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AEROSPACE INFORMATION REPORT

SAE AIR 1812
Issued 10-85

Submitted for recognition as an American National Standard

ENVIRONMENTAL CONTROL SYSTEMS LIFE CYCLE COST

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1. PURPOSE: The purpose of this document is to provide qualitative information on life cycle cost (LCC) aspects of environmental control systems (ECS) design.

2. SCOPE: This report contains background information on life cycle cost elements and key ECS cost factors. Elements of life cycle costs are defined from initial design phases through operational use. Information on how ECS designs affect overall aircraft cost and information on primary factors affecting ECS costs are discussed. Key steps or efforts for comparing ECS designs on the basis of LCC are outlined. Brief descriptions of two computer programs for estimating LCC of total aircraft programs and their use to estimate ECS LCC, are included.

3. BACKGROUND - IMPORTANCE OF ECS LIFE CYCLE COST: An important part of initial ECS development is to compare alternate ECS designs and the total cost impact of these designs over the life of the aircraft in which it is used (i.e., ECS life cycle cost). In the past, ECS were designed to maximize the thermodynamic performance, with compromises to minimize size, weight and initial cost. Since many ECS costs are fixed by early design choices, it is imperative that implications of ECS design decisions on costs be identified. For example, a 1980 estimate (100 production units) for ECS operational and support costs is 2/3 of ECS life cycle costs, while development and procurement costs comprise the remaining 1/3 (Reference 1). Therefore it is important to determine the impact of ECS design decisions on the operational and support cost part of LCC early in an ECS development program. In order to minimize overall aircraft LCC, it is also important to be aware of and to assess the impact that ECS has on other aircraft systems when evaluating candidate ECS approaches.

4. LIFE CYCLE COST CATEGORIES: Life cycle costs for ECS, and for other aerospace systems and structure, are divided into three categories which occur sequentially, but which generally overlap. These costs may be for "one-time" efforts or hardware (non-recurring costs), or for repetitive efforts or multiple items of hardware (recurring costs). The three life cycle cost categories are: 1) research, development, testing and evaluation; 2) procurement; 3) operations and support. These are outlined in the following sections. More detail about these cost elements is found in References 2 and 3.

4.1 Research, Development, Test and Evaluation (RDT&E): Costs for initial ECS research and feasibility studies, through system development, including prototype and pre-production system testing and test evaluation, are non-recurring. RDT and E cost elements are shown in Figure 1.

4.2 Procurement: Procurement of an ECS in production quantities includes costs which are non-recurring, defined as support investment, and costs which are recurring, defined as system investment.

4.2.1 Support Investment: Support Investment costs are required to implement operational use of the system. Support Investment cost elements are shown in Figure 1.

4.2.2 System Investment: System Investment costs are for quantity production of the system and its components. System investment cost per unit produced follow a "learning curve," wherein cost per unit decreases as quantity increases. System Investment cost elements are shown in Figure 1.

4.3 Operations and Support (O&S): Operations and support costs are recurring costs for maintaining the system in operational readiness in the aerospace vehicle. Operational and support cost elements are shown in Figure 1.

5. IMPACT OF ECS ON COST OF AIRCRAFT DESIGN AND OPERATION: Penalties that ECS impose on an aircraft and its subsystens, and the impact of these penalties on aircraft cost are summarized. This is prefaced by a list of normal ECS functions for orientation.

5.1 ECS Functions: Aircraft ECS are designed to perform a multitude of functions. Major functions of the ECS are crew and passenger compartment environmental conditioning and pressurization, avionics equipment thermal control, engine bleed air distribution, and environmental protection for transparencies and flight surfaces. Traditional ECS functions are listed in Table 1. This list indicates that the ECS is involved with many aspects of aircraft design.

5.2 Impact of ECS on the Aircraft: ECS impose penalties on the design and fabrication cost of an aircraft, and on cost to operate and maintain the aircraft. ECS penalties are weight, size, power consumption, drag, and overall level of complexity. These penalties directly and indirectly influence an aircraft's design and operation. Major impacts of the ECS are due to its interface with the engine, avionics, structure, and secondary power system as well as its influence on fuel consumption.

5.2.1 Engine: The engine supplies power for the ECS. Most aircraft ECS use engine compressor bleed air as the power and air source for cabin air conditioning and pressurization, and for avionics thermal control. In some applications shaft power from the engine is used to drive a compressor. Electrical and hydraulic power from an engine driven system also is used. As a result, compressor bleed air and shaft power requirements of ECS impact the engine installed performance by increasing engine fuel consumption.

Normally, engines are more sensitive to bleed air extraction than to shaft power extraction. Engine sensitivity to bleed air extraction increases with engine by-pass ratio. The reduced core flow of high by-pass engines means that a given bleed air flow rate is a greater percentage of the core air flow, with greater effect on aircraft penalty and costs. The penalty associated with extracting air from the engine can be reduced when multistage bleed porting is available by using air from the lowest stage compatible with providing the ECS with sufficient energy to meet its performance requirements.

GO AHEAD ——→ PROGRAM MATURITY ——→ SUSTAINING

RESEARCH, DEVELOPMENT TEST & EVALUATION (RDT&E) NON-RECURRING	PROCUREMENT SUPPORT INVESTMENT NON-RECURRING	PROCUREMENT SYSTEMS INVESTMENT RECURRING	OPERATIONS & SUPPORT (O&S) RECURRING
o REQUIREMENTS DEFINITION			o LABOR - Crew, flight support & maintenance personnel
o INITIAL CONCEPT STUDIES			
o ENGINEERING DESIGN	o ENGINEERING	o DESIGN CHANGES	o EXPENDABLES - Fuel, oil, paper, etc.
o PRODUCIBILITY ENGINEERING PLANNING			
o PROTOTYPE - Tooling - Fabrication (including spares) - Testing	o PRODUCTION - Tooling - Initial spares & repairs	o PRODUCTION - Fabrication - Quality assurance/inspection - Transportation	o PARTS (logistic support & spares) o SOFTWARE (maintain computer programs)
o SYSTEM & TEST EVALUATION - Laboratory - Flight - Qualification	o TESTING - Special testing for production fabric.	o TESTING (ACCEPTANCE) - Component - System functional	o TESTING - Equipment repair & replacement
	o INVENTORY MANAGEMENT SETUP	o INVENTORY	o INVENTORY CONTROL & MANAGEMENT
o DATA - Reports - Drawings - Specifications	o DATA - Reports } - Drawings } Update - Specifications } - Technical manuals (Maintenance & operations)	o DATA - Technical manuals update	o DATA - Maintenance actions & repairs
o TRAINING - Assembly - Maintenance	o TRAINING - Production - Maintenance		o TRAINING - Replacement personnel
o FACILITIES	o FACILITIES		
o MANAGEMENT & ADMINISTRATION	o MANAGEMENT & ADMINISTRATION	o MANAGEMENT & ADMINISTRATION	o MANAGEMENT & ADMINISTRATION
o PROFIT	o PROFIT	o PROFIT	o PROFIT

FIGURE 1 - LIFE CYCLE COST ELEMENTS

TABLE 1

AIRCRAFT ECS FUNCTIONS

Crew/Passenger Compartment

- Cooling, Heating, Temperature Control
- Pressurization
- Ventilation
- Contaminant Control
- Moisture Control

Avionic Equipment/Compartments

- Cooling, Temperature Control
- Pressurization
- Contaminant Control
- Moisture Control

Weapons & Misc. Equipment

- Cooling, Temperature Control
- Pressurization
- Anti-Icing/De-Icing

Engine Bleed Air

- Distribution
- Temperature Control
- Pressure Regulation

Transparent Surfaces

- Rain Removal
- Defogging
- Anti-Icing/De-Icing
- Washing

Flight Surfaces & Ram Air Scoops

- Anti-Icing/De-Icing

5.2.2 Fuel System: A portion of total aircraft fuel is used for ECS operation. Open loop air cycle systems can increase fuel consumption by up to 5%. This fuel is used to provide engine bleed air, to overcome ram air drag, and to lift ECS and ECS induced subsystem and structural weight.

Fuel use is usually lower with: a closed loop ECS; cabin air recirculation; shaft power; use of fuel as a heat sink. The benefits of these approaches is dependent on the aircraft configuration and mission.

5.2.3 Avionics Systems: The degree to which an ECS thermally conditions avionics impacts their reliability. Avionics reliability is strongly related to junction temperatures of solid state electronic devices in the avionics. Components operated at low junction temperatures have low failure rates. Junction temperatures are dependent on internal thermal design and on external cooling. For forced cooled avionic units, the coolant flow rate and temperature are major factors affecting reliability. Information in Reference 4 relates avionics reliability to coolant temperatures. Industry and service data indicate that lower junction temperatures result in reduced component failure rates and consequently lower maintenance costs. Reducing temperature fluctuations of avionic environments or the coolant also improves avionics reliability. (See Reference 5.) Avionics coolant types, their flow rates and their temperatures significantly impact ECS penalties and overall aircraft costs. Reference 6 further discusses the need for integration of ECS and avionics during early design stages to minimize overall LCC.

5.2.4 Structure: An aircraft must be large enough to accommodate the environmental control system and additional fuel used by the engine to provide power for the ECS. Aircraft structure must be strong enough to maintain pressure differential in occupied compartments and equipment compartments. Structural weight increases occur as compartment pressure differential is increased above a minimum value. Structural size and weight to provide the ECS capability directly affect overall aircraft costs.

5.2.5 Secondary Power: The size and performance requirements of secondary (also referred to as auxiliary) power systems may be affected by the ECS. These include the hydraulic, accessory drive, and electrical systems. Hydraulic power may be required for fans and compressors. The accessory drive may be required to provide shaft power (e.g. for compressors) and electrical power (e.g. for valves, fans, compressors). The resultant increase in size, weight, and complexity of these systems to provide power to the ECS has a direct impact on their costs and overall aircraft costs.

6. ECS COST FACTORS AND COST DISTRIBUTIONS: The purpose of this section is to discuss factors which have major impacts on ECS costs, and to relate these to cost distributions among the three cost categories of section 4.

6.1 Primary ECS Cost Factors: Primary ECS design factors that affect cost are the size and type of the heat load to be cooled and the type of airborne application for the ECS. These key design factors influence the type of ECS, the size (weight) of the ECS, and the power it uses. These factors also impact the cost of fuel to lift the ECS and the fuel cost to provide power to the ECS. ECS application and types of ECS heat loads influence complexity of the ECS. ECS complexity directly affects ECS reliability, which impact ECS operational and support costs. These effects are shown in Figure 2 and discussed further in the following subsections.

6.1.1 ECS Design: A key design factor affecting ECS life cycle cost is the size of the heat load being cooled by the ECS. Simply stated, ECS life cycle cost increases as the size of the heat load increases. However, variations in the flow rate and temperature requirements of the heat load, auxiliary functions provided by the ECS, and the airborne system or aircraft in which the ECS is used also have significant impact on the size and cost of an ECS.

The type of airborne application affects ECS costs in several ways. The speed and altitude (i.e. flight envelope) determine the maximum temperature of the ECS heat sink (nominally air) as well as the aerodynamic heat load, and hence influence ECS size.

The location of ECS equipment in the aircraft, relative to the power source and cooling loads, determines ECS ducting size and complexity which in turn impact cost.

6.1.2 ECS Weight: ECS weight affects life cycle cost in several ways. Production costs increase as weight increases because more material is used, and more labor is needed to fabricate and handle larger components. Similar factors affect support costs. Another important factor is the cost of fuel required by the engines to carry the ECS.

Production costs can be related to the weight of ECS components. Cost algorithms differ among components (e.g. see Ref. 7). Ducting has the lowest cost per unit weight. Refrigeration components have a higher cost per unit weight than ducting. Control related components have the highest cost per unit weight. Ducting relative weight and cost (for open air cycle ECS) increase as engine bleed conditions increase and as the distance from the refrigeration package to the engine increases. Relative costs of controls are determined more by complexity than by weight.

ECS weight effect on fuel costs is determined by the aircraft application (i.e., mission and type of engine). If the mission nominally includes significant flight time at efficient engine operation (i.e., low specific fuel consumption), ECS weight impact on fuel cost will be lower per flight hour than for more variable missions.

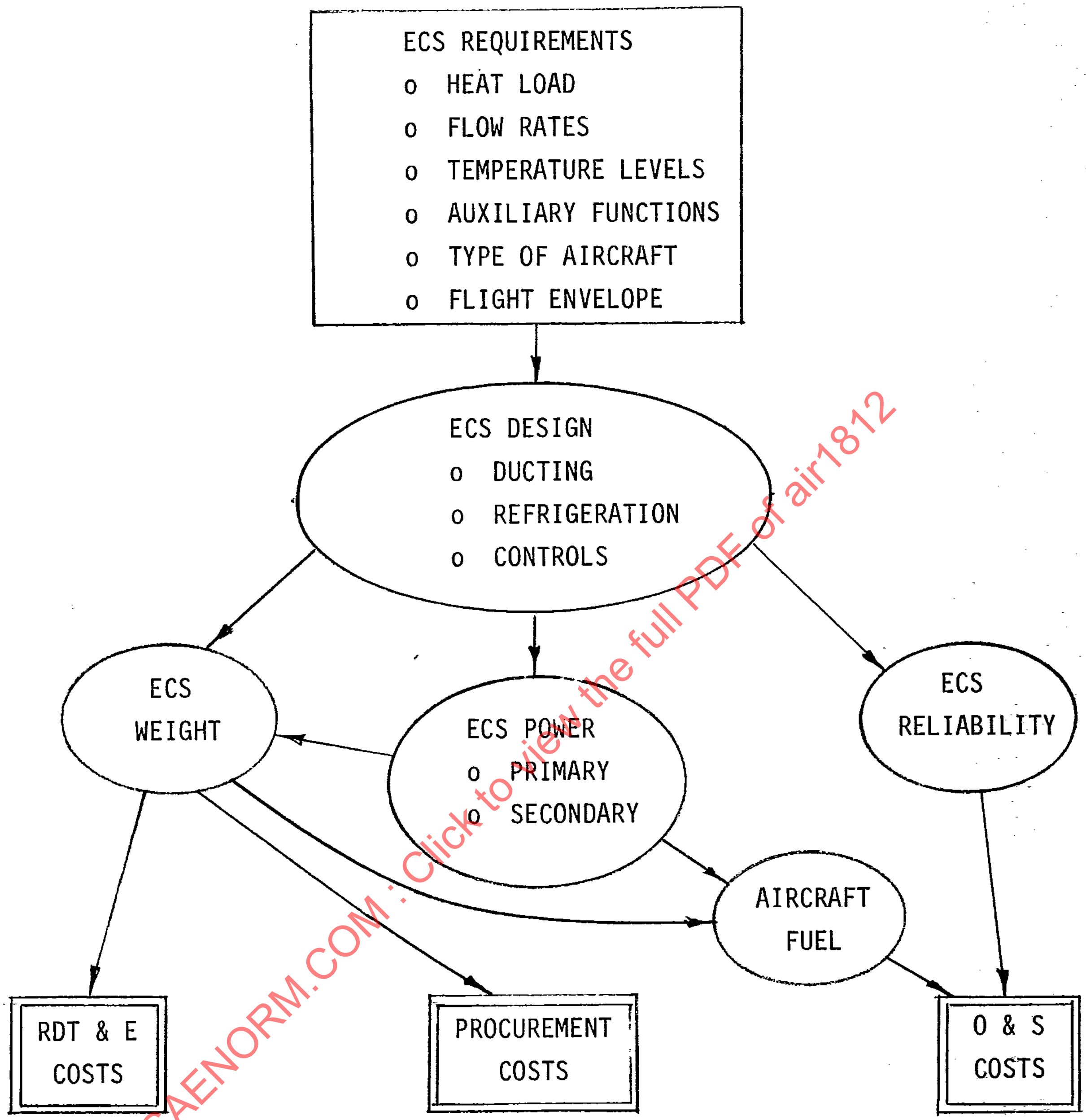

Figure 2 - Primary ECS Cost Factors

6.1.3 ECS Power Requirements: ECS power requirements affect life cycle costs primarily via the effect on engine specific fuel consumption, hence fuel costs. Section 5.2.1 discusses the impact of ECS on the engine.

Engine bleed air is the most common source of power for the ECS, and the source of pressurized air which is conditioned by the ECS. Use of engine bleed air is a convenient means to obtain pressurized air. However, as a power source, bleed air use is generally not as efficient as other alternates. This is partially because bleed air power often is dissipated by regulation to acceptable pressure levels. Electrical and hydraulic power can be provided at relatively high efficiencies. Direct mechanical power use is restrictive on ECS location, but is usually the most efficient.

Efficiency and weight of alternate power systems have differing impacts on ECS life cycle costs. Bleed air powered ECS use high speed components to reduce weight, but require heavy high temperature ducting to transfer power from the engine to the ECS. Electrical and hydraulic power is obtained by first converting engine mechanical power via generators or pumps, but the power transfer lines are small. Electrical motors used are nominally heavier than hydraulic motors, but they may be cheaper. These and other factors affect weight and fuel to provide the power.

6.1.4 ECS Reliability: The reliability of an ECS affects the operational and support costs. ECS with fewer parts will generally have higher reliability resulting in lower unscheduled maintenance costs. Dynamic ECS components (e.g., turbines, compressors, and fans) and control related components (e.g., valves and controllers) are normally the ECS reliability drivers. Overall ECS reliability basically is a function of the number and complexity of these types of components used. Higher RDT&E costs, to increase reliability and to reduce maintenance tasks, can have significant positive effects in reducing O&S costs of ECS.

6.2 Cost Distributions: The relative importance of the three cost categories of Section 4 may vary depending on the type of aircraft and ECS. One reason is that the operational uses of ECS are quite varied (i.e., contrast the long subsonic cruise of a passenger or cargo transport aircraft to the relatively short duration flight of a military fighter). Another reason is that fuel costs have become a more significant factor, hence generalized historical information is not valid (when fuel costs are considered part of operations cost). A third reason is that new ECS designs are being considered that reduce the significance of fuel costs.

6.2.1 RDT&E Cost Distributions: ECS RDT&E costs are largely dependent on system size, complexity, prior development and operational requirements. ECS RDT&E costs relative to total ECS life cycle costs, decrease as the number of units procured increase. A representative estimate for RDT&E costs for current types of ECS is 5% to 10% of ECS life cycle costs (200 aircraft, References 1 and 4). Relative to production costs, a nominal estimate for ECS RDT&E cost is 100 times the ECS unit production cost.

6.2.2 Procurement Cost Distributions: ECS procurement costs are basically dependent on the quantity of units produced. Production cost per unit is dependent on system complexity and size, and on the quantity produced. As the number of systems produced increases, the cost per unit decreases. This reduction of unit cost is termed a "learning curve". A percentage factor is applied to the learning curve definition. The percentage defines a lower unit cost if the number of units to be produced is doubled. A typical percentage value is 95%.

ECS procurement costs vary considerably, relative to life cycle costs, because operational and support cost variations are dependent on aircraft mission requirements (e.g., from References 1, 4 and 7 production costs are from 1/8 of life cycle costs to more than 1/2 of life cycle costs).

An approach for consideration of procurement costs is to classify ECS components according to general function or use. For example, (1) basic refrigeration components (including heat exchangers, turbomachines and fans), (2) ducting, for fluid distribution to and from the refrigeration components and (3) control components, including valves.

With this approach, a comparison of two air cycle ECS, in two aircraft having very different missions, indicates that basic refrigeration components are about 1/6 of production costs, ducting is about 1/2, and control related components are about 1/3.

6.2.3 Operational and Support Cost Distributions: Operational and Support costs are the largest element of ECS life cycle costs, and they are the most variable. The reason for this is the varied applications of the ECS. Three prime factors affecting O&S costs are deployment, the rate of use and the mission of the aircraft. Some support costs increase as deployment increases (i.e., locations at which aircraft are used). Support costs affected by deployment include the cost of additional maintenance personnel, and general administrative support. (The cost of setting up the additional support bases comes under the heading of Procurement-Support Investment Costs). Aircraft use rate, mission and ECS reliability affect fuel costs and maintenance costs. Maintenance costs include cost of replacements (spares) and repair materials, cost of labor to conduct maintenance and costs to repair the ECS on or off the aircraft. Systems with a large number of unreliable parts reduce aircraft availability and increase maintenance hours and spares. Fuel is expended to carry the ECS and to provide its power requirements. In summary, the type of aircraft and its intended use have major impact on ECS operational and support costs.

7. ECS LIFE CYCLE COST COMPARATIVE EVALUATION: This section discusses a method for evaluating on a comparative basis various environmental control systems from an overall aircraft program cost effectiveness point of view.

The methodology consists of two parts. The first part of the evaluation effort consists of gathering ECS and airframe design data such as: take-off gross weight (TOGW), fuel consumption penalties (see Part 3I of Reference 12), ECS component definitions, estimated failure rates and mean times to repair.

7. (Cont'd.)

The design data is used in the second part of the evaluation to estimate life cycle cost. Two cost models can be used - the Modular Life Cycle Cost Model (MLCCM) (Reference 8) for the airframe and engine costs, and the Logistics Support Cost Model (LSCM) (Reference 9) for the logistics costs. The addition of the costs generated by the two models to the RDT&E and Procurement costs results in the ECS life cycle cost to be used for comparative evaluation (see Figure 3). It should be noted that the total LCC numbers generated are for comparison purposes to determine relative merit. They should not be considered quantitatively accurate as stand alone values. It is recommended that true cost values be determined by cost analysts. Reference 10 presents cost estimating information for use in Air Force LCC analyses.

7.1 Design Information: Required aircraft ECS design related information consists of the following for each ECS concept:

1) ECS Performance and Configuration - A system flow schematic, a descriptive listing of components and quantified performance data.

2) ECS Penalties - Weight, power, bleed flow, and ram air flow penalties.

3) ECS Reliability and Maintainability (R&M) Parameters - The mean time between failure (MTBF) and the mean time to repair (MTTR).

4) Aircraft TOGW & Fuel Penalties - The baseline aircraft TOGW and fuel requirements. These can be determined by use of an aircraft sizing program of the nature typically used in preliminary design. The baseline is usually the aircraft without an ECS.

7.2 Cost Analysis: The cost analysis effort consists of the following tasks:

1) Define Costing Ground Rules - Define assumptions and ground rules (e.g., numbers of operational aircraft and production rates, number of sites, aircraft life cycle, flight hours per month, etc.).

2) Determine ECS RDT&E Costs - Using Section 4.1 as a guide, determine the RDT&E costs for each ECS configuration. These are generated by summing the individual RDT&E costs associated with the components within each system along with overall system development costs. The costs pertaining to an item common to all the systems being evaluated can be eliminated because the comparative nature of the approach is concerned only with differences.

3) Determine ECS Procurement Costs - Referring to the cost items of Section 4.2, determine the procurement costs associated with each ECS configuration. Cost items common to all systems being evaluated can be eliminated because of the comparative nature of the evaluation.

4) Determine ECS Logistic Costs - Estimate all logistic costs for all ECS configurations under study (i.e., the combined initial support, and operations and support costs) using the Logistics Support Cost Model Computer Program discussed in Section 7.3.2.