



AEROSPACE RECOMMENDED PRACTICE

ARP292™

REV. D

Issued 1954-12
Revised 2020-05
Reaffirmed 2026-01

Superseding ARP292C

(R) Environmental Control Systems for Rotorcraft

RATIONALE

This revision updates ARP292 per the latest specifications, references, and technology.

ARP292D has been reaffirmed to comply with the SAE Five-Year Review policy.

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1. SCOPE

This SAE Aerospace Recommended Practice (ARP) discusses design philosophy, system and equipment requirements, environmental conditions, and design considerations for rotorcraft environmental control systems (ECS). The rotorcraft ECS comprises that arrangement of equipment, controls, and indicators which supply and distribute dehumidified conditioned air for ventilation, cooling and heating of the occupied compartments, and cooling of the avionics. The principal features of the system are:

- a. A controlled fresh air supply
- b. A means for cooling (air or vapor cycle units and heat exchangers)
- c. A means for removing excess moisture from the air supply
- d. A means for heating
- e. A temperature control system
- f. A conditioned air distribution system

The ARP is applicable to both civil and military rotorcraft where an ECS is specified; however, certain requirements peculiar to military applications—such as nuclear, biological, and chemical (NBC) protection—are not covered. The integration of NBC protection into aircraft ECS is discussed in AIR4362.

1.1 Purpose

The purpose of this ARP is to provide the guidelines and requirements for analysis, design, and installation of rotorcraft ECS.

2. REFERENCES

2.1 Applicable Documents

2.1.1 SAE Publications

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.

AIR860	Aircraft Electrical Heating Systems
AIR1266	Fault Isolation in Environmental Control Systems of Commercial Transports
AIR1539	Environmental Control System Contamination
AIR1812	Environmental Control Systems Life Cycle Cost
AIR1826	Acoustical Considerations for Aircraft Environmental Control System Design
AIR4362	NBC Protection Considerations for ECS Design
AIR7521	Measurement Data and Reference Values for Compounds Potentially Found in Aircraft Engine Bleed Air
ARP85	Air Conditioning Systems for Subsonic Airplanes
ARP86	Heater, Airplane, Engine Exhaust Gas to Air Heat Exchanger Type

ARP89	Aircraft Compartment Automatic Temperature Control Systems
ARP699	High Temperature Pneumatic Duct Systems for Aircraft
ARP731	General Requirements for Application of Vapor Cycle Refrigeration Systems for Aircraft
ARP986	Guide for Qualification Testing of Aircraft Air Valves
ARP1796	Engine Bleed Air Systems for Aircraft
ARP4418	Procedure for Sampling and Measurement of Aircraft Propulsion Engine and APU Generated Contaminants in Bleed Air
AS4073	Air Cycle Air Conditioning Systems for Air Vehicles
AS8040	Heater and Accessories, Aircraft, Internal Combustion Heat Exchanger Type

2.1.2 FAA Publications

Available from Federal Aviation Administration, 800 Independence Avenue, SW, Washington, DC 20591, Tel: 866-835-5322, www.faa.gov.

2.1.2.1 U.S. Code of Federal Regulations

14 CFR Part 27	Airworthiness Standards: Normal Category Rotorcraft"
14 CFR Part 29	Airworthiness Standards: Transport Category Rotorcraft"
14 CFR Parts 121-139	Certification and Operations

2.1.2.2 FAA Advisory Circulars

AC20-135	Powerplant Installation and Propulsion System Component Fire Protection Test Methods, Standards and Criteria
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2.1.3 Military Publications

Available from DODSSP, Subscription Services Desk, Building 4D, 700 Robbins Avenue, Philadelphia, PA 19111-5094.

JSSG-2009	Department of Defense Joint Services Specification Guide, Air Vehicle Subsystems
MIL-E-18927	Environmental Control Systems, Aircraft, General Requirements for
MIL-HDBK-310	Global Climatic Data for Developing Military EquipmentMIL-STD-810Environmental Test Methods for Aerospace and Ground Equipment
MIL-STD-1472	Human Engineering Design Criteria for Military Systems, Equipment, and Facilities
MS33562	Connection, Aircraft Ground Air Conditioning

U.S. Army Technical Report ETL-TR-72-7, "Sand and Dust Considerations in the Design of Military Equipment."

DARPA Study Contract W31P4Q-07-C-0215 Task 5 Final Technical Report, "Sandblaster 2 Support of See-Through Technologies for Particulate Brownout."

2.1.4 NATO Standardization Agreements (STANAG)

STANAG 3208	Air Conditioning Connections
STANAG 3315	Air Cabin Pressurizing Test Connections
STANAG 3372	Low Pressure Air and Associated Electrical Connections for Aircraft Engine Starting
STANAG 3610	Characteristics of Conditioned Breathable Air Supplied to Aircraft on the Ground

2.1.5 Other Publications

Air Transport Association of America (ATA) MSG-3, "Operator/Manufacturer Scheduled Maintenance Development Volume 2 - Rotorcraft."

RTCA/DO-160	Environmental Conditions and Test Procedures for Airborne Equipment
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2.2 Definitions

AC	Alternating Current
ACM	Air Cycle Machine
APU	Auxiliary Power Unit
ASCC	Air Standardization Coordination Committee
BIT	Built-in Test
BITE	Built-in Test Equipment
CFR	Code of Federal Regulations
COP	Coefficient of Performance
DC	Direct Current
ECS	Environmental Control System
ETS	Environmental Tobacco Smoke
FMEA	Failure Modes and Effects Analysis
HX	Heat Exchanger
LRU	Line Replaceable Unit
MSG	Maintenance Steering Group
MTBF	Mean Time Between Failure
MTBO	Mean Time Between Overhaul
NBC	Nuclear, Biological, and Chemical

SDC Shaft-Driven Compressor

STANAG Standardization Agreement

TOGW Takeoff Gross Weight

3. DESIGN PHILOSOPHY

Rotorcraft became much more viable as military and civil aircraft with the proliferation of the turboshaft engine in the 1960s, largely overcoming the drawbacks of their underpowered reciprocating engine predecessors. Unlike most turbojet and turboprop powered fixed wing aircraft, rotorcraft had no need to be pressurized because of their low altitude operation. ECS on these fixed wing aircraft were dominated by air cycle systems, which utilized engine compressor bleed air for pressurization and operation of the system. These systems were integral to the aircraft design from inception, and engines were rated for maximum takeoff power while providing engine bleed air for air conditioning as well as other parasitic engine loads, such as electrical generators or hydraulic pumps. Penalties were measured in terms of fuel burn, with the added advantage of being able to turn off the air conditioning during takeoff to obtain extra engine power in case of an engine failure at this very critical time.

Historically, rotorcraft ECS has been added as an afterthought to an already designed airframe and power plant installation, or as a retrofit to a production aircraft. Because of the extensive aircraft use of air cycle ECS, with its comparative light weight, high reliability and the availability of engine compressor bleed air from a turboshaft engine, air cycle systems have been predominantly used in military rotorcraft applications. However, because rotorcraft engines are not designed to be bled while producing rated power, a double penalty is paid; one for fuel consumption, and one for loss of rated engine power due to the increase in turbine inlet temperature resulting from the loss of compressor core flow. Optimization of the ECS for available bleed pressure, even when added as an afterthought, can minimize these penalties, as can proper design of the engine bleed port. However, the best system for a new rotorcraft must include ECS power requirements in the specifications for main and auxiliary power systems, as is current practice on virtually all fixed wing aircraft.

Several military and civil rotorcraft applications have incorporated vapor cycle ECS. Comparisons between air cycle and vapor cycle ECS producing the same amount of cooling and heating, when full integration with power sources is possible, should include:

- a. Additional fuel consumption due to bleed and/or power consumption.
- b. Installed weight as it relates to higher engine requirements and the subsequent increase in specific fuel consumption.
- c. Installed power requirements as they relate to higher engine horsepower requirements and the subsequent increase in specific fuel consumption.

Steps should be taken to ensure that the design philosophy of the rotorcraft ECS reflects that of the rotorcraft on which it is installed. The rotorcraft systems specification will list primary design parameters (such as rotorcraft use considerations) from which an ECS design philosophy can be formulated. The systems specification should be reviewed in detail prior to ECS preliminary design, and particular attention should be paid to (but not limited to) the following.

3.1 Regulations

The ECS must comply with the airworthiness requirements listed in the rotorcraft systems specification. Although other portions of the systems specification may conflict with airworthiness requirements, airworthiness requirements should prevail.

3.1.1 Commercial Regulations

The FAA regulates the design of commercial rotorcraft for operation in the United States in the Code of Federal Regulations (CFR) Title 14, Part 27 Normal Category Rotorcraft and Title 14, Part 29 Transport Category Rotorcraft. Part 27 and Part 29 applicable requirements include the following in Table 1:

Table 1 - CFR Title 14, Part 27 and Part 29 applicable requirements

Part 27	Part 29	Description
27.561	29.561	General
27.831	29.831	Ventilation
27.833	29.833	Heaters
27.853	29.853	Compartment interiors
27.859	29.859	Heating systems/Combustion heater fire protection
27.861	29.861	Fire protection of structure, controls, and other parts
27.863	29.863	Flammable fluid fire protection
27.1163	29.1163	Powerplant accessories
27.1301	29.1301	Function and installation
27.1309	29.1309	Equipment, systems, and installations
27.1322	29.1322	Warning, caution, and advisory lights
27.1461	29.1461	Equipment containing high energy rotors
AC27 MG14	AC29 MG14	Certification procedure for installation of vapor cycle air conditioning system

Certification and operation of commercial rotorcraft in the United States is regulated by the FAA in 14 CFR Parts 119-139, as applicable.

Operating rules based on FAA or other individual country regulations are applied by the particular country of registry. Adequate provisions should be made in systems design to ensure that it is possible to meet other relevant requirements.

Departure from convention in design or in operating environment may result in special airworthiness requirements being imposed. The requirements may be identified as special conditions until such time as they are incorporated into the applicable code of regulations. The existence and interpretation of such special conditions should be established at the outset.

3.1.2 Military Regulations

3.1.2.1 US Military

ECS requirements are derived for each individual rotorcraft through tailoring of JSSG-2009 and/or MIL-E-18927.

3.1.2.2 STANAG

Certain ECS provisions are the subject of NATO Standardization Agreements. Table 2 shows the NATO Standardization Agreements (STANAG) and Air Standardization Coordination Committee (ASCC) Air Standards which may apply to the rotorcraft's environmental control system:

Table 2 - NATO standardization agreements

STANAG	ACSS	Description
3208	17/33	Air conditioning connections
3315	17/33	Air cabin pressurizing test connections
3372	17/22	Low pressure air and associated electrical connections for aircraft engine starting
3610	--	Characteristics of conditioned breathable air supplied to aircraft on the ground

3.2 Control and Indication

ECS control functions and indications will be dictated by crew station configuration and crew operational roles. System management crew workload should be minimized where possible with the use of automated electronic controls. Additionally, where possible, use of electronic displays and processors should be considered to present relevant information. Such information would include control and overall system status, system health, and maintenance troubleshooting diagnostics.

Control system design should be configured to minimize crew interaction during normal operation, crew intervention during a single failure, and crew indications not requiring corrective action.

3.3 Safety

All aspects of the ECS design must consider the safety of all rotorcraft occupants. The system shall be designed so that failure of one component will not result in failure of another component, and no single component failure will cause an engine operational problem. Failure analysis should include all appropriate combinations of failures. Commercial rotorcraft system design shall meet applicable requirements in 14 CFR §27.1309/14 CFR §29.1309. For military rotorcraft, safety requirements are provided in the individual rotorcraft detail specification.

Additional safety considerations should include, but not be limited to:

- a. Engine bleed ports shall incorporate flow limiting devices if analysis shows that bleed duct failure will compromise the operational characteristics of the engine.
- b. Check valves or controls shall be provided to prevent reverse bleed flow into any bleed port.
- c. Bleed air supply pressure and temperature should be regulated to the lowest values consistent with using system requirements.
- d. Bleed shutoff provisions shall be provided to comply with fire safety requirements.
- e. Bleed shutoff provisions should be as close to the bleed source as practical to prevent bleed flow in the event of a duct rupture, without exceeding engine manufacturer's interface load limitations; unrestrained plug loads must be avoided.
- f. Duct surface temperatures shall not exceed levels that would result in exceeding the thermal limits for nearby structure, wiring, equipment, and autoignition of flammable fluids.
- g. Provisions for overheat detection, pressure relief and ventilation shall be provided in all compartments where bleed air leakage or burst ducts could be hazardous.
- h. Electrical components utilizing conductive material for cases or housings shall be capable of being electrically bonded to airframe structure.
- i. All electrical equipment located in a zone potentially subject to combustible vapors shall meet explosion proof criteria.
- j. All parts of ECS high speed rotating machinery shall be contained in the event of a mechanical failure or wheel burst.
- k. Noxious or toxic substances (including mists and gases) shall be prevented from entering occupied spaces through the fresh air or recirculation distribution systems. Special attention must be given to hydraulic fluids and lubricants. Care should be taken to prevent oil contamination of conditioned air sources in the event of possible oil/air seal failure, and toxic liquid refrigerant/oil mixture vapor resulting from overtemperature due to seized compressors.
- l. Any combination of reasonably probable failures shall not result in excessive temperatures in occupied spaces.
- m. For all components located in areas where flammable fluids or vapors may be present, steps shall be taken to minimize the probability of ignition in accordance with 14 CFR §27.863/14 CFR §29.863.
- n. Steps shall be taken to ensure that motor driven equipment will not start fires in the event of motor protector failure.
- o. Necessary control functions shall be built into the ECS to provide smoke removal after fire extinguishing.
- p. In galley areas, necessary precautions shall be taken to avoid carbon dioxide hazards from dry ice release, and to provide adequate exhaust air filters to avoid the accumulation of flammable oils in ducts. The filters should not burn, should prevent passage of fire/flames, and must be easily replaceable.
- q. Protective devices shall be provided for all electric heaters to prevent overtemperature and/or fire.
- r. Adequate instrumentation/indication should be provided to ensure that significant failures are detected and unambiguously annunciated.

- s. The system control functions should require a minimum use of crew operating procedures, and necessary human factor considerations must be included to prevent incorrect procedures which could cause failure or hazardous conditions.
- t. Materials shall be selected which have a low smoke density and non-toxic rating in the event of fire.
- u. Equipment located in occupied areas shall be mounted adequately enough to prevent injury to occupants in the event of an emergency landing or maneuver. Design load factors listed in 14 CFR §27.561/14 CFR §29.561 or those defined in the aircraft specification should be used.

3.4 Reliability and Maintainability

The rotorcraft system specification will establish the maintenance philosophy and set design objectives for reliability and maintainability considerations. The trend towards “on condition” maintenance emphasizes the need to design for equipment reliability and life which matches that of the rotorcraft service periods. A formal maintenance analysis technique, defined in ATA MSG-3, has evolved which is widely adopted in commercial aviation operations.

The importance of minimizing maintenance burden and failures and configuring for minimum equipment lists for dispatch is playing an increasingly important role in systems design. Specific ECS considerations include but are not limited to:

- a. Accessibility of system components.
- b. Redundancy in critical equipment.
- c. Manual positioning of control valves for dispatch.
- d. Minimizing routine servicing.
- e. Avoidance of specialized tool/equipment requirements for maintenance and repair.
- f. Isolation of system failures to the line replaceable unit (LRU).

Reliability design objectives should be determined from consideration of the system failure analysis. Applicable commercial rotorcraft systems requirements are specified in 14 CFR §27.1309/14 CFR §29.1309. For military rotorcraft, reliability and maintainability requirements are provided in the individual rotorcraft detail specification. Failure analyses should include provisions to insure proper component default settings/positions in the event of individual component and/or system failures so that air conditioning/ventilation can continue.

3.5 Electrical Power

The ECS requires electrical power for at least control system function and probably other major system components. Adequate provisions shall be included for ventilation and smoke removal in the event of an electrical power failure.

Consideration should be given to control settings/positions of all relevant components in the event of a power failure. Components such as valves and solenoids should be chosen to provide the required default position in the event of a power failure so that air conditioning/ventilation can continue. Appropriate functions for battery only operation should be provided, and the use of auto or manual load shedding should be considered for minimizing power consumption when operating on batteries.

3.6 Economics

Cost of ownership is the main driving factor in most programs. Cost of maintenance and fuel chargeable to the ECS are significant. An optimization of life cycle costs should be done at an early stage of the program. AIR1812 provides information on life cycle cost and should be used as a guide. The best tool for estimation of life cycle cost is a system design trade-off study including the major impact of the ECS on the entire rotorcraft system during total life time. More details are discussed in 4.2.

Appropriate rotorcraft performance analyses should be performed for tradeoff studies of various ECS configurations. Sources of power for ECS components include engine bleed air, geared shafts, electric motors, hydraulic motors and air motors. The availability of the various power sources should be weighed against their respective impacts on the entire rotorcraft. A secondary source of power for ECS components can be provided by an on-board auxiliary power unit (APU), used primarily for ground operation, or by external ground support.

4. SYSTEM APPROACHES

Both air cycle and vapor cycle ECS are used for rotorcraft applications. Air cycle systems utilize high pressure air both as a source of power and fresh air supply for the passenger and crew compartments. Vapor cycle systems typically utilize electricity as a source of power and ambient air as a fresh air supply. Both systems usually use ambient air as a heat sink.

Careful consideration should be given to the selection of the type of ECS to provide the lowest penalty and most cost effective system for each rotorcraft application, while satisfying cooling, heating, and ventilation requirements.

4.1 Candidate Systems

Typical rotorcraft ECS include vapor cycle systems, conventional air cycle systems, and integral recirculation air cycle systems.

4.1.1 Vapor Cycle ECS

The vapor cycle ECS operates in a closed-loop Rankine thermodynamic cycle using a refrigerant. The refrigerant is pressurized and cooled causing it to condense into a liquid; the liquefied refrigerant is throttled to expand, and evaporated to provide cooling. The refrigerant, now in a gaseous state, repeats the closed loop cycle.

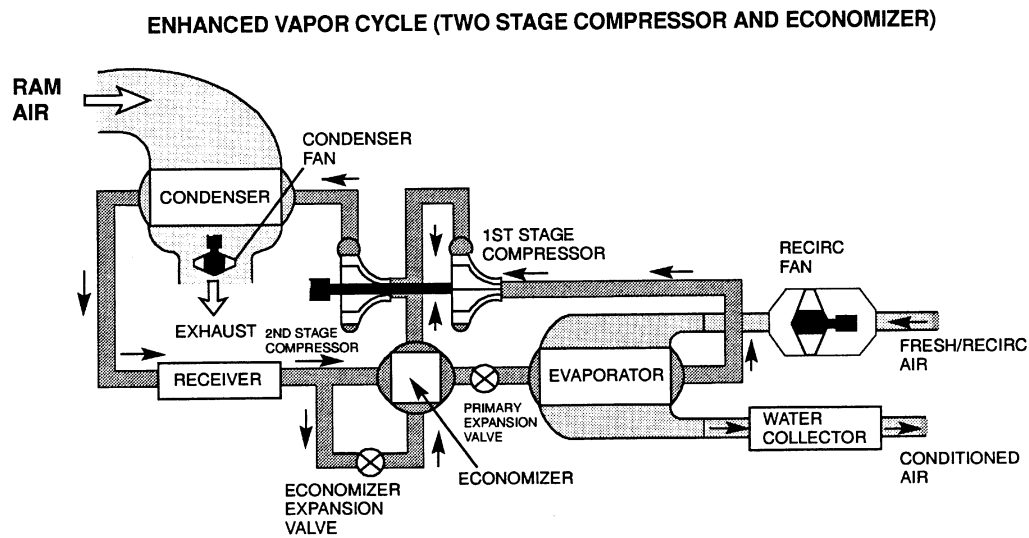
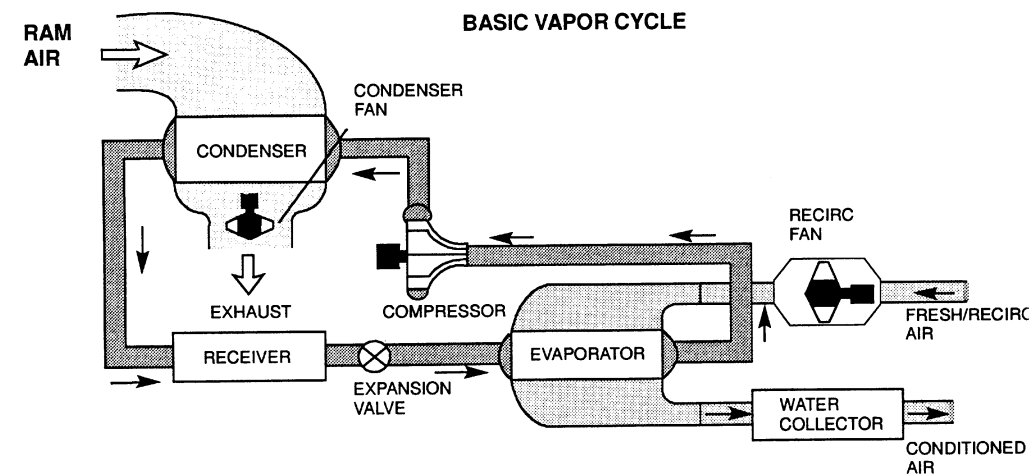
Typical vapor cycle system configurations are shown schematically in Figure 1. Vapor cycle systems provide cabin cooling using fresh air and/or recirculated cabin air refrigerated to about 50 °F (10 °C) in the refrigerant evaporator. The major vapor cycle components include the compressor, condenser, evaporator, expansion valve, and fans for the condenser ambient air heat sink supply and evaporator fresh/recirculated air supplies. Two or more stages of compression may be required to provide the required temperature lift between the evaporator and condenser phase change temperatures. In systems requiring two-stage centrifugal compressors or using a positive displacement compressor, an economizer can be used to improve performance and conserve power at off-design conditions; the reduction in power consumption is realized by subcooling the evaporator inlet refrigerant. The economizer also allows the specific speeds of the centrifugal compressor stages to be matched. The refrigerant compressor and air supply fans are typically electric motor driven, but may also be driven by geared shafts, hydraulic motors or air motors. Compartment supply air moisture condensed in the evaporator is normally drained overboard.

A separate means is required to provide compartment heating; engine bleed air (ARP1796), electric heaters (AIR860), exhaust gas heaters (ARP86A), or internal combustion heaters (AS8040) can be used for this purpose. Design recommendations for vapor cycle systems applicable to rotorcraft are provided in ARP731.

4.1.2 Air Cycle ECS

The conventional air cycle ECS operates in an open-loop Brayton refrigeration cycle similar to the Brayton power cycle of gas turbine engines; the difference between the two cycles is that for the power cycle heat is added by burning fuel while for the refrigeration cycle heat is removed in a ram air heat exchanger. The air cycle ECS utilizes high pressure air extracted from the gas turbine engine compressor or other bleed air source as the source of conditioned air (cooled and heated) for the rotorcraft. The compression of this ambient fresh air by the engine represents the power input to the air cycle ECS.

Air cycle systems cool the compressed fresh air supply with heat exchanger(s) using ambient air as the heat sink, and refrigerate this air supply with an expansion turbine (air cycle machine); the turbine power is absorbed by an ambient air fan and/or a supply air compressor. These air cycle machine (ACM) configurations include simple cycle (turbinefan), bootstrap (turbinecompressor), and three-wheel (turbinecompressorfan); shown schematically in Figure 2.



DG2055004bk

Figure 1 - Vapor cycle system configurations

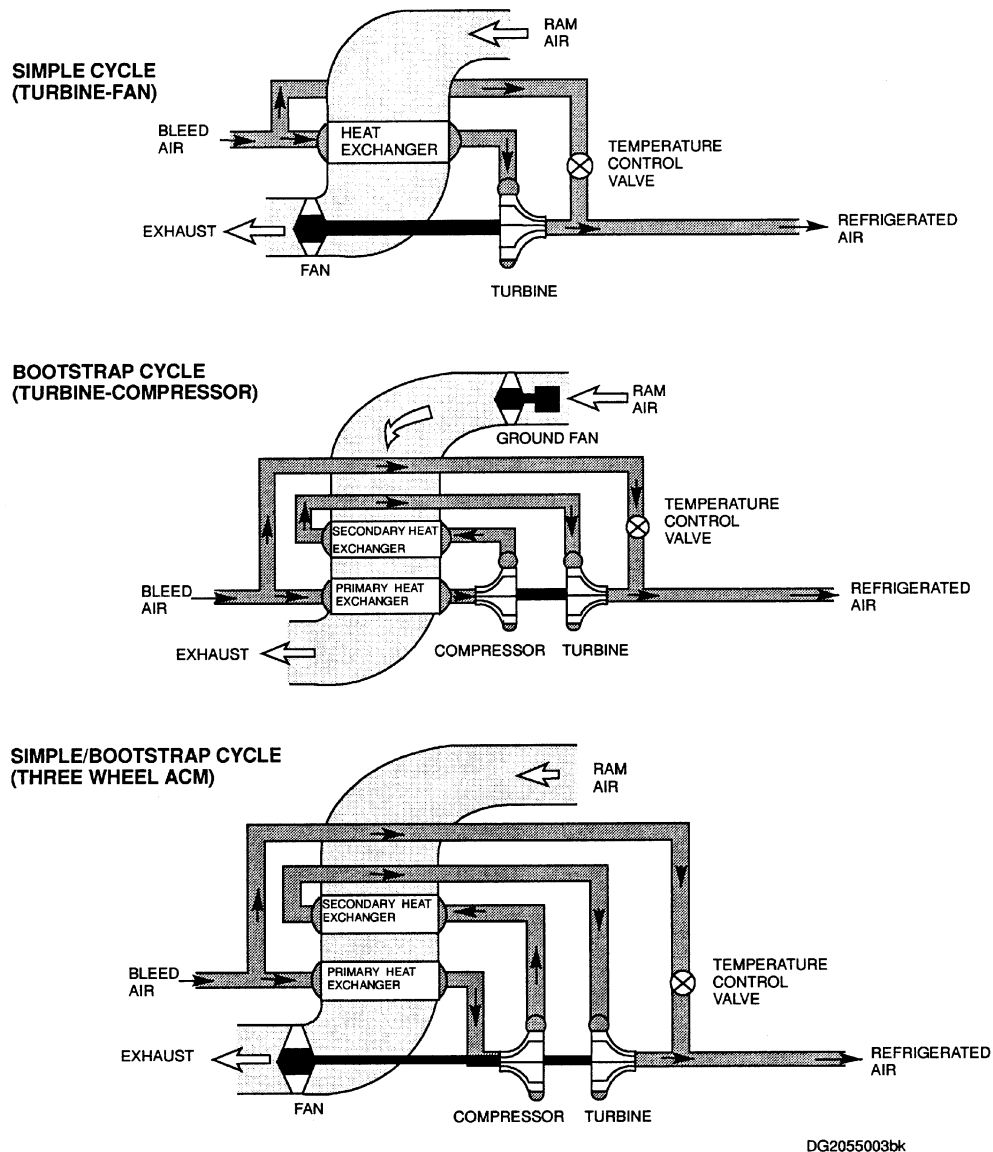


Figure 2 - Air cycle system ACM configurations

4.1.2.1 Simple Cycle

The simple cycle was the first air cycle system developed, and operated at high pressures obtained by bleeding the final compression stage of the aircraft jet engines. The simple cycle remains a viable option for rotorcraft since the turboshaft engine power levels can provide adequate bleed pressure, even if lower compressor stages are bled. The simple cycle has the advantage of providing the heat exchanger ambient airflow during ground operation, hover, or low speed flight where ram airflow is insufficient.

4.1.2.2 Bootstrap Cycle

The bootstrap cycle provides a significant increase in cycle efficiency over the simple cycle system at the expense of additional system complexity. It does this by providing an additional stage of compression of the bleed air supply by replacing the ACM fan with a compressor rotor. This increases the inlet pressure at the cooling turbine resulting in increased turbine power. However, this necessitates an additional heat exchanger (intercooler) to remove the added heat of compression, and a separate fan or ejector to provide heat exchanger cooling air during ground operation and low speed flight/hover conditions.