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# (R) Design Guidelines for Air-Conditioning Systems for Off-Road Operator Enclosures

RATIONALE

This document has been substantially revised to increase the scope and the information contained within to make it more comprehensive. It has also changed to comply with the new SAE Technical Standards Board format.

The experience gained from automobile air conditioning is very important, but it must be remembered that operating conditions for automobiles and off-road equipment are vastly different. Off-road equipment shall be designed to meet severe conditions of heat, dust, vibration, and general rough usage.



## 1. SCOPE

The purpose of this document is to establish air-conditioning design guidelines that will apply to most systems rather than the specific design of any particular system. Operating conditions and characteristics of the equipment will determine the design of any successful system; since these characteristics and conditions vary greatly from one application to another, the designer shall determine the goals expected to be reached under the conditions encountered. To determine the capacity of such items as blowers, condenser fans, condenser coils, evaporator coils, filters, compressors, etc., will require the adherence to several guidelines, some of which are outlined in the following paragraphs.

## 2. REFERENCES

### 2.1 Applicable Documents

The following publications form a part of this specification to the extent specified herein. Unless otherwise indicated, the latest issue of SAE publications shall apply.

#### 2.1.1 SAE Publication

Available from SAE International, 400 Commonwealth Drive, Warrendale, PA 15096-0001, Tel: 877-606-7323 (inside USA and Canada) or +1 724-776-4970 (outside USA), www.sae.org.

SAE J1503 Performance Test for Air-Conditioned, Heated, and Ventilated Off-Road, Self-Propelled Work Machines

SAE J2064 Coupled Automotive Refrigerant Air-Conditioning Hose Assemblies

SAE J3078/1 Off-Road Self-Propelled Work Machines Operator Enclosure Environment, Part 1: Terms and Definitions

SAE J3078/2 Off-Road Self-Propelled Work Machines Operator Enclosure Environment, Part 2: Air Filter Element Test Method

SAE J3078/3 Off-Road Self-Propelled Work Machines Operator Enclosure Environment, Part 3: Operator Enclosure Pressurization System Test Procedure

SAE J3078/5 Performance Test for Windshield Defrosting Systems for Off-Road, Self-Propelled Work Machines

SAE J3078/6 Off-Road Self-Propelled Work Machines Operator Enclosure Environment, Part 6: Determination of Effect of Solar Heating

Eischen, F., "Producing a Quiet and Comfortable Cab," SAE Technical Paper 680587, 1968, https://doi.org/10.4271/680587.

2.1.2 ISO Publications

Copies of these documents are available online at http://webstore.ansi.org/.

ISO 6682 Zones of Comfort and Reach for Controls

ISO 10263 Earth Moving Machinery Operator Enclosure Environment

ISO 14269 Tractors And Self-Propelled Machines for Agriculture and Forestry - Operator Enclosure

2.1.3 ASTM Publications

Available from ASTM International, 100 Barr Harbor Drive, P.O. Box C700, West Conshohocken, PA 19428-2959, Tel: 610-832-9585, www.astm.org.

ASTM D380 Standard Test Methods for Rubber Hose

2.1.4 ASHRAE Publications

Available from ASHRAE Headquarters, 1791 Tullie Circle, NE, Atlanta GA 30329, Tel: 800-527-4723 (U.S. and Canada only) or 404-636-8400, www.ashrae.org.

ASHRAE Guide and Data Book, Vol. 1, Fundamentals and Equipment.

2.1.5 Other Publications

AS 2823 Agricultural Tractors and Self-Propelled Machines - Test Procedure for Performance of Air-Conditioning Systems - Australian Government

ASABE-S613 1-3 Air Quality Systems for Cabs

EEC/78/317 Defrost Test

SMS 2864 Test Procedure for the Performance of Defroster Systems for the Windscreen in Cabs

SMS 2865 Test Procedure for HVAC Cabs

Vogelaar, B.F., "Engineering and Operational Characteristics of Air Conditioning Cab." Paper 59-639 presented at ASAE meeting, December 1959.

## 3. DEFINITIONS

### 3.1 EFFECTIVE TEMPERATURE

Combination of relative humidity and temperature which can indicate the level of comfort perceived by the human body.

### 3.2 AIR FLOW

The direction, velocity, and volume of air moved to and around the occupant space.

### 3.3 OPERATOR ENCLOSURE

Part of the machine which surrounds the operator, preventing the free passage of external air, dust, or other substances into the area around the operator.

### 3.4 AIR CONDITIONING SYSTEM

System which lowers the effective temperature of the air within the operator enclosure.

### 3.5 EXTERNAL AIR

Controlled air entering the system or opening from outdoors before any air treatment.

### 3.6 RECIRCULATED AIR

Air within the operator enclosure which passes through the air-conditioning system.

### 3.7 COOLING

A decrease in the temperature of the air inside the operator enclosure.

### 3.8 HEATING

An increase in the temperature of the air inside the operator enclosure.

### 3.9 VENTILATION

A system or means of providing fresh air into an operator enclosure.

### 3.10 VENTILATION SYSTEM

System which provides external air to, and maintains air circulation within, the operator enclosure.

### 3.11 PRESSURIZATION

Positive pressure differential between the static pressure inside and outside of the operator enclosure.

### 3.12 PRESSURIZATION SYSTEM

Means used to create a state of positive pressure within the operator enclosure including any components which influence the performance of the system.

### 3.13 FILTRATION

Removal of contamination particles from the air forced or drawn into the operator enclosure by mechanical means.

### 3.14 FILTRATION SYSTEM

Means for removing contamination particles from air entering or being recirculated in the operator enclosure.

3.15 SOLAR HEATING

Heating factor from the sun to be considered in determining air circulation and cooling requirements necessary to maintain a comfortable temperature inside the operator enclosure.

3.16 SOLAR RADIANT ENERGY

Process by which solar heating is generated.

3.17 LATENT HEAT

Amount of energy in the form of heat released or absorbed by a substance during a change of phase state.

3.18 SENSIBLE HEAT

The heat required to change the temperature of a substance.

3.19 HVAC SYSTEM

Heating, ventilating, and air-conditioning system.

3.20 HVAC MODULE

The evaporator, heater, and blower that is contained in an enclosure and designed to operate as a system.

## 4. AMBIENTS AND OPERATING CONDITIONS

### 4.1 Ambient Temperature

The ambient air temperature at which the equipment will normally operate is one of the most significant factors to be considered in determining the capacity required for proper heating or cooling of the operator enclosure.

### 4.2 Solar Heating

Solar heating shall be considered carefully when designing the system. Solar radiant energy causes a heating effect to be considered in determining cooling capacity and insulating requirements. Also, direct radiation on the operator can cause discomfort not easily overcome by the system.

### 4.3 Mechanical Load

The mechanical load is heat transferred to the operator enclosure from the engine, transmission, hydraulics, etc. This load shall be considered when locating system components and may require special insulation.

### 4.4 Dirt and Dust

Contamination particles shall be considered when designing the filtration system and when locating components, particularly—but not limited to—those outside the operator enclosure, such as the external air inlet.

### 4.5 Global Factors

Ambient conditions of the various markets that the vehicle will operate in shall be considered (consider North American versus European average ambient conditions). For example, environments with high heat and humidity will need higher AC capacity as condensing water vapor from the air requires removing significant energy as heat. Environments with extremely low temperatures will require a higher heating capacity to keep the occupants comfortable and defrost windows.

4.5.1 Durability

4.5.1.1 Normal Duty

Off-road equipment normally encounters shock and vibration conditions requiring more robust design than automobiles and trucks. However, unless the operating conditions are severe, normal manufacturing techniques used for off-road equipment are usually adequate.

4.5.1.2 Severe Duty

Equipment such as track mounted off-road equipment and accessories for such equipment are often subjected to greater shock and vibration than usually encountered in other off-road equipment. Therefore, provisions should be made in the air-conditioning system to withstand such conditions. This may require shock mounting of some components. Sheet metal parts may have to be fastened together with more robust methods. Additional vibration testing may be required.

5. SYSTEM BASICS OF OPERATION

The HVAC system consists of the following parts: refrigeration loop, heater circuit, air circulation system, and control system. The refrigeration loop and heater circuit remove and add heat to the air through the evaporator and heater cores which act as heat exchangers.

5.1 Refrigeration Loop with TEV/TXV (Thermostatic Expansion Valve)

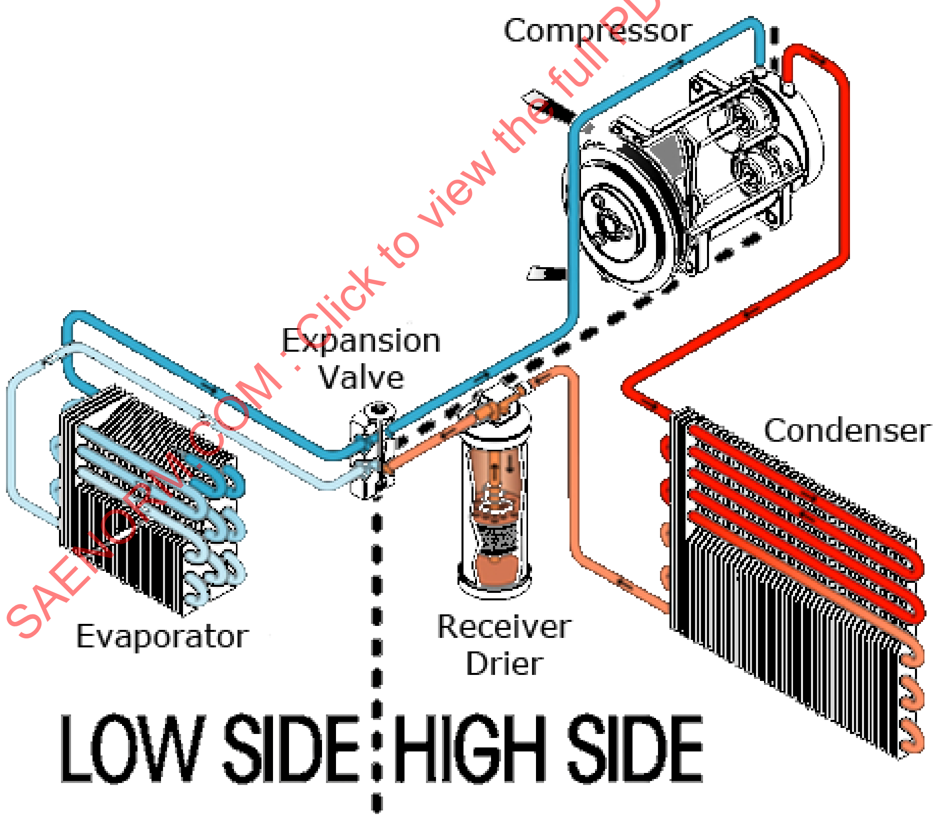


*Figure 1*

5.2 Refrigeration Loop with Orifice

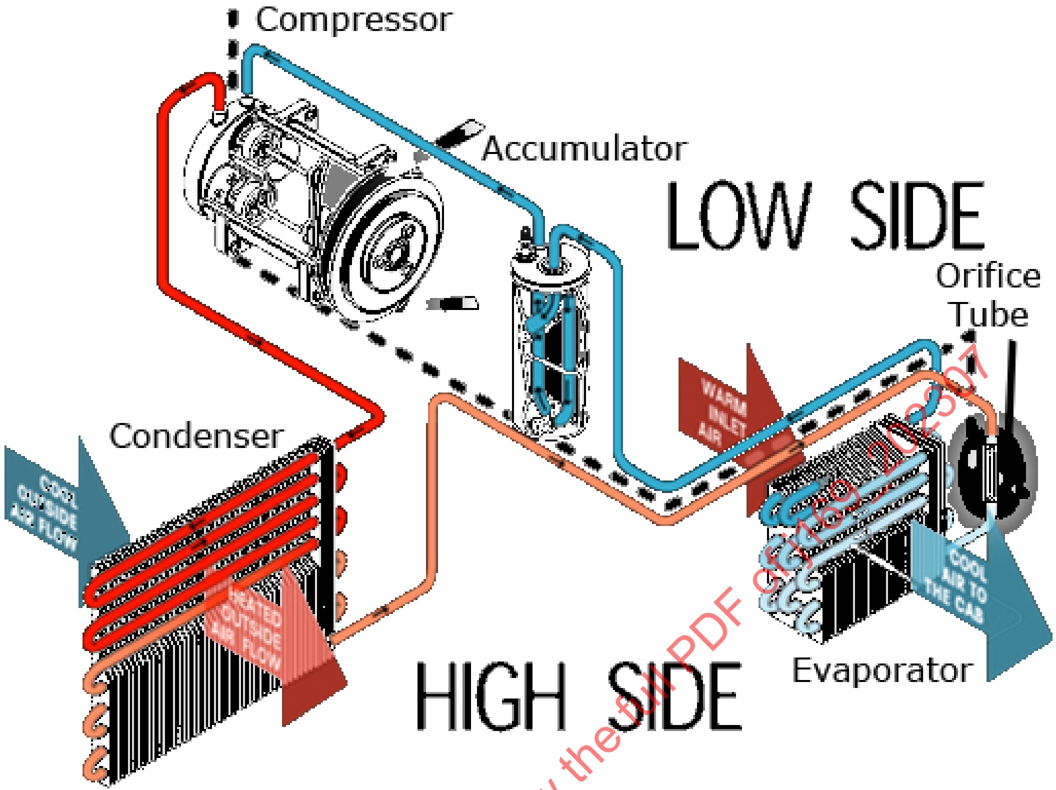


*Figure 2*

A compression refrigeration cycle consists of the following phases: compression, cooling and removing superheat, condensation subcooling, expansion, evaporation, and superheating. Compression is accomplished by means of an AC compressor where superheated vapor enters the compressor at low pressure and temperature and is compressed to a higher pressure and temperature.The high-pressure superheated vapor is carried to the condenser, where the refrigerant undergoes the following transformations utilizing outside ambient air; the heat is removed from the refrigerant vapor to bring its temperature to a condensing point, then gas is condensed to a liquid phase, and finally the liquid is subcooled to a specified level. The subcooled liquid refrigerant then undergoes expansion through an orifice device changing to a low temperature and pressure mixture of liquid and vapor. The mixture of liquid and vapor enters the evaporator where the latent and sensible heat from air passing through the evaporator core vaporizes and then superheats the refrigerant. The superheated vapor then flows back to the compressor and the cycle repeats. There are additional components in the refrigerant loop which perform non-refrigeration cycle roles. These are components such as receivers, filter-driers, accumulators, moisture indicators, sight glasses, etc.



5.3 Heater Circuit

The heater circuit usually taps into a high-pressure point on the engine cooling system to bring hot coolant into the heater core and then returns it to a low-pressure point on the engine or radiator. The amount of heat added by the heater circuit is controlled by regulating the amount of coolant flow through the heater core by means of a coolant valve or by controlling the amount of air going through the heater core.

5.4 Air Circuit

The air circuit has the following functions: bring and filter a specified amount of outside and inside air through the HVAC module and distribute it into the operator enclosure. The air distribution system needs to be able to meet the requirements of cooling, heating, dehumidification, defogging, and defrosting. The blower fan(s), which can be either an integral part of the HVAC module or of the operator enclosure, are utilized to bring the air through the air circuit. There are two major types of air circuit designs: reheat and blend.

5.4.1 Reheat Air Systems

In reheat systems, air first passes through the evaporator to remove heat and moisture and then flows through the heater core to adjust the temperature level. This approach allows for the active dehumidification of air by cooling and reheating. The heater valve is utilized to regulate the amount of heat added to the air by controlling coolant flow.

5.4.2 Blended Air Systems

In blended air systems all the air generally flows first through the evaporator core as well. However, in blend air systems, some or all air may bypass the heater core. The mode door position regulates the proportions of air flowing through the heater core and bypassing the heater core.

5.5 HVAC Control

There are two general approaches: manual temperature control and automatic temperature control (ATC). ATC uses a micro processor to maintain a constant operator enclosure temperature. Manual control relies on the operator to adjust controls to maintain cab comfort levels. Both manual and ATC systems utilize common methods to control cooling and heating output. The cooling output is controlled either by cycling the compressor clutch, varying compressor displacement (in case variable displacement compressor is used), or varying compressor speed. The amount of heat added is controlled by either varying the coolant or air flow through the heater core.

There are other control devices such as evaporator temperature sensors and high-pressure and low-pressure switches that are used to provide proper functionality, and protection of the system and its components.

6. HVAC SYSTEM DESIGN GUIDELINES - SYSTEM LEVEL

6.1 Location of Components

6.1.1 General

The type of equipment and location of the operator enclosure on the equipment will greatly affect the location of the system components. In general, refrigerant components should be isolated or insulated from high heat sources such as exhausts, engines, transmissions, etc. All components should be positioned in such a manner that they will not hamper the operator when entering or leaving the enclosure, or while operating the equipment. In many systems, it is practical and cost effective to locate the condenser upstream of the vehicle's radiator, which will yield good results if properly sized. Careful consideration shall be given to the problem of dust and dirt clogging the heat exchangers, which reduces their efficiency. An alternative is to mount the condenser in some other location and cool it with a motor (electric or hydraulic) driven fan(s). The advantage of cooling with motor-driven fans is that the condenser can be mounted in the best possible location relative to the rest of the system, minimizing exposure to dirt and dust.

6.1.2 HVAC Module Location within the Cab

The major HVAC system components can be located in multiple places within the cab. One of the key decisions is where to place the HVAC module. Several things impact this location.

6.1.2.1 Performance

6.1.2.1.1 In general, the closer the HVAC module to the louvers (vents), the closer the louver air temperatures will be to the air temperature leaving the heat exchangers. In other words, there will be less heat loss or gain as the air travels through the ducts.

6.1.2.1.2 In air-conditioning mode, operators usually put a priority on aiming the conditioned air to flow to the front of the upper body. Therefore, louvers that are facing the operator and close to the upper body are best for getting flow during air-conditioning mode. To reduce heat gain, the best location for the HVAC module is in the roof area or in the front console, to keep the duct length to a minimum.

6.1.2.1.3 During the heating mode, operators put a priority on aiming the conditioned air to flow to the lower body. In this case, louvers that are close to the lower body are best for getting flow during heating mode. To reduce heat loss, the best location for the HVAC module is around the floor area, or in the front console.

6.1.2.2 Condensate Drainage

Condensate drainage off the evaporator (water being removed from the air as it is cooled in the evaporator) is an important consideration in the design of an HVAC module. It will affect the design and layout of the components in the module. The amount of condensate produced by an air-conditioning system running in high humidity can be liters per hour. If this condensate is not handled properly, it can lead to decreased performance, operator dissatisfaction, vehicle damage, and encourage the growth of mold. This can be more challenging for modules mounted high in a cab, such as on the roof, versus in the floor. This is due to several reasons:

6.1.2.2.1 Modules mounted in the roof are further from the vehicle drivetrain, which means that as equipment is driven on hills and bumpy terrain, there will be a greater amount of "sloshing" of the water in the drain pan as compared to modules mounted low. This "sloshing" can cause carry over of the water, which may leak into the headliner or blow out the louvers.

6.1.2.2.2 Ducts out from a roof mounted HVAC module shall be routed down to the operator space, which means that they may become the lowest spot for water to run if it "sloshes" out of the evaporator drain pan. On the other hand, with modules mounted low, ducts tend to be routed up, preventing any water from being blown out the louvers.

6.1.2.2.3 Condensate drains on an HVAC module mounted in the ceiling in the middle of the cab may not be possible. In this case some kind of mechanical pump would need to be used.

6.1.2.3 Control Location

All controls, switches, etc., should be positioned for the convenience of the operator. Operators prefer controls that are located in one location, for ease of use. Refer to component guidelines for specific control information.

6.1.2.4 Operator Comfort

Human thermal comfort is an incredibly complex design parameter, because it is affected by so many conditions. Comfort is also affected by the type of machine that is being operated, the type of work being done, and the time of day and year that the work is occurring. Some basic parameters that affect operator comfort level are: mean cab temperature, relative humidity, air flow around Operator environment, and fluctuations of air flow and temperature out of the louvers as well as of the overall Operator enclosure. SAE J1503, SAE J3078, ISO 10263, and ISO 14269 provide basic comfort performance values for heating and air conditioning. However, each application should review its performance in the field historically and study what improvements could be made to performance.

6.1.2.5 Airflow

The position of the cooling vents and the direction of airflow will affect the comfort of the operator and is equally important as the effective temperature in the operator enclosure. As mentioned in the previous section, cooling outlet registers should be placed as high in the operator enclosure as is practical and should be directed at the front of the operators head and torso. Excessive velocity across the operator's eyes can cause drying and discomfort and should be avoided. Heating outlet registers should be lower in the enclosure. Most off-highway HVAC systems provide 340 to 600 $m^3$/h total system flow.

It is important to remember that some operators like a lot of airflow, while others prefer minimal airflow on the body. The amount of airflow the operator would like may also vary with the amount of solar heating they are receiving.The HVAC system should be able to accommodate both types of operators and under most conditions, potentially via mode controls or adjustable louvers. HVAC noise also needs to be considered, as excessive noise will lead to operator discomfort.

The airflow to the operator should be as balanced as possible—for example, the airflow on the left side of the body should feel the same as the right. A significant imbalance could lead to dissatisfied operators.

6.1.2.6 Cab Pressure

A cab that is pressurized compared to ambient is important to maintain cleanliness as well as maximize air conditioning and heating performance. In addition, a well-sealed cab will reduce the amount of ambient noise transmitted into the operator environment. Target positive cab pressure at all operating settings, not to exceed 200 Pa—levels above this pressure will lead to operator discomfort, and lower levels will lead to reduced performance and dirt in the cab. Two main design parameters affect cab pressure: the amount of external air flow and cab sealing.

6.1.2.6.1 External Air Flow

The amount of external air flow is a careful balance for the design team. Too much external air flow will apply a large heat requirement on your evaporator and heater core and can lead to overpressurization of the cab. Too little flow can lead to a lack of ventilation for the operator, poor defrosting/defogging, increased $CO_2$ levels, and lack of cab pressurization. Minimal requirements per SAE J1503, SAE J3078, ISO 10263, and ISO 14269 are 43 $m^3/h$, and, in general, the system should pull in less than 170 $m^3/h$.

6.1.2.6.2 Cab Sealing

All the cracks around doors and windows and any other opening in the operator enclosure should be carefully sealed. This helps the heating or cooling system because it prevents the loss of conditioned air from the operator enclosure, and therefore helps the pressurization system. To help understand the amount of leakage allowed, the following captures hole size versus flow:

***Table 1***

| If the total cumulative size of the various leakage points is equivalent to a hole of this diameter: | It will take this much airflow to pressurize the cab to 125 Pa: |
|---|---|
| 50 mm | 68 $m^3/h$ |
| 75 mm | 152 $m^3/h$ |

6.1.2.7 Noise

Fans or blowers should be properly located and balanced to avoid objectionable noise and vibrations in the operator enclosure. Usually, the more turbulent the airflow, the more noise that is created. Therefore, it is best to design ducts with smooth, large radius corners and to avoid airflow “deadheads.” Usually, the slower the blower wheel spins, the lower the blower noise level—this factor needs to be balanced with spinning the wheel fast enough to blow the needed amount of air. Consider making ducts from soft materials, such as foam, to absorb noise.

6.2 Sizing the HVAC System

There are many things to consider when sizing the HVAC system in a cab. The vast majority of the heat load on a cab is normally from external sources, although it is important to consider if there are major sources of heat inside the cab (hydraulic hoses, for example). The operator adds some heat to the cab; normally, in off-highway equipment, a typical operator adds about 0.22 kW (750 Btu/h) to the cab environment. If the machine will often have additional riders for training, the additional heat load should be considered.

6.2.1 Heat Load Factors

External cab heat loads shall be considered when sizing an HVAC system. It is good practice to meet with the various vehicle design personnel to discuss possible heat loads. Examples of external heat loads include:

6.2.1.1 Engine Fan Blast

Hot air coming out of the engine compartment blown onto the cab glass. HVAC external air intake should be located away from vehicle heat sources such as engine fan blast.

6.2.1.2 Solar Load

The heat load from the sun changes depending on the location, time of year, and time of day. Good visibility is a necessity in all vehicles, but the amount and type of glazing in an operator enclosure becomes a very definite factor in the design of an air-conditioning system. The use of tinted glass, which does not affect visibility, may be advantageous in improving operator comfort. Solar reflective glass is better than tinted for reducing solar load, but is usually more costly. Also, solar radiation during the winter helps keep the cab warm; solar reflective glass reduces this benefit. The use of plastic in place of glass requires consideration of the relative heat transfer characteristics. The use of thermopane glass is desirable for its insulating properties but is not usually practical from a cost standpoint. Outside machine color is also a consideration—radiation from the sun is absorbed very differently from radiation from a “black body” object (exhaust, for example). Compare two steel panels in which one is painted white while the other is a dark paint (red, brown, etc.): the amount of heat from an exhaust muffler onto the panels is nearly identical; it’s nearly independent of color. However, if the panels are exposed to the sun, the dark colors will absorb one to two times more radiation than the light colored panel.

6.2.1.3 “Hot Spots” on the Vehicle

These include hot hydraulic or transmission components, and the vehicle exhaust system.

6.2.1.4 External Air

Contributes to the A/C heat load. An excessive amount of external air will reduce A/C system performance.

Judicious use of insulation is important in the design of an efficient system. Sometimes it is impossible or impractical to locate cooling components away from heat sources. Therefore, it becomes necessary to insulate the components from the heat source. Insulating the operator enclosure also minimizes the effect of the ambient air temperature and solar heating.

The size of the operator enclosure has normally a fairly linear relationship with cab heat load; i.e., larger cabs will have more heat load on the HVAC system. This is due to the larger surface area of the cab walls conducting heat in from the outside ambient environment as well as the tendency for larger cabs to have more glass, which transmits more solar radiation into the cab. Surface materials are also a consideration—steel conducts heat very well, glass and plastic are moderate conductors, and foam is a good insulator.

6.3 Electrical Requirements

Sufficient power shall be available to operate electric fans, blower(s), and the compressor clutch. The cab blower and condenser fans are typically the vast majority of the power required for the HVAC system with a belt driven compressor. Normally this will not exceed the vehicle’s available capacity but it must be considered in the design stage. For example, available power may limit the size of blower motors. If special components such as an electric motor to drive the compressor are used, it may be necessary to use a large capacity alternator and heavy-duty battery.

Be sure to consider what system voltage will be at the components. In many cases, if the component is some distance from the alternator, the component may see one to two volts less than what the alternator is generating. For example, if the machine system voltage is 14.4 V from the alternator, the cab blower may only be getting 13 V, so size the blower for 13 V input rather than 14.4 V. Using the appropriate wire gage will help reduce the voltage drop in large vehicles with long wire harnesses.

6.4 System Protection

Mechanical or electronic devices should be incorporated into the system to provide protection for loss of refrigerant charge, and to prevent excessively high or low operating pressures. See the pressure switch for more details.

Examples of conditions that can cause high pressures: debris plugging fins on the air side of the condenser, internal plugging of the condenser tubes which blocks refrigerant flow, blocked receiver/dryer, or a kinked or blocked AC hose.

Examples of conditions that can cause low pressures: low refrigerant level, malfunctioning expansion valve or orifice tube, malfunctioning freeze or thermostat switch, debris plugging fins on the air side of the evaporator, or low-temperature ambient conditions.

# 7. HVAC COMPONENT GUIDELINES - COMPONENT LEVEL

## 7.1 Air-Conditioning Components

### 7.1.1 Refrigerant

This document describes design guidelines for systems equipped with R-134a refrigerant—the media which carries heat through the system. It absorbs heat while in the evaporator by changing state from a liquid to a gas and gives heat up again as it is changed back to a liquid in the condenser. Refrigerant will absorb or give up heat as it is heated or cooled without a phase change but that amount is small compared with the amount absorbed or released during a phase change. Refrigerant as a vapor heated to above its vapor saturation point at a given pressure is refered to as superheated. Refrigerant as a liquid cooled below its liquid saturation point is referred to as "subcooled."

A refrigerant is selected based on the amount of heat it takes to change its state, its pressure-temperature curve, and its chemical composition. R-134a is an hydrofluoro carbon (HFC) and does not have the ozone depleting potential like a chlorofluorocarbon (CFC) based refrigerant such as R-12. However, R-134a is a greenhouse gas and is therefore a controlled substance. It requires specific training and equipment for proper handling and disposal. The regulations on this vary from country to country. Its pressure-temperature curve makes it a good choice for an air-conditioning application and is found in the majority of mobile vehicles with air conditioning. The amount of refrigerant used in a system depends on system size and the refrigerant used. A typical air-conditioning system used in a construction machine will contain between 0.7 to 2.7 kg (1.5 to 6 pounds) of R-134a.



At the time of the release of this document, there is a move to introduce new referigerants that have lower global warming potential (GWP) than current refrigerants. One such refrigerant is HFO-1234yf.

### 7.1.2 Refrigerant Oil

The purpose of the refrigerant oil is to lubricate the moving parts of the compressor. Some of the oil will remain in the compressor and some is carried by the refrigerant through the system, eventually returning back to the compressor. Proper oil return to the compressor is a system design consideration. Suction (compressor inlet) hose diameter is a major factor for oil flow into the compressor; if the diameter is too large, refrigerant velocity may be too slow and not provide proper oil return. Most applications utilize hoses with 15.8 to 19 mm (0.63 to 0.75 inch) inner diameter for the suction hose.

The type of oil used depends on the refrigerant used and the compressor manufacturer. The amount of oil used depends on the compressor, air-conditioning hose lengths, and the amount of refrigerant in the system. Many compressors come precharged with oil from the manufacturer but oil may still need to be added at the time of charging depending on the system refrigerant charge. Refer to the compressor manufacturer's guidelines for this. Typical systems today use synthetic oil like polyalkylene glycol (PAG) or polyolester (POE). These oils are created by combining different acids. A byproduct of this process is water. When these oils absorb moisture, they again revert to an acid. It is therefore important that the system be kept dry by using a proper drier and good charging and service methods. It is also important that exposure of the oil to the open atmosphere be limited.

### 7.1.3 Compressor

The compressor draws in superheated refrigerant vapor at a low pressure and temperature and discharges superheated vapor at a higher pressure and temperature. The compressor is most often driven via a belt off the engine but can also be driven by an electric or a hydraulic motor. In this case, an engine-driven compressor power is transmitted from a belt to the compressor pistons via an electromagnetic clutch. A piston-type compressor is most common, but there are other types such as scroll or rotary vane compressors. Compressors are sized based on their swept volume per revolution

Typical compressors used in this type of equipment vary from 80CC to 210CC per revolution. Compressor manufacturers publish performance data curves showing heat transfer (refrigeration capacity), volumetric efficiency, and power consumption versus compressor speed at a given running condition. Compressors are sized to meet the desired heat transfer rate at target operating conditions. Typical target compressor speeds during normal vehicle operation are between 2000 rpm and 3000 rpm. Typical compressor failures are caused by a lack of lubrication. This can be caused by a number of factors, such as low oil, high temperature and pressure at the compressor, low refrigerant charge, and low refrigerant flow. Failures can also be caused by excessive speed or liquid refrigerant returning to the compressor. Other common compressor failures include clutch failure due to dust infusion and rapid cycling of the clutch due to abnormally high or low system pressures that trigger pressure switch activation. Good system design and maintenance can prevent the majority of these failures.

#### 7.1.4 Condenser

Refrigerant enters the condenser as a high-pressure superheated vapor, releases heat, and leaves as a high-pressure subcooled liquid. The condensing system normally consists of a heat exchanger and fan(s). The fan may be the radiator fan if the condenser is part of the cooling package, or it may be a dedicated electric fan if the condenser is remote mounted. The coil can be constructed in several different types; some common types are fin and tube, crossflow, and serpentine. The coil may be constructed of steel, aluminum, copper, or a combination of these materials. It may be coated to give corrosion resistance.



The condenser shall reject the heat absorbed by the evaporator plus the heat of compression added by the compressor. The high pressure and therefore the condensing temperature in the system rises until the condenser is able to do this. Aproximately, the condenser shouldl be sized to reject 1.3 times the evaporator heat load. The size of the condenser coils, location, and air flow shall be such that the head pressure at the compressor is not excessive. Typical systems prefer to operate at below 2068 kPa (300 psi) during normal steady-state operation. Excessive head pressure could cause rupture in components such as hoses, resulting in loss of refrigerant and possible physical harm. It is more likely to result in early compressor failure unless it is kept below the manufacturer's recommendations. Size, cost, and operating conditions will determine what kind of condenser is selected. Some important considerations are that if the condenser is used in a cooling stack, it should get the the coolest air possible, fin spacing and pressure drop should be kept to a minimum, and the core face should be accessible for cleaning. Durability under vibration should also be noted as a criterion when selecting or designing a condenser.

#### 7.1.5 Evaporator

The evaporator cools and dehumidifies a mixture of recirculated and outside air for operator comfort. Air passing over the coil fins is cooled by refrigerant that is changing state from a liquid to a gas inside the coil. Coils come in various types such as fin and tube and serpentine. Coils are constructed from aluminum, copper, or both. Coil capacities are specified in terms of heat transfer rate under particular airflow, entering air temperature and humidity, and refrigerant conditions.

The design is driven by the required capacity, cost, space availability, and level of air filtration. Fin spacing and condensate drainage is a major consideration. The evaporator is normally located in or near the operator environment to minimize heat gain through the ducting to the cooled air. Other design considerations include the durability under vibration and leak rate under normal operation. The core face should also be accessible for cleaning.

#### 7.1.6 Drain Pan

A considerable amount of condensate from cooling the air accumulates on the evaporator coil, and provisions shall be made to drain it from the case without leaking into the operator enclosure, especially if the evaporator is in the roof. It is also necessary to prevent the condensate from being carried into the operator enclosure by the air stream. If the evaporator is upstream from the blower, a negative pressure as much as 2 inches of water gauge may result and this shall be considered in the design of drip pans and drains. This negative pressure can pull ambient air and debris into the condensate hoses; in some cases, checkvalves are installed into the hoses to prevent debris from being pulled into the HVAC system.

#### 7.1.7 Expansion Device

The expansion device throttles the refrigerant from a high-pressure hot liquid to a low-pressure two-phase mixture of liquid and vapor. Adjustable types are thermostatic expansion valves (TEV). Fixed types are orifice or capillary tubes. TEVs control the superheat of the refrigerant leaving the evaporator. TEVs are divided into internally and externally equalized versions.

The type and location of the expansion device is determined primarily by the refrigerant system design and not by vehicle requirements. The expansion device will be most likely installed very close to the evaporator coil.

7.1.8 Receiver/Accumulator

The receivr/accumulator is the device that holds liquid refrigerant; it can also be combined with the sight glass and moisture indicator. The use of a receiver or accumulator is primarily determined by the system design, but also their location in the vehicle affects line length.

7.1.9 Filter Drier

The filter drier removes moisture and particulate from the system. Located in the liquid line for systems with receiver/dryers, and in the suction line for orifice tube systems, they should be changed when ever the system has been exposed to contamination or open to the atmosphere for a period of time. Examples of contamination would include a major failure like a compressor or hose failure. In TEV systems, the receiver is often combined with a filter drier. Newer systems often integrate the receiver/driver into the condenser.

7.1.10 Lines-Refrigerant

The suction line from the evaporator to the compressor carries low-pressure gas. The discharge line from the compressor to the condenser carries high-pressure gas. The liquid line from the condenser to the receiver and then to the expansion valve carries high-pressure liquid. Lines can be made of rubber hose, copper, steel, or aluminum. If a rubber hose is used then a high quality refrigerant grade hose material shall be used to minimize leakage; refer to SAE J2064 for more information.

Refrigerant lines should be kept as short as possible and should be large enough to minimize pressure drop. This is particularly true of the suction line from the evaporator to the compressor. The lines connecting the compressor should be long enough to compensate for engine rock. Care should be taken not to route flexible lines over sharp edges and hot spots. Typically, the suction hose is the largest, the discharge is the middle-sized hose, and the liquid lines are the smallest hoses in the system.

7.1.11 Pressure Switches

Pressure switches protect the system from operating outside of acceptable parameters. They are typically wired in series with the compressor clutch. A high-pressure switch is located on the high side of the compressor and will protect the system from running at excessive high pressures. A low-pressure switch is located at the low side of the compressor or evaporator outlet and will prevent the compressor from running under very low loads or with low refrigerant charge. The pressure limits of these devices should be determined by the compressor manufacturer’s recommendations. Many high-pressure switch settings are in the range of 2413 to 2930 kPa (350 to 425 psi), and low-pressure switches on the low side of the system in the range of 14 to 41 kPa (2 to 6 psi). There are also systems available that instead have a refrigerant loss (low pressure) or binary switch on the high side of the system, in lieu of a low-pressure switch on the suction side of the system. These switches are typically in the 138 to 207 kPa (20 to 30 psi) range.

7.1.12 Thermostat

The thermostat cycles the clutch to prevent the evaporator fins from freezing up. There are both mechanical or electronic types. Mechanical types uses a capiliary tube placed between the coil fins while the electronic types use a sensor in the fins or on a pipe. In some systems with automatic temperature control, an after coil sensor can be used as part of the freeze management.

7.2 Heater Components

7.2.1 Heater Core

The heater core transfers heat from the engine coolant to the air flow circulated to the operator enclosure through a heat exchange surface. The function of the heater core is to provide a sufficient quantity of heat to achieve minimum cab temperature, defrost, and demist requirements. The heater is generally located inside the operator enclosure. Heater cores can vary in design, although typical constructions include mechanical bond tube and fin designs and aluminum brazed designs with tanks. The core is sized for the given design parameters such as coolant and air flows, associated pressure drops, required heat rejection, fin density, and number of tube passes. Coolant system pressure must also be taken into account when choosing/designing a heater core.

7.2.2 Water Valve

The water valve is utilized to modulate the amount of coolant flowing through the heater core to vary the heater output. The valve can either be mechanically or electrically controlled. Performance parameters include pressure drop, coolant flow with valve position, and torque required to adjust valve position. In the blend air systems, a blend air door is utilized instead of a coolant valve to control the temperature of the air.

7.2.3 Lines - Heater

Heater hoses transport coolant from the engine to the heater core and return coolant either to the engine water pump inlet or radiator return hose. Hoses will contribute to the flow restriction and should be treated as a part of the system when internal diameter and length are determined. Typically heater hoses are 16 mm (0.625 inch) inner diameter. Flexible lines should not be kinked or routed over sharp edges and should be routed away from hot engine and exhaust manifold surfaces.



7.3 Airflow Components

7.3.1 Blower

The first function of the blower is to draw air from the cab, circulate air through the heat exchangers, and deliver air through the ducts and louvers into the cab. The second function is to bring outside external air and pressurize the cab. Both of these functions can either be achieved with the single blower or separate dedicated blowers.

Pressurization will prevent the entrance of dust and hot air through any cracks or small openings that are not sealed. Pressurization is achieved by balancing the amount of outside air brought into the operator enclosure and cab sealing such as cracks around door and window openings and other openings in the enclosure. In a well-sealed operator enclosure, it may be necessary to provide extractors to allow a controlled amount of air to be vented from the enclosure. These extractors should be located where they will aid the circulation of air from the outlet registers across the operator.

The blower and motor combination is usually located in the operator enclosure in close to the evaporator. The blower can either be located upstream or downstream of the evaporator and heater cores. In systems where the blower is located upstream of the evaporator, adequate distance should be provided between blower discharge and evaporator inlet to avoid high local air velocities through the core which may result in carrying condensate into the duct work. Also, poor air flow distribution across the evaporator and heater cores will degrade heat transfer performance. Blower location upstream of the evaporator, as opposed to downstream, will provide positive pressure to facilitate condensate drainage. When the blower is located downstream of the evaporator, the distance between the core and blower maybe shorter and the potential for blowing condensate through the core is minimized; however, the condensate drain system will need to be designed to overcome some negative pressure.

Blower performance is given in terms of pressure rise versus air flow and current draw at a specified voltage. The blower should be sized for the required system matching ducts, filters, HVAC cores, and cab restriction.

7.3.2 Blower Speed Control

A resistor may be used with the electric blower motor to control the voltage supplied to the motor and thus the airflow provided by the blower. Resistors typically have multiple taps along their resistive winding to give the ability to set multiple speeds. Resistors are commonly made of a ceramic or wire wound construction. Care shall be taken to locate the resistor where it can receive cooling from the airflow and to keep it away from flammable materials. Blower speed may also be controlled by the use of a PWM (pulse width modulated) or linear motor drive.

7.3.3 Ductwork

Ductwork transports air from the cab to the HVAC unit and then to the louvers, while fresh air is ducted from the external air filter to the cab. The ductwork pressure drops should be matched to the blower performance. To minimize pressure drops it is recommended to maintain constant duct area, design minimal contraction and expansion, have gradual transitions, minimize number of bends, and provide smooth generous radii for the required bends. A good rule of thumb for design is to have 650 to 775 $mm^2$ of duct cross-sectional area for every 17 $m^3/h$ of airflow (1 to 1.2 $in^2$ of duct cross-sectional area for every 10 cfm of airflow). Duct size is a balance between being too restrictive and having high velocities (which can cause noise), and having too low of flow which can cause the air to excessively gain or lose heat in the duct.

Ducting also needs to be properly insulated or isolated from the outside of the cabin especially in air-conditioning mode. Parasitic losses in the ducting can be the difference betweeen a system with satisfactory performance and one that is unsatisfactory.

7.3.4 Louvers

The purpose of the louvers is to give control and direction to the airflow in various modes (heating, cooling, defrosting, demisting) as it leaves the ducts. They come in various types (shutoff, directional, etc.) and sizes. They must be properly located and sized to give sufficient airflow for each mode.

7.4 Ventilation/Filtration Components

Proper filtered external air is critical to off-highway systems for many reasons including maintianing clean heat exchangers, providing a clean cab environment, and preventing ingestion of debris by operators. Typical filter construction is pleated paper media with a sheet metal, plastic, or urethane foam frame in either a rectangular or cylindrical arrangement.

Successful systems are typically designed to deliver a minimum of 43 $m^3/h$ (25 cfm) of filtered fresh air per occupant through a filter capable of 96% efficiency against SAE fine dust (SAE J1503, SAE J3078/2). More fresh air may be desirable to improve defogging capabilities; however, this increases demands on the system and may cause heat exchangers to be larger than is practical. It also increases the amount of dust that the filter will capture, and therefore shortens filter service life. It is desirable to balance this external air delivery against the nominal cab leakage to provide adequate cab pressure. By maintaining cab pressure, dust ingress through the cab is minimized and therefore recirculated air filtration requirements are diminished. External air filters shall be of sufficient surface area to meet customer expectations for filter service intervals. To extend the external air filter life, a powered debris separator may be used upstream of the filter. In a well-sealed system, the majority of debris is introduced into the system when the filter is changed. For this reason, service intervals should be as long as practical and/or the design of the filter housing should be such that ingress of residue from the used filter is minimized. Inlets for the external air filter should be positioned on the machine in an area with the lowest possible temperature and debris and it is especially important to prevent engine exhaust from entering the cab. For typical off-highway applications, the recirculated air filter is typically made of paper media or 20 ppm or denser foam. For mining applications or other applications where the cab doors may be opened frequently in a dusty environment, a high-efficiency pleated paper recirculation filter similar to that used for the external air filter is recommended.

Where operator air quality is critical such as in silica mining, orchard pesticide operations, or dumpsites, special consideration shall be given to the filtration and ventilation system. This may require the use of special external air filter media, such as spun polyester, with a 99.9% efficiency with SAE fine dust. Sealing of all connections between the external air filter and the pressurizing device must be effective against leakage so that no opportunity is given for the unfiltered air to enter the cab. A similar filter should be used for the recirculated air so that any silica dust introduced into the cab from entering or exiting the cab can also be effectively filtered. For orchard tractors and dumpsites, activated carbon external air filters and recirculation filters may be used to reduce the pesticide particles from the air. In either case, cab pressurization is critical and should be monitored with a device that alerts the operator of a loss of pressure. Also, it is important to activate the pressurization system whenever the vehicle is in use regardless of the HVAC control setting. This can be accomplished by having a pressurization blower activated by some engine start function such as keyed power, oil pressure sensor, etc.

Outside air filters should be easily accessed outside the operator enclosure and should require simple tools or no tools. Recirculated air filters should be located so that repair or replacement does not present the opportunity for introducing dirt or dust into the operator enclosure and should require simple tools or no tools.

7.5 Control Components

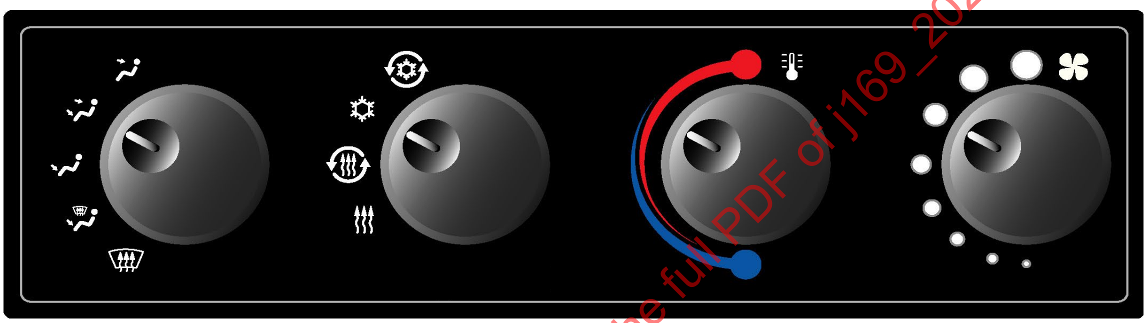

***Figure 3***

Figure 3 demonstrates one scenario for manual controls on off-highway HVAC systems. In this example, the panel is designed to conform to DIN standards for dash mount similar to those used for aftermarket car audio components. Sealing of the controls is important to prevent dust or moisture ingress and premature failure of the controls. Control knobs are desirable by operators since off-highway vehicles cause the operator to be shaking about in the cab; therefore, it may be difficult to push a button or flip a switch. The soft texture and ample clearance around the knobs makes it possible for the operators to make changes to control settings while the vehicle is moving and they are wearing gloves. The switches and potentiometers used in this type of control will typically have external mechanical stops to limit travel. This is necessary since most potentiometers do not have stops that are sturdy enough for the high torque inputs of off-highway operators. Instead of potentiometers, some systems may have controls with cables or other mechanical devices.

The left-most knob is used to control the flow of air from the louvers of the vehicle. Usually, this is accomplished by means of electronic actuators and mode doors. Many off-highway systems do not have this functionality. Instead, a series of closable adjustable louvers are used to allow air to exit at various locations in the cab. The mode control descriptions are listed below.