the basis on which the objectives are set; e.g., a one-off type approval or a requirement for the compliance of production units. If the latter is the case then due allowance must be made for the possible variation between individual machines of the same model.

13.4.2 Composition of Total Machine Noise

The contributors to machine exterior and in-cab noise levels include:

- Bare engine airborne noise (excludes any bolt-on engine ancillaries)
- Additional noise radiated from engine mounted components and their support brackets
- Induction air system (gas-borne and shell noise)
- Exhaust gas and aftertreatment system (gas-borne and shell noise)
- Machine cooling systems for: engine coolant, charge air, fuel, hydraulic fluid, machine operator
- Structure-borne noise transmitted from the powertrain to the rest of the machine through any contact points which have poor isolation characteristics
- Transmission/propulsion system airborne noise
- Hydraulic system — hoses, including structure-borne noise through clipping points, ram, and valves
- Body panels, including cab panels, responding to structure-borne and airborne excitations
- Machine equipment (boom, bucket joints, tools, etc.)
- In-cab equipment (air conditioning system, control levers etc.)

The relative magnitude of the various sources can show a considerable variation depending on engine, machine type, and configuration.

Depending on the machine type and microphone position, the component and noise ranking can vary considerably. The pie charts shown in Figure 13.2 show how the rankings on one machine vary. The two rankings below are taken from the same machine but at different operating conditions because one is relating to exterior noise for legislation and the other is relating to internal cab noise for operator comfort.

A significant point is that the noise emitted directly by bare engine is only around 20-30% of the total noise of most machines. In these cases a major reduction in engine noise would obviously have a much smaller effect on overall machine noise and it will be necessary to apply noise reduction techniques to the other major sources to achieve the optimum noise reduction.

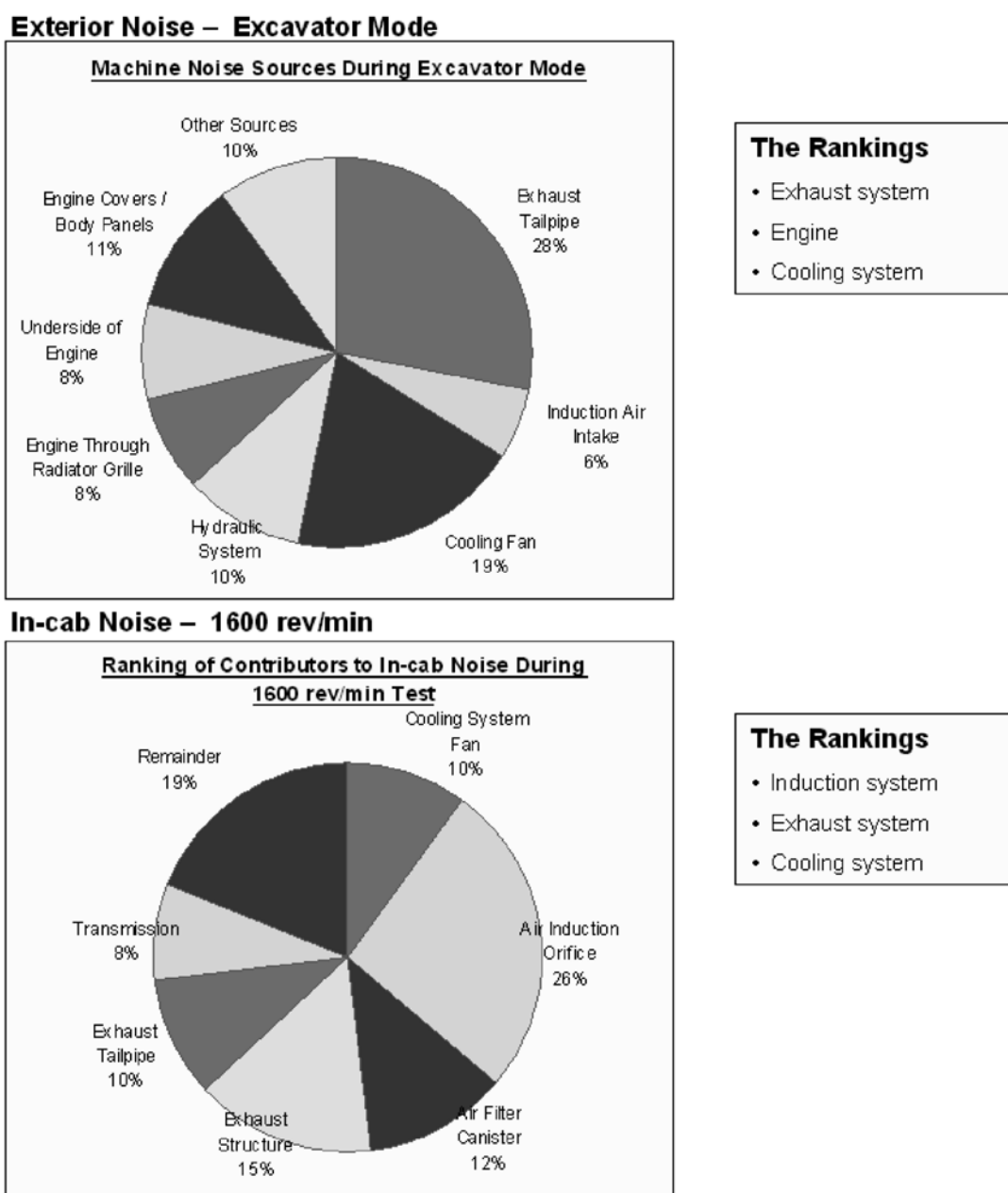


Figure 13.2

13.4.3 Experimental Identification of Noise Sources

In order to be able to carry out noise reduction of an existing application methodically and effectively, it is obviously most important to know which of the various constituent noise sources are actually significant. Some indication can be obtained experimentally by suppressing individual sources in turn, thus:

Cooling Fan

- Can be temporarily removed.

Exhaust System

- Exhaust note can be suppressed by piping away the exhaust or by fitting an additional silencer in series.
- Noise radiated by the silencer shell and exhaust pipes can be suppressed by lagging.

Induction System

- Intake can be piped to a remote position.

Engine and Transmission

- Improvising shielding may reduce noise from these units.

The causes, characteristics, and methods of reduction of noise from the above sources are described in the following sections.

13.5 Engine Noise

13.5.1 Nature of Engine Noise

Engine noise is considered as being that radiated directly from the basic engine structure alone, with noise from other engine-related systems (exhaust, induction, and fan) and accessories completely eliminated. It is, however, possible for engine noise to be transmitted to, and radiated from, interconnected systems (for example, transmission units).

13.5.2 Sources of Engine Noise

Engine structural noise is excited by both combustion and mechanical sources. The areas of the engine which respond to this excitation are typically the sump, cylinder block and crankcase, cylinder head covers, timing case cover, and crankshaft pulley.

13.5.3 Methods of Engine Noise Reduction by Attention to the Engine

Apart from fundamental redesign of the engine structure, direct methods of reducing engine noise radiation include speed reduction, combustion system modifications, component modifications, acoustic treatment of engine surfaces, and the use of close-fitting engine shields.

Since engine noise increases rapidly with speed, speed reduction is a most effective technique, and has the advantage of also reducing the effects of other engine-related noise sources (fan, exhaust and induction). In consultation with the engine manufacturer, the lowest possible rated speed compatible with performance requirements should therefore be chosen.

Direct engine treatment is, however, the responsibility of the engine manufacturer alone, and, where required, is incorporated in the original engine specification. Engine noise reduction methods available to vehicle and machine manufacturers are therefore applicable only to the installation and complete application.

It is important to bear in mind that any noise reduction achieved by direct treatment of the engine alone will usually have a lesser effect on the total vehicle or machine noise, assuming that other sources remain constant. The reduced effect will vary with the type of application, but as a rough guide an engine noise reduction of 2 dBA could be expected to give a reduction of about 1 dBA on a road vehicle. In the case of industrial and construction machines the effect would probably be considerably less, typically 0.5 dBA.

13.5.4 Methods of Engine Noise Reduction by Attention to Installation and Application

The obvious area for attention is the engine compartment, which should be designed from the outset to provide as much shielding of the engine as possible. Different combinations of basic acoustic treatments can achieve various degrees of noise reduction, namely:

- **Insulation** — The use of machine-mounted shields or covers to prevent airborne transmission of noise to the observer, both by direct radiation and by reflection from the ground.
- **Absorption** — Acoustic absorbent material [approximately 25 mm (1 in) thick] applied to inner surfaces of the engine compartment to reduce build-up of noise. The material may be held in place by means of wire mesh or thin metal straps. Absorbent material can also usefully be applied to the surfaces of noise shields.
Note: care must be taken to ensure that linings do not become a fire hazard due to absorption of fuel oil. Some suppliers offer absorbent material complete with protective surface treatment.
- **Damping** — Treatment applied to resonant panels to reduce their vibration response and noise radiation capacity.

An example of a typical compound barrier/absorbent material is illustrated in Figure 13.3.

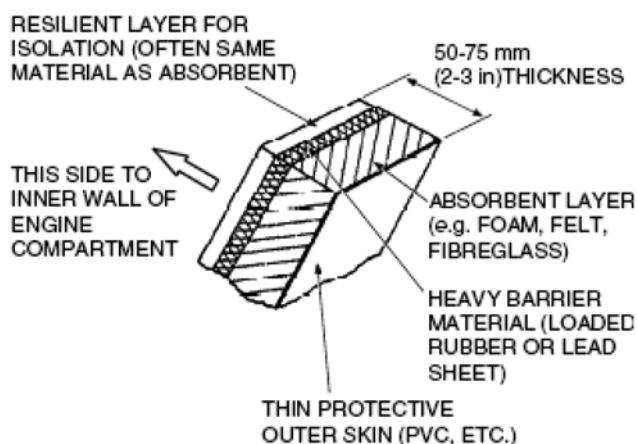


Figure 13.3

In the extreme case, for an ultra-low-noise machine, treatment should comprise a completely enclosed engine compartment, with cooling air inlet and outlet by means of either a silencing duct, or acoustic louvres lined with absorbent foam or similar material. Apart from the cooling air inlet and outlet, the compartment should be as nearly airtight as possible, with acoustic absorbent linings to the sides and top. Sealing strip should be fitted around the edges of detachable panels.

The choice of suitable resilient engine mounts is very important in minimizing transmission of vibration and excitation to the machine frame and bodywork.

The avoidance of fouls between engine and the machine frame and bodywork is also obviously essential.

13.6 Exhaust Noise

13.6.1 Nature of Exhaust Noise

On many applications, this is one of the principal noise sources. The noise arises from the intermittent release of high-pressure exhaust gas from the engine cylinders, causing strong gas oscillations in the exhaust pipe. These lead not only to discharge noise at the outlet, but also to noise radiation from exhaust pipe and silencer shell surfaces. The purpose of the exhaust system is to reduce these gas oscillations and, with the aid of a properly matched silencer, not only can efficient exhaust noise attenuation be achieved, but also sometimes a decrease in the power loss of the exhaust system.

13.6.2 Exhaust Silencing Requirements

For exhaust noise not to be significant, its contribution should be at least 10 dBA lower than the target overall noise level of the complete machine or vehicle. The aftertreatment systems that are to be used at Tier 4 do not attenuate the exhaust system noise in the same way as traditional mufflers or silencers did. The aftertreatment systems provide good attenuation of high frequency (> 500 Hz, approx.) exhaust noise, but they have little effect at low frequencies. The strongest pulsations in the exhaust system occur at engine firing frequency and its first two harmonics, all of which are well below 500 Hz. In applications where these frequencies are found to be a problem, the use of an additional silencer will be required.

Selection of the most suitable silencing arrangement for a particular application is, to a certain extent, a matter of experience, taking into account the relevant operating factors, which include:

- Degree of noise attenuation required
- Exhaust noise frequency characteristics
- Permissible backpressure
- Configuration required
- Space available
- Cost

Silencer manufacturers generally are best qualified to advise on the most suitable designs to meet particular requirements and it is recommended that they are consulted at the earliest opportunity.

Important elements of the design that will need to be considered are:

- Silencer type
- Silencer dimensions

Volume — for effective silencing, this should be of the order of 3 to 5 times engine cubic capacity.

Cross-sectional area — this should be large; e.g., a silencer of 180 mm (7 in) diameter by 300 mm (12 in) length is preferable to one of 100 mm (4 in) by 900 mm (36 in) length, although both have volumes of approximately 7.5 litres (460 cubic inches). Ideally, the ratio of silencer body diameter to inlet pipe diameter should be of the order of 4 or 5 to 1.

The most elementary silencer in accordance with the above guidelines on dimensions should give 10-15 dBA attenuation of open exhaust noise, while more sophisticated designs (i.e., of more complex internal construction, or having double-skinned or wrapped casings) may give up to 25-35 dBA reduction.

The guidelines on silencer volume and cross-sectional area apply equally to cylindrical and oval section units although from manufacturing and reliability considerations the cylindrical form is preferable.

- Silencer position
- Exhaust pipe work
 - Tailpipe length and outlet position
- Exhaust System Construction
 - Silencers and exhaust pipes are commonly of 16 gauge steel (1.5 mm thickness). Where larger degrees of noise attenuation are required, radiated noise from body shells and pipes may be reduced by means of silencers having wrapped or sandwich-type constructions, and by use of double-skinned exhaust pipes, obtainable from some manufacturers.
- Any interactions will affect the aftertreatment system
 - The addition of any silencing system must not adversely affect the aftertreatment system such that it would not function correctly, for the whole of its normal life.

13.7 Induction Noise

13.7.1 Nature of Induction Noise

The induction system can make a significant contribution to overall bystander or operator noise on some application types. Intake noise is caused by the pulsating flow of air through the system. The fundamental frequency of the sound waves thus created is equal to the engine firing frequency, but harmonics at higher frequencies also occur. The noise characteristics will be influenced by manifold and inlet port arrangements, valve timing, ducting arrangement, filter dimensions, etc.

13.7.2 Induction Silencing Requirements

For this source not to be significant, its contribution should be at least 10 dBA lower than the target overall noise level of the complete machine. Air filter manufacturers are well qualified to advise on the best choice of silencer to meet particular requirements, but the following notes are offered as initial guidelines.

Important elements of the design that will need to be considered are:

- Air filter types
- Induction system selection and installation
- Intake silencer dimensions

In general, air filters having volumes matched to airflow requirements will provide adequate silencing, although the ratio of body diameter to intake diameter should be large. Ratios of 3 or 4:1 should give reductions in induction noise ranging from 10 dBA in the case of simple units, up to 20-25 dBA for more elaborate units.

- Intake System Configuration
 - The air filter should be located as close as practical to the engine, while the intake should be directed or positioned away from the observer or microphone. Intake stacks may be helpful for this purpose. The use of an additional absorption-type silencer unit at the intake may also be found beneficial in suppressing high-frequency noise.
- Installation
 - Pipes should be of round section, and of heavy wall construction to ensure good acoustic barrier properties. It is very important to ensure that the system is airtight at all times.

13.8 Cooling System Noise

13.8.1 Nature and Causes of Fan Noise

The term fan noise is commonly used to describe noise created by the interaction between the fan and the cooling system airflow. It is now widely recognized that on heavy vehicles and machines this noise source can make a significant contribution to total noise of the installation.

Fan noise may comprise discrete frequency components (characteristic of obstructions in the airflow path) or cover a wide frequency range, due to eddies and turbulence in the airstream. In either case the noise is greatly influenced by the design and configuration of the whole cooling system.

13.8.2 Cooling System Design

For a given power unit heat rejection, there are many combinations of fan type, fan speed, and radiator type which will provide the required cooling. The choice of a cooling system package giving the optimum combination of components for low noise is therefore important.

There are also considerable benefits to be obtained in respect to cooling efficiency, low noise, and low fan power absorption, by ensuring that the system layout provides for a smooth cooling airflow path free from obstructions and deviations. The use of an efficient fan cowl with low blade tip clearances is strongly recommended.

Important elements of the design that will need to be considered are:

Radiator Selection

As a general rule the largest possible core area which can be accommodated should be specified. This enables both airflow volume and system pressure drop to be kept to a minimum, with consequent minimization also of fan noise. For the same reasons the use of high-efficiency radiators is recommended. As an approximate guide, it has been found that on applications having low cooling system noise levels, the air velocity through the radiator core is usually less than 8 m/sec 25 ft/sec).

Fan Selection

From a noise perspective a puller fan is preferable to a pusher fan. The engine and ancillary components situated on the inlet side of a pusher fan severely affect its noise level and performance, whereas a puller fan will have the engine on its outlet side, where it has less effect.

In general the largest diameter, lowest speed fan should be used, with the lowest possible tip clearance (ideally less than 1% of fan diameter). If a large tip clearance must be used (say, greater than 2% of fan diameter), care must be taken to ensure that the fan is not running in the stall condition (ref. fan manufacturers' performance data).

Fan Speed

Where a choice of fan drive ratios is available, the ratio which gives the lowest practical fan speed should be selected, taking into account airflow volume and pressure characteristics.

On some applications there may be considerable advantages to be gained in terms of noise, efficiency, and power saving by the use of viscous or clutch fan drives.

Cooling System Layout and Installation

Fan noise is greatly increased by distortion of the air flow passing through it, but this can be minimized by attention to the following:

- The fan should lie on the same flow axis as the radiator, and should not overlap the edges of the radiator core.
- If fan diameter is well matched to the radiator dimensions, the optimum spacing between fan and radiator is in the range 1/2 to 1 blade width. For poor matching the spacing should be increased.
- Obstructions likely to induce air flow distortion should be removed from the fan inlet, particularly with pusher fans. Obstructions downstream of the fan produce less distortion in the fan plane, and, if kept one-third of a diameter from the fan, should have negligible effect. Examples of typical obstructions include hoses, pipes, alternators, etc.
- A fan cowl should always be used to increase airflow efficiency which may enable fan speed and power absorption to be reduced.
- Blade tip clearance can be minimized by use of an engine-mounted fan ring. This eliminates relative movement between fan and ring, while relative movement between the engine and radiator can be accommodated by means of a flexible section in the cowl.
- Barriers should be used where necessary to prevent recirculation of air between downstream and upstream sides of the radiator, as this creates turbulence, with consequent increase in noise.

For further information on cooling system details and layout, see Chapter 6 — Cooling Systems.

13.8.3 Methods of Cooling Airflow Regulation

Radiator Shutters and Blinds

Thermostatically controlled shutters may be used to maintain optimum working temperatures. In the open position they can however create considerable interference to smooth cooling airflow, with consequent increase in fan noise, while in the closed position they can also cause a significant increase in noise, since the reduced airflow is likely to cause the fan to go into a stall condition. Closed shutters also create additional internal reflecting surfaces which can lead to further build-up of noise within the engine compartment.

Thermostatically Controlled Fan Drives

As a means of airflow control, thermostatically controlled fan drives of either the on-off or variable-speed type are preferable to shutters in respect not only to noise but also to efficiency and power saving.

13.9 Other Installation Noise Sources

13.9.1 Transmission and Drive Train

Noise under this heading falls into two main categories:

- Noise originating from transmission units and drive train, arising from design, manufacture or assembly, or from excessive wear of components.
- Noise radiated from transmission casings, housings, etc. due to direct excitation from the engine structure.

Some reduction of noise at source may be achieved by the transmission manufacturer and installer by attention to manufacturing tolerances, etc., and by use of effective isolation techniques. Further noise reductions will require the use of shielding or enclosure techniques, as described in Methods of Engine Noise Reduction by Attention to Installation and Application. Transmission shields may in fact, most conveniently be combined with engine shields as single units. (Note: Care should be taken to ensure that safe working temperatures are not exceeded.)

13.9.2 Hydraulic Systems

Hydraulic systems may add significantly to overall noise levels. They can also create a nuisance, particularly inside a cab, due to their distinctive frequency characteristics, which may cause them to be clearly audible to the human ear. Noise problems associated with the pump unit itself should be referred back to the pump manufacturer for assistance. Other hydraulic system noise may be minimized by attention to the following points:

- Pumps and associated valves, etc. should, if possible, be flexibly mounted to prevent transmission of vibration.
- The main hydraulic components should, if necessary, be sited inside an acoustic enclosure (e.g. the engine compartment), or positioned remotely from operators, observers, etc.
- Flexible pipes should be used in preference to rigid pipes to avoid pipe resonance.
- Avoid rigid pipe attachment, particularly to large panel structures; e.g., the cab floor.
- Avoid sudden changes of section and direction in the hydraulic system.
- Servo-actuated controls can reduce noise transmission to cabs.

13.10 Cab Noise

13.10.1 Nature and Causes of Cab Noise

Cab noise usually comprises a combination of airborne noise entering the cab from various external sources (engine, exhaust, fan, etc), and noise radiated from directly excited structural parts of the cab itself. Noise due to both causes may be reinforced by reflection or reverberation within the cab interior.

Note: radiated and reflected noise can also occur where overhead guards are fitted.

Substantial noise reductions can often be achieved by judicious application of the basic principles of insulation, damping and absorption.

The following points should be considered to help reduce cab noise:

- Eliminate the paths by which airborne noise can enter the cab interior (holes, gaps etc.).
- Minimize noise transmission through floor panels and engine housing panels by use of substantial barrier.
- Isolate the cab from the machine frame vibration; attenuation across the mounts should be at least 10 dB.
- Reduce panel vibration by careful choice of a highly damped material or application of damping treatment – adhesive damping pads.
- Make use of acoustic absorbent material in the cab to reduce reflected noise.

13.11 Noise Reduction Checklist

- Which legislative procedures and noise limits are relevant to:
 - The application?
 - The market territories? (legislative and marketing considerations)
- What degree of noise reduction is necessary to meet the required limits?
- Which are the most prominent noise sources? (Noise measurements are carried out to both customer's own product objectives and to ensure compliance with legislative limits.)
- Cooling system (Refer to Cooling Fan Noise)
 - Is the largest possible radiator fitted?
 - Is the fan well matched to the radiator?
 - Could a lower fan speed be used?
 - Is a fan cowl fitted?
 - Is the air stream free from obstructions?
- Exhaust system
 - Is the silencer large enough?
- Induction system
 - Is a silencer required in addition to the aftertreatment?
 - Is the air cleaner large enough?
- Engine
 - Could the rated speed be reduced?
 - Would the application of simple shielding to the machine be beneficial?
 - Could the engine compartment be redesigned as a complete enclosure?
- Transmission
 - Should shielding be applied to the machine? (Refer to Transmission and Drive Train)
- Hydraulics
 - Are the pipes resonating?
 - Can any rigid pipe attachments be eliminated?
 - Can any sudden restrictions or sharp bends be avoided?
- Cab noise
 - Are there holes and gaps through which airborne noise can be transmitted from various sources to the cab interior?
 - Are there any paths by which mechanical vibration can be directly transmitted to the cab structure?
 - Are cab floor, side, and roof panels sufficiently well treated with acoustic material?

14.0 Cold Weather Operation

14.1 Introduction

Diesel engines are more demanding than spark ignition engines when starting at low ambient temperatures because ignition of the fuel relies on the compression of the air.

Satisfactory starting is the ability of the engine to fire and pick up speed without damage or abuse to the engine, starting equipment, or driven machinery. In order to achieve a satisfactory cold-start and operate under cold weather conditions the engine and machine must be specified with the correct equipment suitable for the engine type and intended machine operation. This equipment must be correctly operated and maintained and the correct fuel and oil must be used.

Particular care must be taken in selecting and installing the relevant equipment, and the necessary information must be provided for the machine operator.

The following chapter details the mandatory requirements and aspects that need to be taken into consideration when operating a machine in low ambient conditions. It has been written to complement but not change the other installation requirements and recommendations within this manual. Further details can be found in Chapter 11 of this manual, Chapter 10 of the Electrical and Electronic Application Manual LEBH0005, the Tier 4 Interim Starting and Charging document TPD1749, the relevant engine specification manual (E.S.M.), and also in the OMM.

14.2 Cold Weather Operation Mandatory Requirements

All emission-related installation instructions are highlighted by the **EM** symbol.

Failing to follow these instructions when installing a certified engine in a piece of nonroad equipment violates federal law (40 CFR 1068.105(b)), subject to fines or other penalties as described in the Clean Air Act.

14.2.1 General

In order to achieve satisfactory cold-start performance:

- The engine must be operated with the correct fuel and oil for the machine operating temperature (ref OMM)
- The engine must be equipped and operated with the necessary cold-start aids for the machine operating temperature
- To achieve satisfactory starting with either Caterpillar or OEM supplied rotating electrics and glowplugs fitted as standard, the following conditions must be achieved at the lowest ambient temperature in which the machine is expected to operate:
 - Minimum cranking speed over TDC > 60 rpm
 - The minimum mean cranking speed must be > 100 rpm

14.2.2 Ether

- Ether start is only permitted with Caterpillar approved and supplied ether kit. (Reference IGB 1200-14.01.)
- Ether start must be enabled in the engine software and correctly wired as detailed in the Electrical and Electronic Installation Manual LEBH0005.
- Ether must be controlled by the ECU. It must not be used when glow plugs are active or used in conjunction with any form of engine combustion aid or any other electrical air-heating device.
- Ether must be operated and installed in accordance with the requirements detailed in IGB 1200-14.01.
- The use of hand-carried aerosol spray cans to aid starting is not permitted.

14.3 Cold-start Fundamentals

14.3.1 The Effects of Low Ambient Temperature

Cold weather has a significant influence on the performance of both the engine and machine. It not only affects the ability of the engine to successfully fire and run up to an operation speed, but once operational, the coolant, oil, and air temperatures must be maintained in order to ensure the engine is operating efficiently and that the emission reduction system operates normally.

Engine and machine performance in low ambient conditions is influenced by the following:

- The individual design features of the particular engine type. The cold-start system performance is summarized in the E.S.M. It is based on controlled cold chamber testing of each engine type, simulating various parasitic load conditions using starting equipment of known performance.
- The specification of the engine, including flywheel inertia and starter motor
- The starter circuit
- An increase in current flow
- An increase in the losses in the starter circuit due to cable resistance and connections. (This increases as the square of the current flow rate.)
- An increase in demand for cranking power from the starter
- A reduction of the available cranking power from the battery
- An increase in viscosity of the lubricating oil used within the engine that increases the torque required to turn the crank and of the oil used within the transmission and hydraulics.
- The fuel specification and its properties
- A reduction in the air charge temperature.
- The use of auxiliary cold-start aids
- The parasitic load of the driven equipment and any additional auxiliary loads applied at start-up or low speed

The reason for the cold weather effects on these parameters is discussed in more detail in the sections below.

14.3.2 Engine Design and Specification

Cranking Speeds

The minimum engine cranking speed necessary for satisfactory starting varies according to the engine design features and starting aid. If the required speed is not reached, starting is unlikely to be achieved. Where a starting aid is employed, the minimum speed requirement is lower for a particular engine than with unaided starting. The minimum cranking speeds specified in the Mandatory Section 14.2 must be achieved. This is with glow plugs fitted. In all cases, it is beneficial to reach a higher cranking speed as this increases the compression temperature. A low cranking speed will adversely affect firing times and the time for the engine to run up.

Starting Smoke

White smoke is normally attributed to unburned fuel, which can be more prevalent under cold-start conditions. The cold-start map within the engine calibration optimizes engine performance to reduce this start-up smoke; however, white smoke may still be evident even after passing through the DPF. Sometimes this smoke is caused by evaporation of the water from the DPF itself when the engine starts to warm up.

Aftertreatment

Cold weather can have an effect on aftertreatment regeneration, which may increase in duration.

Crankcase Breathing

Refer to Section 10.2.1 Crankcase Ventilation System Mandatory Requirements. All C4.4 ACERT-C7.1 ACERT Cat engines are supplied fitted with an insulated breather canister to help maintain the temperature of any ventilated gases and reduce the likelihood of the vapour condensing and freezing in very low operating temperatures. Freezing can lead to fouling of the breather pipe, which increases the system restriction and can subsequently lead to damaged oil seals, engine oil leaks, and effect engine emission compliance. In cold weather conditions, prolonged idle periods should be avoided. In very low ambient temperatures, additional measures are required. Please refer to Section 14.6 for further information.

Flywheel

Flywheel inertia influences the relationship between mean cranking speed, the instantaneous speed and, in particular, the minimum instantaneous speed around Top Dead Center (TDC) of a piston on the compression stroke. An example of this is shown in Figure 14.1.

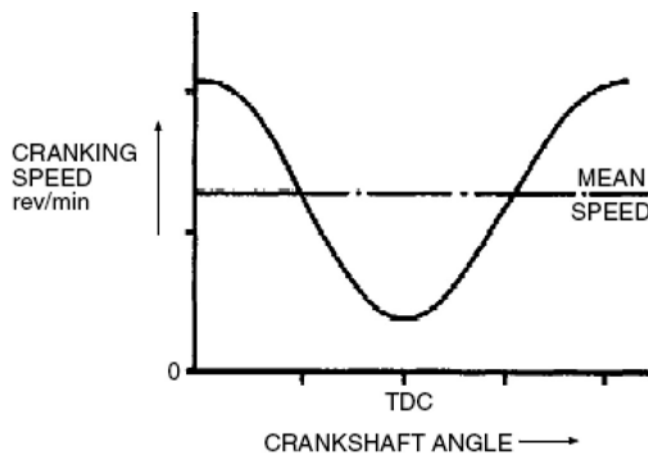


Figure 14.1

Several important functions take place at this time and a low instantaneous speed could result in the combustible mixture not being in the condition where burning could start. Therefore, a minimum rotating inertia is necessary to ensure sufficient speed while the piston is near TDC. This assists in providing satisfactory fuel injection and reduces the chances of premature ignition where advanced timings are used.

The use of a flywheel with inertia below the specified minimum can reduce starting efficiency, particularly if there is an excessive load on the engine during cranking. Inertia value details are available for all Cat flywheels and are detailed in the E.S.M.

Cold-start requirements must be balanced against the normal operating requirements of the machine when high inertia can adversely affect the machine performance, especially under transient conditions.

Starter Pinion/Ring Gear Ratio

In order to optimize starting efficiency, it is essential to have the correct gearing ratio between the starter motor pinion and the flywheel ring gear. This is required to ensure that the starter motor torque characteristics match the engine turning requirements during cranking, with sufficient reserve of torque and speed to assist the engine to pick up and run properly after firing has commenced.

The gearing ratio on Caterpillar supplied flywheel assemblies has been optimized with Cat standard starter motors. When the customer supplies one or both of these components these requirements should be taken into consideration.

14.3.3 Starter Motors

The starter motor simply receives electrical energy and converts it into mechanical energy, meshing the starter pinion with the engine ring gear and cranking the engine. If an excessive load or inadequate electrical power is provided, the starter will stall or turn very slowly. At lower speeds the starter efficiency falls off rapidly and the heat build-up increases. If the starter continues to operate in this condition then the starter will be damaged.

In normal ambient temperatures, the required cranking current is relatively low and the engine fires readily so the circuit resistance is not a great factor. As the temperature decreases, however, the required cranking current gets progressively higher and the engine has to be cranked longer before it starts. Under these conditions the starter circuit and resistance becomes a lot more important.

Different starter motors vary considerably in their performance, particularly in the current draw during cranking, even when they are of similar size or of the same nominal power output. Caterpillar supplied starter motors have been fully tested and validated to ensure that they perform adequately under normal and cold-start conditions. Caterpillar advice should be sought, concerning the use of any starter motor not referred to in E.S.M.

Non-Electric Starters

Non-electric starters may be used for various reasons, for example: in flame-proof environments, as a secondary cranking system, to prevent battery theft, or as a low-cost alternative. Various types of non-electric cranking systems can be specified. Caterpillar does not supply these normally, but can be contacted for advice concerning the proposed use of particular equipment.

Impulse Action Starters

The most common type of impulse starter is the spring starter, with pinion engagement on the flywheel starter ring. The units are self-contained and are wound up using a cranking handle. Space must therefore be allowed in the installation for operating the handle. The spring starter is a relatively inexpensive unit, and is favored for use in contractors' plant where there is a risk of battery theft.

A disadvantage of these devices is that they turn the engine over at high speed for only a small number of revolutions before the stored energy is dissipated. It is therefore very difficult to prime the fuel system, and in practice a slave electric starter and batteries must be used to start the engine if it runs out of fuel.

Hydraulic and Air Operated Cranking Motors

These motors use a conventional pinion, but the motor is powered by compressed air or hydraulic oil under high pressure. The torque/speed characteristics of these motors are significantly different from those of an electric starter motor. Much higher speeds are achieved, but for a very short duration; even with a substantial reservoir, capacity cranking time never matches that of an electric system. Charging up of the reservoir is commonly

done mechanically by an engine-driven pump during engine running and there is always a supplementary hand-operated pumping system available for hydraulic systems, for which operator accessibility is required. The reservoir and operating equipment is often relatively bulky, and the systems, even in their simplest form, are expensive. These cranking systems, because of their short cranking duration, do not generally give unaided starting at such low temperatures as electric systems.

Starter Cables

The starter leads are an important part of the cranking equipment, and installations having perfectly adequate starter motors and batteries may be rendered totally unsatisfactory by poor leads. This includes the quality of the terminals which can give rise to very high resistance if not fitted to a high standard.

Details of the maximum resistance values, and other relevant information, are given in Chapter 11. It should be remembered that these are maximum values, and every effort should be made to make the total circuit resistance as low as possible — this becomes vitally important on high-drag applications. Poor quality battery isolator switches can also give a high resistance.

14.3.4 Batteries

The battery and its connection leads must be capable of delivering sufficient energy to the starter motor for the engine to be cranked fast enough and long enough to get it started. A diesel engine is more demanding than a spark ignition engine in these requirements, so it is important to ensure that the starter motor is getting adequate energy during starting. Not only should this be adequate, but the resistance in leads which connect the battery to the starter motor must be within prescribed limits to ensure that the battery energy is transmitted to the starter.

A battery relies on a chemical reaction to create energy. The speed of this reaction significantly decreases in low temperatures, causing an overall reduction in the performance capability of the battery in low ambient conditions. At -12°C, batteries will have only about 75% of their cranking power available, at -20°C this reduces to approximately 60% and by -40°C all the cranking power has virtually diminished. In these very low ambient conditions the use of battery heaters or blankets may be required.

In order to maintain adequate performance it is essential that the battery is good quality and the correct battery rating is specified for its operating conditions. Besides giving poor starting the use of a low performance battery can result in cranking motor problems due to motor overheating.

Battery ratings are dependant on temperature, voltage, and current flow during discharge. They can be rated to various internationally recognized standards but the most common standards that we use are the two SAE standards detailed below. Other standards such as EN CCA and DIN CCA are used but these are not directly comparable to the SAE standard and a conversion factor should be used when doing so.

• Reserve Capacity (RC)

This rating is defined as the time in minutes that a battery will carry a 25 amp load and maintain a minimum terminal voltage of 10.5.

• Cold Cranking Amps (CCA)

This rating is defined as the current in amperes which a new, fully charged battery at -17.8°C can continuously deliver for 30 seconds and maintain terminal voltage equal to or higher than 1.2 volts per cell.

Available power from the battery systems is determined by its CCA rating, age, temperature, state-of-charge, and connecting cables. Increasing the RC and CCA of the system generally increases the cyclical capability and life of the batteries.

14.3.5 Lubricating Oil

The lubricating oil has a major effect on starting performance and requires as much care in its choice as does the starter motor and battery. Guidance on the selection of oil viscosity grades is given in the E.S.M. and OMM.

Oil used in equipment which is driven when the engine is cranked is equally important, and equipment manufacturers should be encouraged to specify oil viscosities which are realistic in relation to ambient operating temperature.

As a general rule, the viscosity of oil increases as its temperature is lowered. This can create two basic problems when using a temperate grade lubricating oil and starting the engine at low temperatures.

1. The oil pump will have to do more work to lift the thicker oil from the sump and pump it round the system.
2. There will be extra resistance when the moving components displace the thicker oil.

These conditions can be improved by using a lower viscosity of oil, but when the engine reaches normal operating temperature, the lower viscosity oil will become thinner at higher temperatures and it may not be possible to maintain an adequate oil film between moving parts when the engine is started at higher temperatures. This effect can be mitigated to some degree by the type of oil selected, which can restrict the change in viscosity over a given temperature range (multigrades). In some cases it may be necessary to select oil with a synthetic base to give adequate viscosity across the operating temperatures. The choice of oil is generally a compromise in achieving a sufficiently acceptable cold-start performance while maintaining the performance of the engine components under varying temperature conditions. Refer to OMM.

14.3.6 Fuel

For each engine design there is usually a particular air-to-fuel ratio that will most readily promote combustion. Any deviation from this ideal ratio is likely to make combustion more difficult.

During low-speed cranking the injection pressure is reduced so there is a tendency for the fuel to be injected less finely atomized than when operating normally. This can lead to an unhomogeneous charge which may hinder the efficiency of the burn. This is further exacerbated by the small fuel quantities used. If the mixture does not have a sufficiently even distribution of fuel and the burning is not sufficiently uniform, the temperature of the combustion chamber may not rise enough for the engine to pick up speed. This may cause the engine to stop or fail to increase in speed to an operational idle speed when cranking is discontinued. There may also be considerable white smoke due to the vaporization of the unburned fuel.

Specific engine cold-start strategies and software calibrations, which measure and/or control the fuel temperature, pressure, and engine timing, are employed to optimize all aspects of engine startability. In addition to this optimization, it is critical that the correct fuel specification is used for the ambient temperature of the operating environment. Details of how the fuel specification affects engine performance are explained in the section below.

Fuel Specification

The properties of diesel fuel can have an effect on many important performance characteristics. These properties are subject to various specifications which are governed by a number of industry standards such as the ASTM D975 (US), EN 590 (Europe), and JIS K2204 (Japan). Premium diesel grades are also available which can be covered by separate standards. Certain properties (i.e., sulphur content) may be subject to environmental regulations.

The properties of a given diesel fuel depend on its exact formulation and its performance in cold ambient varies accordingly. Alkanes contained within the fuel precipitate as wax in cold ambient temperatures, which can lead to clogging of fuel filters and may compromise fuel supply. This can be seen to occur at relatively high temperatures and sometimes even above 0°C.

Various parameters are used to help define the fuel's low temperature properties. These are summarized in Table 14.1.

Parameter	Definition	Standard
Cloud Point (CP)	The temperature at which wax first becomes visible	ASTM D2500
Pour Point	The temperature at which the amount of wax out of solution is sufficient to gel the fuel	ASTM D97
Cold Filter Plugging Point (CFPP)	The lowest temperature at which fuel will pass through a fine wire mesh screen	EN116:1981, ASTM D6371
Low Temperature Flow Test (LTFT)	North American procedure similar to the CFPP	ASTM D4539

Table 14.1

Another part of the specification, which can affect startability, is the cetane number. This number is an indication of the ease with which the fuel will start to burn under compression-ignition conditions. The higher the cetane number, the easier the fuel will burn. Cetane numbers in excess of 45 are normally expected from current diesel fuel. However, a cetane number of 40 may be experienced in some territories. The United States of America is one of the territories that can have a low cetane value. A minimum cetane value of 40 is required during average starting conditions but in high altitudes and/or cold weather a higher cetane number is recommended.

14.3.7 Antifreeze Mixture

Commercial antifreeze of an approved ethylene glycol (ethyenediol) type, with corrosion inhibitor, should be used for sustained ambient temperatures down to -40°C (-40°F). An engine coolant should never contain more than 50% by volume of antifreeze, because at stronger concentrations, the freezing point temperature of the mixture actually rises. Also, owing to the increased viscosity of the coolant mixture, the engine will not be warmed up properly during the pre-warming period, and could suffer from cooling problems while working. For ambient temperatures below -40°C the appropriate antifreeze manufacturer should be consulted regarding the use of a suitable antifreeze for diesel engine operation.

14.3.8 Machine Specification

Drag Effects

The cranking equipment recommendations are usually based on tests either on a bare engine, or on one fitted with a typical manually operated gearbox and clutch. If driven equipment is fitted, which imposes extra loading during cranking, this drag effect must be compensated for by the use of heavier-duty starter motor/battery etc. Caterpillar will advise where necessary.

Manual Gearboxes

These may cause up to 3°C reduction in ambient temperature bottom limit compared with a bare engine. It may be helpful to depress the clutch during cranking, and this procedure is always recommended.

Torque Convertors

The use of a torque convertor drive with automatic or semi-automatic transmissions nearly always causes a significant drop in starting efficiency against a bare engine, due to the oil drag effect. This imposes penalty of up to 5°C on the starting limit compared to the bare engine. The deterioration in starting may be offset by using more powerful cranking equipment.

Hydrostatic Transmissions

These may give fairly high drag, depending on the design characteristics. If direct coupled hydraulic equipment is fitted to the engine, specification of a heavy-duty starter motor will be essential for low temperature applications. In the case of hydrostatic pumps, a fluid bypass relief circulation arrangement helps reduce drag.

Driven Machinery

All equipment which has to be motored over together with the engine during cranking will provide some drag effect. This may be particularly significant with machinery of the reciprocating piston type, those incorporating oil pumps, and other hydraulic/hydrostatic devices. If a centrifugally operated clutch is used, which isolates the machine from the engine when cranking, it must be made certain, when starting at low temperatures, that the cold engine is capable of turning the machinery over without stalling when the clutch cuts in. In some cases, machinery drag may be reduced by the use of suitable low temperature operation oil or grease, and the equipment manufacturer involved should be encouraged to use lubricants of similar viscosity to the recommended engine oil, specifying multigrade oils as appropriate. Engine accessories such as hydraulic pumps, air brake and cab refrigeration system compressors, additional water pumps, and large output alternators and fans, etc. may add significant drag, particularly when several are fitted together.

Driven Load Reduction Devices Effect

The effect of driven equipment loads during cold weather engine starting must be considered. Hydraulic pumps, air compressors, and other mechanically driven devices typically demand more horsepower when they are extremely cold at start-up. The effect of this horsepower demand may be overcome by providing a means of declutching driven loads until the engine has been started and warmed up for a few minutes. This is not always easy or practical, so other means of relieving the load at cold-start-up may be required if the engine-load combination cannot be started with sufficient ease using the engine starting aids described earlier.

Some engine-driven air compressors provide for shutoff of the air compressor air inlet during cold-starting. This greatly decreases drag on the engine and improves cold-startability. This approach can only be used when the air compressor manufacturer provides this system and fully approves of its use. Air compressor damage could result.

14.4 Auxiliary Cold-start Aids

Starting aids are required for the engine to start satisfactorily below a certain ambient temperature. Unaided starting limits are given in the E.S.M. and it can be seen that the limiting minimum ambient temperature varies according to engine specification, electric starting equipment, and the engine lubricating oil viscosity.

All C4.4 ACERT-C7.1 ACERT Cat engines are supplied with glowplugs as a standard factory fit. Other starting aids can be used in addition to this for more extreme operating ambient conditions.

Fig 14.2 shows the effectiveness of different cold-start aids in different ambient conditions and shows how this varies with altitude. This should only be used as a guide and not a definitive source for correct starting aid selection. When using these starting aids it is important to follow manufacturers' recommendations to ensure smooth starting and to avoid damage.

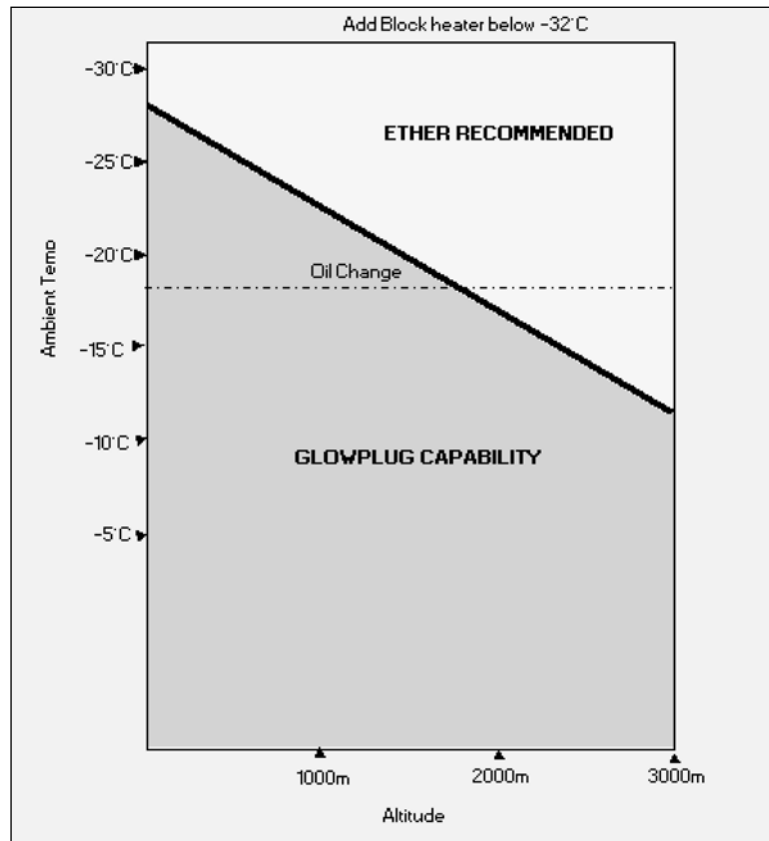


Figure 14.2

Further detail of the various different starting aids can be found below:

14.4.1 Glow Plugs

The glow plug is a device which protrudes into the combustion chamber of each cylinder, and when activated, has a high temperature that ignites the fuel/air mixture. Precise tip protrusion is required to enable the sprayed fuel to be properly ignited during cranking, without causing a significant drop of combustion efficiency during engine running. As glow plugs enable the engine to start instantaneously, no other starting aid is necessary down to -25°C and below. Due to their high current draw a suitable relay must be used to actuate glow plugs.

Activation of the glow plugs is controlled by the ECU, which monitors the coolant and air inlet temperature and decides whether the glow plugs are required. The exact control strategy for glow plug control can be found in the Electrical and Electronic Applications and Installation Manual — LEBH0005.

14.4.2 Ether Starting

Refer to Mandatory Requirements 14.2.2.

Ether is a volatile and highly combustible agent. Small quantities of ether fumes added to the engine's intake air during cranking reduce the compression temperature required for engine starting. It can therefore be used as an effective cold-start aid, particularly in very low ambient temperatures, when glow plugs are less effective.

When low temperatures dictate the need for an ether-type starting aid, a Caterpillar approved and supplied ether kit must be used. This is a permanently fitted, controlled-flow system where the ether is contained in a high-pressure metallic capsule, which is placed in an injection device and pierced, allowing ether to pass into the intake manifold. It is imperative that only this approved system is used as the atomizer and ether control valve have been specifically sized and optimized to inject the correct amount of ether under specific operating conditions. This takes into consideration both temperature and altitude and enables safe operation without damaging the engine. This type of system also requires few special precautions for handling, shipping, or storage.

System approval includes: branded start fluid mixture, pressurized supply device or hand pump make, and model number, nozzle type including spray orifice arrangement, fluid storage container or capsule capacity size and supply pipe work bore. A typical ether system is shown in Figure 14.3. For full details of the approved system refer to IGB 1200-14.01.

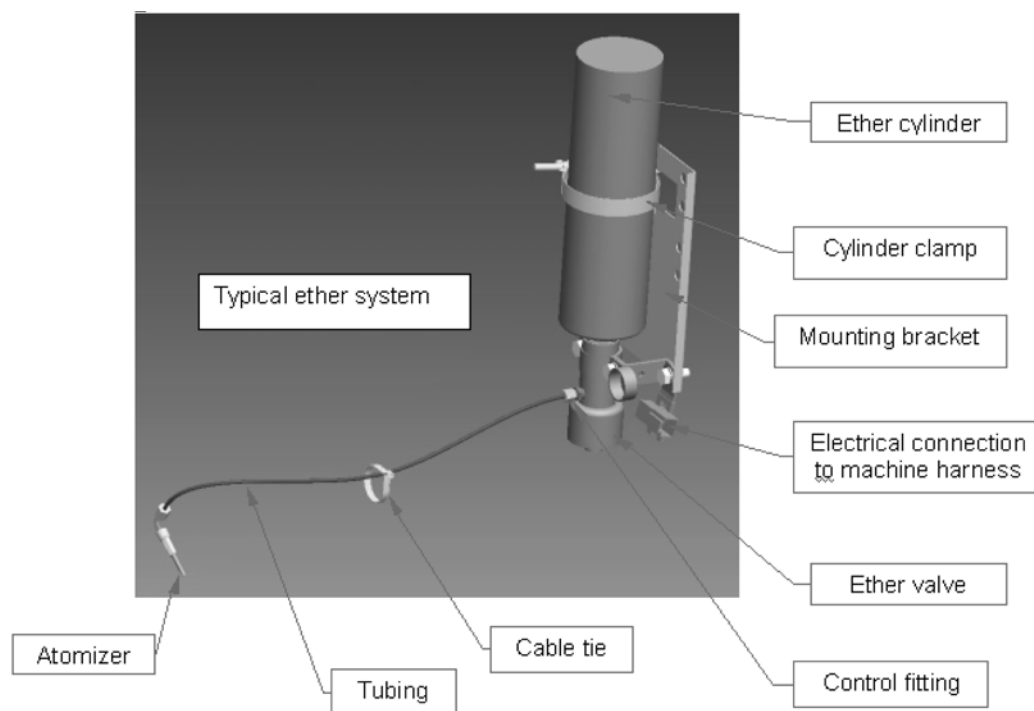
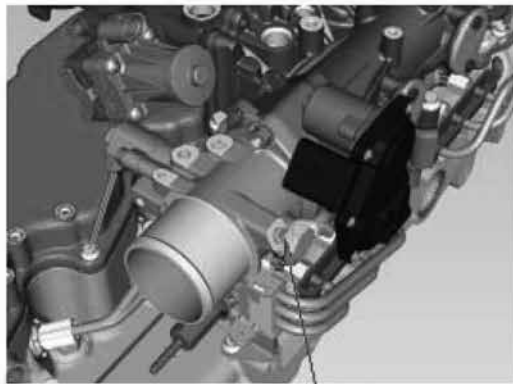


Figure 14.3

In order to use ether on C4.4 ACERT-C7.1 ACERT Cat engines, ether start must be enabled in the engine software. Ether activation is controlled by the ECU and is based on temperature, barometric pressure, and settings in the engine cold-start map. In general, if ether is installed it will only activate at temperatures below -18°C at sea level; however, in higher altitudes this may activate earlier. Refer to Figure 14.2 and also to the Electrical and Electronic Application and Installation Manual — LEBH0005 for further detail on the control strategy.

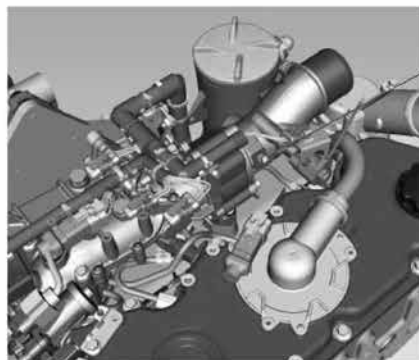
The ether system is not available as a factory fit option, but every engine has a threaded boss on the air inlet connected to enable fitment of this system as shown in Figure 14.4.

C6.6 ACERT



Ether boss tapped
1/8" NPTF

C4.4 ACERT



Ether boss tapped
1/8" NPTF

Figure 14.4

Warning! Ether starting fluid aid systems must only be used while the engine is cranked and must not be used in conjunction with any form of engine combustion aid or if the engine is fitted with glow plugs or any other electrical air-heating device.

The use of hand-carried aerosol spray cans as a consistent aid to starting is not permitted, due to the danger of over-application.

As all engines are fitted with glow plugs as standard, an ether-warning label is fitted on the engine air inlet connection to warn against the use of ether in a non-approved form, i.e., spray can. If this label is not clearly visible or the air filter inlet location is not in close proximity to the engine air inlet connection, it is strongly recommended that an additional ether-warning label be fitted near the air filter inlet.

14.4.3 Block Heaters

Block/jacket water heaters are electrical heaters that maintain the jacket water at a temperature high enough to allow easy starting of the engine. Heaters pre-condition engines for quick starting and minimize the high wear of rough combustion by maintaining the coolant temperature during shutdown periods. Heaters thermostatically control jacket water temperature near 30°C to 50°C to promote fast starts. Higher temperatures accelerate aging of gaskets and rubber material.

All C4.4 ACERT-C7.1 ACERT Cat engines have a tapped hole suitable for fitment of a block heater. The location of these ports is shown in Figure 14.5 and Figure 14.6.

C4.4 ACERT — LHS Face Industrial Block 3/4" NPTF

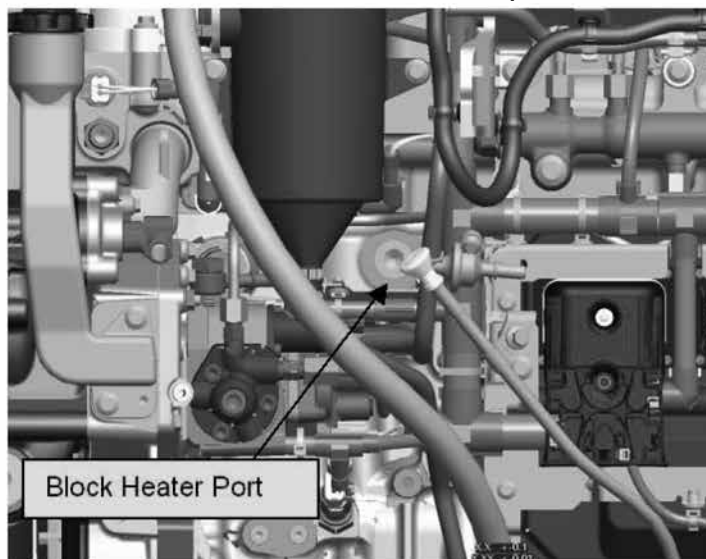


Figure 14.5

C6.6 ACERT — RHS Industrial Block

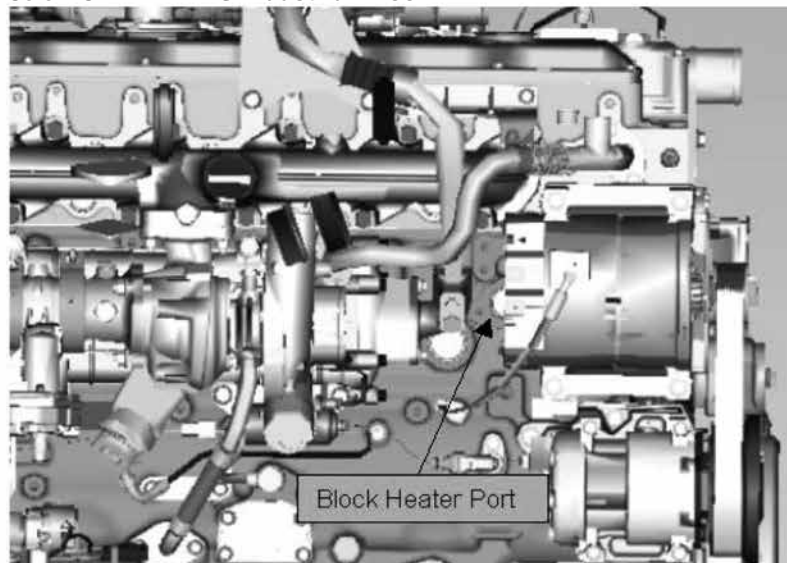


Figure 14.6

When using a block heater it is essential that the unit selected is compatible with the engine. Due to tight internal clearances in the water jacket, care must be taken to ensure that the element does not touch the internal walls of the casting, cause damage to the bore, and result in subsequent leaks. A typical block heater suitable for use with our engines is depicted in Figure 14.7. For further advise on block heaters contact your application engineer. Refer to IGB 1200-14.02.



Figure 14.7

14.4.4 Elevated Idle

For C4.4 ACERT and C6.6 ACERT engines, applications requiring operation at low idle for long periods of time at an ambient below -18°C , a regeneration aid is required. This regeneration aid is designed to allow the engine to passively regenerate when required by elevating the engine speed from its current low idle position to a fixed speed of 1200 rpm. The engine will only take control of engine speed if the associated wiring is completed and the engine determines that a regeneration is required.

Increasing engine speed to 1200 rpm allows the engine control strategy to maintain the engine exhaust temperatures required to activate passive regeneration of the engine DPF. This feature is available on all C4.4 ACERT and C6.6 ACERT engines and requires no specific configuration. For further information refer to the Electrical and Electronic Manual — LEBH0005.

14.5 Cold-start Design Considerations

14.5.1 Environment

The anticipated operating temperature must be known in order that the correct starting equipment can be selected. This is particularly important where machines are likely to be exported. Reference can be made to official meteorological data published for this purpose, but as a guide, the following are considered to be the lowest ambient temperatures for starting purposes in different areas.

European (Temperate zone)	-15°C
European (Cold zone)	-21°C
North America (General)	-29°C
Scandinavia	-29°C

The type of installation may have an influence on the cold-starting requirements, e.g., stationary equipment installed in a sheltered building, even if unheated, may not have such severe starting conditions as a mobile machine which is close by but kept and worked outside.

Special care must be taken with machinery which is liable to be transported and worked at widely spaced locations. High altitude operation, e.g., at 1500 m or above, should be treated as a special case. Please contact your application engineer for further advice.

14.5.2 Starting Equipment

It is not practical to supply an engine fitted with standard equipment to meet all possible starting requirements. It is, therefore, the responsibility of the OEM, in conjunction with the distributor or dealer where applicable, to make certain that the engine equipment specified is suitable for the severest cold-starting requirements which will be encountered at any time during the engine's service. Refer to the Tier 4 Interim Starting and Charging document TPD1749.

14.5.3 Installation Requirements

Engine Compartment

There are many conflicting design considerations to be made when considering the design of the engine compartment, which vary according to operational conditions. In cold weather conditions, for example, maintaining temperature is key, so enclosing the engine compartment is beneficial which may also help from a noise perspective. Under high ambient or regen conditions, however, it is necessary to dissipate the heat and prevent overheating of critical components so an open compartment with plenty of areas for the air to escape is critical, which may also aid service accessibility.

Considerations should be made to the position of apertures and the use of shielding and baffles to control the airflow so that cold air is not guided directly onto sensitive components such as the fuel, oil, and breather filters, but also does not allow air to stagnate which may cause problems in higher temperatures. The use of temporary shielding should be avoided, as this may not be removed under higher temperatures and risks damaging the engine.

Batteries

The battery must be positioned as close to the starter motor as possible, to minimize the length and resistance of the leads. It must be protected from the cold, as battery performance deteriorates with decrease of electrolyte temperature. If the battery is encased, there must be adequate ventilation to dispel the emitted gases, with access to the battery for checking and topping up the electrolyte. Battery heaters are usually recommended in cold ambient temperatures. The heaters should be set to maintain battery temperature in the range of 32 to 52°C (90 to 125°F) for maximum effectiveness.

Care should be taken to ensure that the battery location does not adversely affect the battery performance by maintaining a suitable temperature in both high and low ambient temperatures. Consult your battery supplier for temperature limitations.

Radiator Shutters

Radiator shutters will promote quicker engine warm-up and maintain a warmer general under hood condition during machine operation. They must however be of a reliable make and fully automatic, operating thermostatically from the temperature of the engine cylinder head coolant.

Note: The use of radiator shutters may increase the noise emission from the installation. Also see Chapter 6 — Cooling Systems.

Fan

A preferable alternative to the radiator shutter is the use of an electronically controlled fan sensing coolant and intake manifold temperature. The fan and drive arrangement must be of proven reliability and the cooling efficiency must be cleared for the maximum expected summer ambient. During the majority of operating time in very cold climate areas the engine will be overcooled using a conventional fan/radiator system. However, it is not recommended practice to run without a fan. See also Chapter 6 — Cooling Systems.

Controls and Instructions

The engine starting controls must be positive in action, easily understood, and arranged for convenient operation. All applications should be fitted with clear instructions giving the correct starting sequence for cold-starting. If the proper procedure is not followed, poor starting performance may result, even if the starting equipment is correct. Refer to Electrical and Electronic Application and Installation Manual — LEBH0005.

Fuel

Special precautions may be required to ensure that the fuel will be supplied satisfactorily to the fuel injection pump, both at engine starting and during the machine operation. It will be particularly necessary to prevent fuel waxing effect and/or water content freezing at any point which could block the supply or return lines.

The use of elbow bend connections, banjo connections, or sharp bends should be avoided. Filter gauze should not be fitted to any component in the fuel system. The fuel return pipe to the tank can be run directly alongside the fuel feed pipe where practical, to conserve warmth. It may be found necessary to lag the fuel pipelines, either along the whole run from tank to engine lift pump and return (including connections for very severe conditions), or in any particular area exposed to the weather elements.

Fuel Filters

The inlet strainer, ELP and any approved remote primary or secondary filter should be located in a sheltered but accessible and visible position while keeping fuel line lengths as short and direct as possible. On-engine secondary filters are particularly beneficial in cold weather as they receive warmth from the engine during preheating and machine operation. Off-engine remote-mounted fuel system components are more vulnerable, particularly when located outside of the engine compartment. Care should be taken to ensure these components are not situated close to the engine fan or directly in the air-flow.

Fuel filter heaters are available, and may be essential in some countries.

If a machine is required to operate in cold climates, it is recommended that a cold chamber test is conducted to ensure that the engine and machine starts and performs satisfactorily. This should be conducted at the lowest ambient temperature in which the machine is expected to operate. Refer to Caterpillar cold-start test procedure documented in Tier 4 Interim Application and Installation Test Procedures TPD1746.

14.6 Extremely Low Temperatures

Temperatures below -30°C (-22°F) usually require special measures to be taken by the OEM to ensure consistent starting. Various proprietary equipment makers specialize in the winterizing of engines and machinery, and should be consulted as early as possible in the machine building stage. Under these extremely low temperature conditions it is even more important to follow the recommendations on fuel oil and antifreeze mixture outlined in Fuel Oil and Antifreeze Mixture.

Cat engines are only designed for starting in temperatures above -30°C. For temperatures below this, the engine must be preheated before it is started to protect the engine's internal components from damage or any durability issues. For example, seals within the engine will lose flexibility at lower temperature and are therefore likely to suffer damage.

Caterpillar will not accept any responsibility for the consequences of starting unheated engines at lower temperatures. Engines may be stored at lower temperatures, but should only be started after restoring the engine to a temperature above -30°C, unless a suitable heating system as described is used.

When operating at these lower temperatures the following additional guidelines should be taken into consideration:

Starter Motor

A 24V cranking system is essential for temperatures below -32°C (-26°F). The starter motor should be the most powerful that can be fitted to the engine. The starter lead resistance should be kept to the absolute minimum. Refer to document Tier 4 Interim Starting and Charging TPD1749.

Batteries

Since the chemical activity within conventional batteries virtually ceases at -40°C (-40°F), it is important to use batteries that are suitable, and battery manufacturers' recommendations should be sought. As a guide, for use in extremely low temperature, batteries should have a minimum reserve capacity of 200 minutes. Most modern batteries are reluctant to accept a significant charge if the battery itself is at low temperature. If the battery is remote from any other source of heat, a self-energized battery heater combined with good insulation would be advantageous. (For further information see Battery Warming.)

Alternator

This must be of sufficient output to cover any extra demands made on the electrical system due to the use of engine heating systems, additional cab heater fans, lighting systems, de-icers, etc.

Lubricating Oils

Particular attention must be given to the oils used in the engine, transmission, and hydraulic systems. In environments where the average ambient temperature is expected to reach -18°C or lower for prolonged periods, no lubricant having a higher viscosity than OW should be used in the moving parts, which are in operation during cranking, unless advised otherwise by the equipment supplier.

Starting with Engine Heating

Where engine heating is used, starting should not be a problem provided the heating is rated to suit the lowest required temperature and is operated for the correct time. Heating times of less than two hours are unlikely to be fully effective, and it may be more appropriate to leave the heat switched on overnight. The use of radiator shutters and side screens is essential where engine heating is used.

The type of heating system used will depend to a great extent on the facilities available. It is preferable to use one working directly on an AC electrical supply if this is available at the garaging location. Otherwise, fuel burning combustion heater systems give good results, particularly under severe weather conditions. Any system used must be thermostatically controlled to prevent coolant-overheating occurring.

For air temperatures down to not lower than -34°C (-30°F), the use of an effective electrical cylinder block heater alone will be adequate, and will give sufficient heat soak to warm the oil in the sump if this is sheltered from the wind. However, the necessary pre-warming time will be longer than if both block and sump heaters are used. In extreme cases, where the overnight air temperature approaches -40°C, heating may be required continually when the engine is not running.

Electrical, Sump, and Cylinder Block Heaters

These are sheathed elements operated at main voltages, mounted in either the sump or in the block, and supplied from an external source. Their use is limited to maintaining the engine temperature while the machine is stationary and, with moving machines, they are connected by a plug which should be designed to automatically disconnect if the machine is driven away without disconnecting.

These heaters are common in extremely cold climates and with standby vehicles such as fire engines, which must rapidly achieve working temperature. The wiring for these heaters must be independent of the 12V or 24V battery circuit, although the circuit may be controlled by the machine supply. The insulation and the routing of the cables must comply with the relevant safety regulations.

Sump Oil Heater (Electrical)

C4.4 ACERT-C7.1 ACERT Cat engines do not have the necessary tapped bosses in them for fitment of a heater element, so it may be practical to use a proprietary sump external heater pad arrangement instead of an immersion heater. If a heater element is fitted into the sump it should be situated as low as possible without the element coming into contact with the sump bottom or side walls, and it must adequately clear engine moving parts and the oil pump and suction assembly.

Combustion Heater Device

This type of device heats up the engine coolant by the burning of diesel fuel, kerosene, or possibly butane or propane, according to the design. The system's operation is often battery powered and circulates engine coolant liquid around the burner system to the engine, and also, if required, through cab heaters, jacketed battery container, etc. The hot liquid is fed into the cylinder block electric heater position, or the water pump suction inlet connection, and out of the cylinder head through a suitable point such as the rear cover. If the lubricating oil is to be heated, the hot liquid should be fed through the heat exchanger in the sump before passing to the cylinder block. All connections should be capable of being quickly disconnected and should provide leak-proof sealing.

Battery Warming

Batteries must be relatively warm for cranking and provision may be required to heat them when the engine is not running. Whether electric or liquid heating is used, excessive heat at any particular point must be avoided. The battery manufacturers should be consulted for their recommendations. For machine operation in air temperatures approaching -40°C (-40°F), it may be necessary to warm the batteries while the machine is working to enable possible engine restarting. This can be arranged by passing the hot engine exhaust gas through a battery container made of suitable anti-corrosion material. The exhaust backpressure must be within the recommended limits (refer to Chapter 5 — Aftertreatment and Exhaust, Section 5.2) and with drain provision for the exhaust gas fluid content. However, the battery must not be allowed to become too hot, as its condition may deteriorate if its temperature reaches approximately 50°C (125°F).

Fuel Heating

Special precautions may be required to ensure that the fuel will be supplied satisfactorily to the fuel injection pump, both at engine starting and during the machine operation. It will be particularly necessary to prevent fuel waxing effect and/or water content freezing at any point which could block the supply or return lines.

The use of elbow bend connections, banjo connections, or sharp bends should be avoided. Filter gauze should not be fitted to any component in the fuel system. Subject to meeting any applicable insurance requirements, the use of suitable nylon pipe material in a well engineered system may be of advantage due to its thermal insulation property. The fuel return pipe to the tank can be run directly alongside the fuel feed pipe where practical to conserve warmth. It may be found necessary to lag the fuel pipelines, either along the whole run from tank to engine lift pump and return (including connections for very severe conditions), or in any particular area exposed to the weather elements.

Crankcase Breathing

For temperatures below -25°C the breather canister and hose requires additional protection. A kit of parts is available for all C4.4 ACERT-C7.1 ACERT Cat engines, which includes an insulated and heated breather canister and a set of insulated hoses. Refer to IGB 1200-14.03 for further information. This heated breather canister has the same space claim as the standard canister but the breather hoses are substantially bigger and may require special packaging considerations.

Fan Operation

When operating in very cold climates (-40°C) it should be noted that fan power absorption can increase by up to 25% until the engine warms up and the air temperature onto the fan stabilizes.

15.0 Production and Manufacturing

15.1 Introduction

The purpose of the Production and Manufacturing chapter is to provide awareness at the machine design stage, of some of the considerations that need to be made and adhered to when installing these engines in the production facility.

15.2 Production and Manufacturing Mandatory Requirements

All emission-related installation instructions are highlighted by the **EM** symbol.

Failing to follow these instructions when installing a certified engine in a piece of nonroad equipment violates federal law (40 CFR 1068.105(b)), subject to fines or other penalties as described in the Clean Air Act.

- **EM** The correct fluids must be used in the engine, refer to the relevant engine OMM for details.
- **EM** At no point within the production process should the engine, aftertreatment, 7.2 of the thermal management section.
- **EM** The flexible exhaust Installation kit must be assembled following the correct procedure detailed in Appendix A Chapter 5 — Flexible Exhaust Installation Assembly Procedure.
- **EM** It is not permitted to modify, tamper, or affix anything to the supplied emissions critical components during the manufacturing or assembly process.
- If electrostatic paint spraying is used the engine must be specially prepared. Refer to Section 13.2 in the Tier 4 Interim Electrical and Electronic A&I Manual LEBH0005.
- Painting of the aftertreatment, flexible installation kit, and any associated electronic components is prohibited.
- If any overspraying of the engine is required, the engine must be correctly masked. Please contact your application engineer for further information.

15.3 Production and Manufacturing Design Considerations

15.3.1 Engine and Aftertreatment Pairing

It is the responsibility of the machine manufacturer to ensure that their production facility has the ability to correctly pair the engine and aftertreatment and keep the necessary records to comply with Tier 4 Interim, Stage IIIB obligations. Please contact your account manager for further information.

The DPF identification module described below is a device supplied on all C4.4 ACERT-C7.1 ACERT Cat engines which verifies this pairing is correct.

15.3.2 DPF Identification Module

The DPF identification module is a device used to ensure that engine and DPF are correctly matched within the production facility. It is used on all C4.4 ACERT-C6.6 ACERT Cat engines. The module is used on engine start-up to verify that the aftertreatment serial number corresponds to that stored within the engine ECU. The ECU carries out the serial number verification for the first 25 hours of engine operation only. If the engine ECU detects that the wrong aftertreatment has been fitted to the engine, a fault code indicating the mismatch is raised and the engine derates by 100%. No DPF identification module configuration is required, all data contained within the ID module is preprogrammed prior to delivery of aftertreatment hardware. Refer to Section 5.4.4 of the Tier 4 Interim Industrial Engines Electronics A&I Guide — LEBH0005 for further information.

15.3.3 The Cat Regeneration System Ignition Test (C6.6 ACERT Engines Only)

Due to the additional connections required for the correct operation of the >130 kW product range there is a need for the customer to verify the correct connection of the engine and aftertreatment system. To do this, a first fire aftertreatment activation procedure, or Cat Regeneration System ignition test, has been developed. This must be completed before the engine will operate correctly. This does not require the use of EST. Refer to Section 14.7.2 of the Tier 4 Interim Industrial Engines Electronics A&I Guide — LEBH0005 for further information.

15.3.4 Handling and Storage

15.3.4.1 Lifting

The engine and aftertreatment must be lifted using the correct lifting equipment and following the correct lifting procedure detailed in the applicable engine Operator and Maintenance Manual (OMM). The lifting eyes supplied fitted to the engine are only designed and approved for lifting the mass of the engine. For instances where the aftertreatment is supplied mounted to the engine, the engine lifting eyes are approved for lifting both the engine and supplied aftertreatment. When the aftertreatment is not supplied mounted to the engine then this must be lifted separately. For C4.4 ACERT and C6.6 ACERT engines the aftertreatment solution does not include lifting eyes. For the C7.1 ACERT engine, lifting eyes are supplied as part of the aftertreatment solution.

Using the engine lifting eyes to lift additional mass (i.e., transmissions and pumps, etc.) unless specifically approved to do so by Caterpillar, may lead to lifting eye failure. Lifting eyes are designed and installed for specific engine arrangements. Alterations to the lifting eyes, mounting joint and/or the engine make the lifting eyes and the lifting fixtures obsolete. It is recommended that the engine lifting eyes are not removed after assembly and are retained as part of the installation to enable engine removal during service. If this is not possible, the lifting eyes should be retained and located with the machine for service purposes.

15.3.4.2 Storage

If the engine needs to be stored for a period of time prior to use, the correct storage procedures must be followed to retain engine warranty. Refer to the applicable engine OMM or contact your application engineer for further information.

15.3.5 Aftertreatment Fitting Instructions

The following document is available to help ensure correct fitment of the engine-to-aftertreatment connection.

- Appendix A Chapter 5 — Flexible Installation Assembly Procedure

Additional information is available to aid correct handling and assembly of the aftertreatment, where applicable. This information is contained within the internal documents listed below. Please contact your application representative or product support representative for more information.

C4.4 ACERT

- EDR C4.4.1.9 Remote engine aftertreatment lifting and handling information
- EDR C4.4.1.10 Engine-mounted aftertreatment lifting and handling information (also includes aftertreatment assembly information)
- EDR C4.4.17.1 Aftertreatment DPF & sensors removal and replacement instructions

C6.6 ACERT/7.1 ACERT

- EDR C6.6E.1.9 Aftertreatment lifting and handling information
- EDR C6.6.17.1 C6.6 Aftertreatment DPF removal and replacement instructions
- EDR C6.6.17.2 C7.1 Aftertreatment DPF & sensors removal and replacement Instructions

15.3.6 Painting

Electrostatic Paint Spraying

The high voltages used can cause damage to on-engine electronics. Refer to mandatory requirements 15.2. Refer to Section 13.2 in the Tier 4 Interim Electrical and Electronic A&I Manual — LEBH0005.

Painting of the aftertreatment, flexible installation kit, and any associated electronic components is prohibited. If any overspraying of the engine is required, care must be taken to ensure that correct masking procedures are in place to protect certain engine components. This includes, for example, electrics, belts, pulley grooves, labels, etc. Contact your application engineer for further information.

15.3.7 Fluids

The correct fuel, oil, and antifreeze must be used in the engine from first fire and therefore must be available for use within the manufacturing facility. Please refer to the OMM for further information.

16.0 Installation and Audit Testing

16.1 Introduction

Application and installation test procedures have been developed to detail the required Caterpillar test methods for the C4.4 ACERT-C7.1 ACERT Cat engine ranges. They cover the purpose, acceptance criteria, instrumentation and preparation, test method, and the data reduction and reporting.

16.2 Installation and Audit Testing Mandatory Requirements

16.2.1 Testing Method

All engine testing for the purpose of installation audit and sign-off should be performed as detailed within the latest revision of the test procedures as listed in Section 16.2.2 and detailed in the Tier 4 Interim Application and Installation Test Procedures obtained through your application engineer.

16.2.2 Test Procedures

The application and installation test procedures do not contain the pass/fail values for the engines, as this is platform and rating specific. This information will be held within the relevant E.S.M.

The application and installation test procedures are as follows:

- AITP 01 – Air Inlet Restriction Test
- AITP 02 – Air Charge Cooler Restriction Test
- AITP 03 – Air Charge Cooler Efficiency Test
- AITP 04 – Installed Engine Cooling Test (Ambient Clearance)
- AITP 05 – Coolant Fill Rate Test
- AITP 06 – Deaeration and Hot Shutdown Test
- AITP 07 – Exhaust Backpressure
- AITP 08 – Starter Circuit Resistance Test
- AITP 09 – Cold-start Test
- AITP 10 – Auxiliary Regeneration Test
- AITP 11 – Fuel System Test

These can all be found detailed in Tier 4 Interim Application and Installation test procedures TPD1746.

16.3 Supporting Information

16.3.1 Order of Testing

Wherever possible, the correct order of testing should be used to help ensure test results do not become invalid due to system redesign. This can often be the result of other systems failing to meet the pass criteria. The preferred order is shown below:

Order of Tests	If test fails do not proceed to...
AITP 01 Air Inlet Restriction Test	AITP 07, 02, 03, 04
AITP 10 Auxiliary Regeneration Device Test	AITP 07
AITP 07 Exhaust Backpressure Test	AITP 02, 03, 04
AITP 02 Charge Cooler Restriction Test	AITP 03, 04
AITP 03 Charge Cooler Efficiency Test	AITP 04
AITP 04 Jacket Water Cooling Test	
AITP 05 Cooling Fill Rate Test	AITP 06
AITP 06 Deaeration and Hot Shutdown Test	
AITP 11 Low Pressure Fuel System	
AITP 08 Starter Circuit Resistance Test	AITP 09
AITP 09 Installed Cold-start Test	

Table 16.1

16.3.2 Test Procedure Purposes

AITP 01 — Air Inlet Restriction Test

- To establish (with a clean air filter element) that the certified restriction of the air system at turbo inlet is not exceeded at a full load rated speed (or maximum load that the machine is capable of applying)

AITP 02 — Charge Cooler Restriction Test

- To establish that the customer air charge cooler and associated pipe work do not exceed the certified limit at a full load rated speed (or maximum load that the machine is capable of applying)

AITP 03 — Charge Cooler Efficiency Test

- To establish that the customer air charge cooler and cooling fan have sufficient capacity to reduce the temperature of the charge air to the certified limit and ambient at a full load rated speed (or maximum load that the machine is capable of applying)

AITP 04 — Jacket Water Cooling Test

- To establish that the customer's jacket water cooler and cooling fan has sufficient capacity to limit the temperature of the jacket water to the Cat top tank limit at a maximum ambient of 48°C (worldwide clearance); the test cycle used to establish this must reflect the worst case for the specific machine.
- To establish that the oil temperature at the main gallery does not exceed the Caterpillar limit at a maximum ambient of 48°C (worldwide clearance); the test cycle used to establish this must reflect the worst case for the specific machine and may be a different cycle to point 1 above

AITP 05 — Cooling Fill Rate Test

- To establish that the cooling system can be filled at a minimum continuous rate of 10 L/Min
- To establish that the cooling system vents air satisfactorily

AITP 06 — Deaeration and Hot Shutdown Test

- To establish that the cooling system is capable of withstanding repeated hot shutdowns without expelling excessive amounts of coolant
- To establish that the cooling system vents air satisfactorily
- To establish that under hood temperatures during repeated hot shutdowns will not cause component failures due to excessive heat

AITP 07 — Exhaust Backpressure Test

- To establish that the customer's exhaust system and associated pipe work do not exceed the certified backpressure limit at a full load rated speed (or maximum load that the machine is capable of applying)
- To establish that the parasitic load of the machine is sufficient to enable passive regeneration with the assistance of the engine-mounted backpressure valve

AITP 08 — Starter Circuit Resistance Test

- To establish that the customer's starter motor wiring does not exceed the starter motor manufacturer's resistance limit

AITP 09 — Installed Cold-start Test

- To establish that the machine starts and runs up in line with the product objectives (Caterpillar and customer agreed objectives)

AITP 10 — Auxiliary Regeneration Device Test

- To establish that installed auxiliary regeneration device is installed correctly

AITP 11 — Low Pressure Fuel System

- To establish that the customer's low-pressure fuel system does not exceed the Caterpillar inlet restriction limit(s)
- To establish that the customer's low-pressure fuel system does not exceed the Caterpillar return pressure limit
- To establish that the fuel inlet temperature(s) does not exceed the Caterpillar limit for fuel pump and ECU

16.3.3 Channels Required for Data Acquisition

Temp Channels	ATP 01 Air Inlet Restriction Test	ATP 07 Exhaust Back Pressure Test	ATP 02 Charge Cooler Restriction Test	ATP 03 Charge Cooler Efficiency Test	ATP 04 Jacket Water Cooling Test	ATP 05 Cooling Fan Water Cooling	ATP 06 De-aeration and Hot Shot Down Test	ATP 11 Low Pressure Fuel System	ATP 10 Auxiliary Fuel Device Test	ATP 08 Regeneration Resistance Test	ATP 09 Starter Circuit Test	ATP 03 Installed Cold Start
Exhaust (After Turbo)	Y	Y	Y	Y	Y	Y					Y	
Engine Oil (Gallery)				Y	Y	Y					Y	
Coolant Top Hose				Y	Y	Y						
Coolant Bottom Hose				Y	Y	Y						
Compressor Air Outlet			Y	Y	Y							
NRS air Inlet			Y	Y	Y							
Air before turbo/ after air cleaner			Y	Y	Y	Y						
ECM Surface							Y					
Under Hood 50 mm from ECM							Y					
Fuel after ECM							Y				Y	
Fuel before Fuel Cooler							Y				Y	
Air onto Charge Cooler Core			Y	Y	Y	Y						
Air onto Coolant Radiator				Y	Y							
Air off Coolant Radiator				Y	Y							
Under Hood thermals - as required see tab for possible areas of concern				Y		Y						
Pressure Channels												
Fuel Pre transfer pump							Y				Y	
Fuel Pre fuel cooler							Y					
Fuel at ARD manifold								Y				
Compressor Air Out			Y									
NRS Inlet			Y									
Coolant Pump Outlet (Modified cover)			Y			Y						
Coolant Top Hose					Y							
Coolant Bottom Hose					Y	Y						
Exhaust restriction 1		Y										
Exhaust restriction 2		Y										
Exhaust restriction 3		Y										
Inlet restriction	Y											
Speed Channels												
Engine Speed	Y	Y	Y	Y	Y	Y	Y					
Fan Speed				Y	Y	Y						
Electrical Channels												
Battery Voltage										Y	Y	
Starter circuit current										Y	Y	

Table 16.2

**Caterpillar.
Your Local Resource.
Worldwide.**

Your Cat dealer is prepared to answer any questions you may have about Cat Power Systems, customer support, parts or service capability anywhere in the world. For the name and number of the Cat dealer nearest you, visit our website or contact Caterpillar Inc. World Headquarters in Peoria, Illinois, U.S.A.

World Headquarters:

Caterpillar Inc.

Peoria, Illinois, U.S.A

Tel: (309) 578-6298

Fax: (309) 578-2559

Mailing Address:

Caterpillar Inc.

Industrial Power Systems

P.O. Box 610

Mossville, IL 61552

www.cat-industrial.com

E-mail: cat_power@cat.com



Materials and specifications are subject to change without notice.

Rating ranges listed include the lowest and highest available for a specific engine or family of engines. Load factor and time at rated load and speed will determine the best engine/rating match.

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