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ECS INTEGRATION FOR FUEL EFFICIENT/LOW LIFE CYCLE COST DESIGN

by

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Abstract

Current technology environmental control systems (ECS) in airplanes suffer from deficiencies in two major respects (a) the fuel penalty for engine bleed air extraction and ram air drag is high, and (b) lack of adequate system temperature and moisture controls result in excessively high avionic equipment failure rates, thereby adversely affecting Life Cycle Costs.

Studies conducted in development of energy efficient, low life cycle cost ECS are discussed with a tactical mission airplane used for illustrating problems, new concepts and payoff's. Concepts which significantly reduce fuel consumption, thrust and drag penalties to an aircraft are related to reliability of interfacing systems, in particular the avionics. Relationship to life cycle cost of ECS/Avionic Systems is discussed.

Introduction

Aircraft environmental control systems (ECS) have multiple functions including crew/passenger cabin conditioning and pressurization, avionics and weapon system thermal control, and cooling of power generating accessory systems, Figure 1. ECS use varied thermodynamic cycles commonly known as simple or bootstrap air cycles, open or closed loop cycles, vapor cycles etc. The heat rejection is usually to ram air although greater interest is being shown in the use fuel as a heat sink.

CREW (& PASSENGER) COMPARTMENT
- o Cooling, heating, temperature control
- o Pressurization
- o Contaminant control
- o Moisture control

AVIONIC EQUIPMENT (COMPARTMENTS)
- o Cooling, temperature control
- o Pressurization
- o Contaminant control
- o Moisture control

ACCESSORIES & MISC. EQUIPMENT
- o Cooling, temperature control

WEAPONS
- o Cooling, temperature control

MISCELLANEOUS
- o Engine starting
- o Hydraulic reservoir pressurization
- o On-board nitrogen generation
- o Anti-icing/de-icing of flight surfaces
- o Windshield/canopy clearance
- o Canopy sealing

Figure 1. Aircraft Environmental Control System (ECS) Functions

ECS have a significant impact on the airplane performance and operating costs in performing these functions. Airplane performance (e.g., range, engine thrust) is affected since the source of power for ECS (bleed air, shaft power), ram air usage and the weight of the equipment impact the SFC (specific fuel consumption) of the engine and the airframe weight and drag. Operating costs are affected through the use of higher quantities of fuel and the cost of maintenance. Inadequacies in the capacity and performance of environmental control systems also adversely impact reliability of other interfacing systems such as avionics, thereby increasing maintenance costs.

Synthesis of systems to get a low penalty/low life cycle cost (LCC) combination of air sources, heat sinks, cooling cycles and controls is a major objective of any airplane program. Efficient design integration with the airframe and the engine is a necessity in view of the rapidly rising fuel, material and labor costs. The objective of this paper is to discuss three aspects of such an integration activity necessary for design of new high performance aircraft: (a) How the energy or fuel consumption of advanced cooling cycles can be made significantly lower than current technology aircraft systems, (b) the impact of stable temperature coolants for avionics on life cycle costs, and (c) the importance of conducting these studies early in the RDT&E phases of a program to minimize the overall life cycle costs. Simplified examples are shown and discussed in each category to demonstrate the benefits.

Low Fuel Penalty ECS

Figure 2 shows a simplified mission for a tactical aircraft along with representative avionic heat loads and engine power characteristics for purposes of illustrating the importance of developing appropriate combinations of air sources, heat sinks, and cooling cycles.

Most current aircraft utilize open loop air cycle cooling as shown schematically in Figure 3. High pressure bleed air is extracted from the engine compressor and cooled to a temperature range required by the crew, accessories and avionics. Ram air is used as a heat sink for precooling the bleed air and then the high pressure air is expanded through a turbine to temperatures low enough for the various heat loads. Heat sink availability is augmented by use of turbine exit air or a water boiler for supersonic flight segments where ram air temperatures are too high. The operating penalties of a system like this result from the cost of bleeding large amounts of air from the engine, from use of ram air, and from the weight of the equipment.

	Pressure KPa	Temperature °K	Fuel Penalty per Kg/Sec Bleed
HIGH PRESSURE BLEED	772	892.2	.0516 Kg/Sec
LOW PRESSURE BLEED	138	538.8	.0328 Kg/Sec
SHAFT POWER	—	—	3.88×10^{-5} Kg/Sec/KW

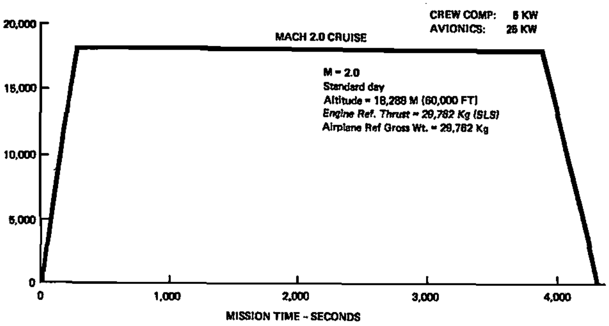


Figure 2. Study Aircraft Mission Profile

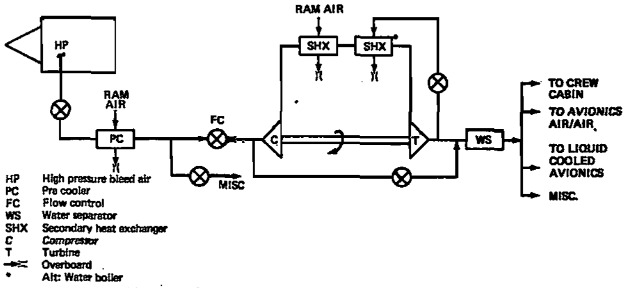


Figure 3. Open Loop ECS Concept

The penalty to the aircraft can be represented in a number of ways such as thrust loss from the engine, take-off gross weight, decrease in range or reduced maneuverability. Figure 4 (curve A) shows the penalty of the open loop system example in terms of operational fuel penalty during the supersonic cruise segment of the mission.

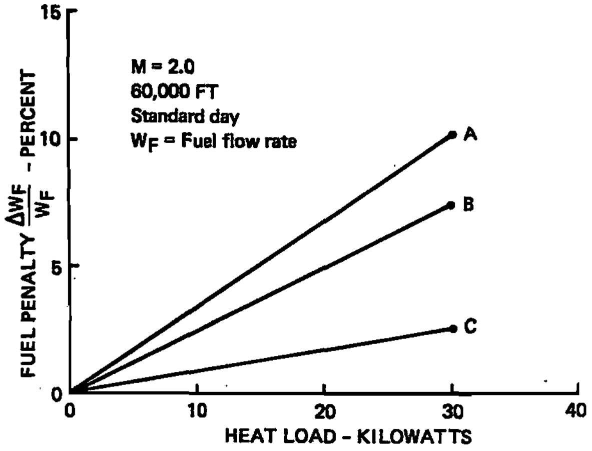


Figure 4. Comparison of Fuel Penalty

Since one of our objectives is to reduce fuel usage attributed to the ECS, while at the same time maintaining the same required environmental conditioning capability, the changes necessary to reduce the fuel penalty can be divided into two categories; (a) through reduction of penalty due to power extraction from the engine, and (b) through use of heat sinks other than ram air. Reduction in equipment weight will, of course, help also.

Two concepts are shown as alternates to the system in Figure 3. The first, Figure 5, makes use of the regenerative air as a heat sink. The expanded bleed air used for cooling the crew and avionics, instead of being discharged overboard, is recirculated to the heat exchangers in lieu of ram air. Fuel is also used as a supplementary heat sink. This concept results in a significant reduction of ram air drag and a corresponding decrease in fuel penalty as shown in Figure 4 (curve B). Bleed air usage is also reduced from that in the open loop concept since expanded bleed air is not directly used in the secondary heat exchanger. An additional feature is the use of a high pressure water separator or condenser for moisture removal which aids in avionic reliability.

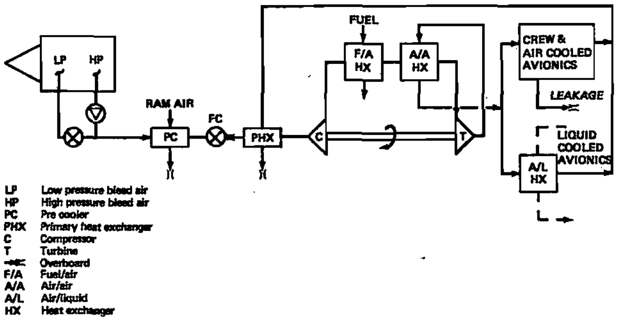


Figure 5. Regenerative Loop/Fuel Heat Sink ECS Concept

The second alternate concept, shown in Figure 6, goes a step further in the direction of reducing bleed air usage. Since high pressure bleed air extraction is typically the largest contributor to high fuel penalties, (Figure 2), this concept uses shaft horsepower from the engine as the primary mode of power extraction, and limits the bleed air usage to the quantity required for make-up of duct and compartment leakage losses, and for providing fresh air for the crew only. This closed loop system results in penalty characteristics as shown in Figure 4 (curve C), for the supersonic cruise segment of flight.

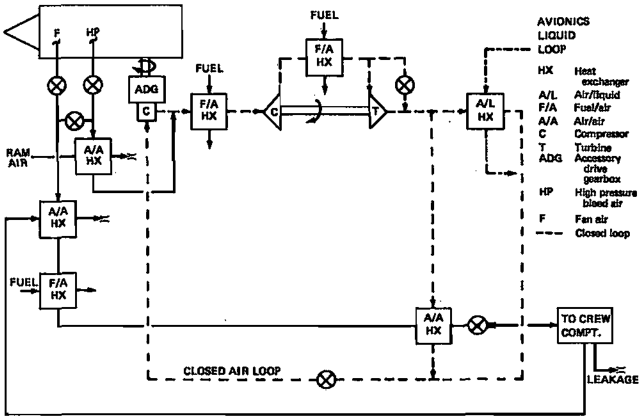
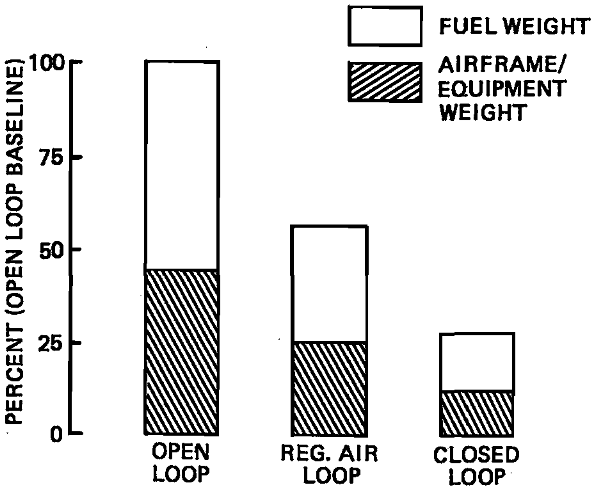


Figure 6. Closed Loop Air Cycle Concept

Figure 7 shows a comparison of the three concepts in terms of design takeoff gross weight, assuming a constant range. The changes in the airframe weight result from the ECS cycle SFC penalty. Figure 8 shows how the changes in fuel usage and airframe weight impact the operational cost for a representative fleet of aircraft over a period of 15 years in terms of constant dollars and fuel price.

CONCEPT	HEAT SINK REQ'D, KW		ENGINE POWER EXTRACTION			FUEL PENALTY, Kg	TAKE-OFF GROSS WEIGHT PENALTY KG-FUEL
	RAM AIR AT 121°C	FUEL AT 65.5°C	BLEED AIR, Kg/S		SHAFT POWER, KW		
			HIGH PRESS	LOW PRESS			
OPEN LOOP	507	0	.81	0	0	123.6	700.3
REG. LOOP	175.7	121.3	.47	0	0	69.0	396.8
CLOSED LOOP	25.6	121.3	7.56×10^{-3} Leakage	.18	66.9	33.0	183.9

Figure 7. Penalty Comparison of ECS Concepts



FUEL SAVINGS OVER OPEN LOOP*

REG. AIR LOOP:	\$55.81 Million
CLOSED LOOP:	\$92.76 Million

AIRFRAME COST SAVINGS OVER OPEN LOOP**

REG. AIR LOOP:	\$32.56 Million
CLOSED LOOP:	\$44.12 Million

*15 years, 250 flights/year/aircraft, 200 airplanes, \$0.40/kg fuel
**\$1100/kg/airplane, 200 airplanes

Figure 8. Relative Take-off Gross Weight Penalty

The fixed weight of the three concepts has been assumed constant in the above examples although this is not strictly true. Figure 9 shows the typical sensitivity of airplane gross weight to changes in the ECS fixed weight for closed and open loop cycles and can be considered representative of this type of aircraft and mission (1). Use of closed loop cycles, even at the cost of slightly greater fixed weight due to larger number of components, offers significant fuel cost savings to make them a serious contender in the design trades.

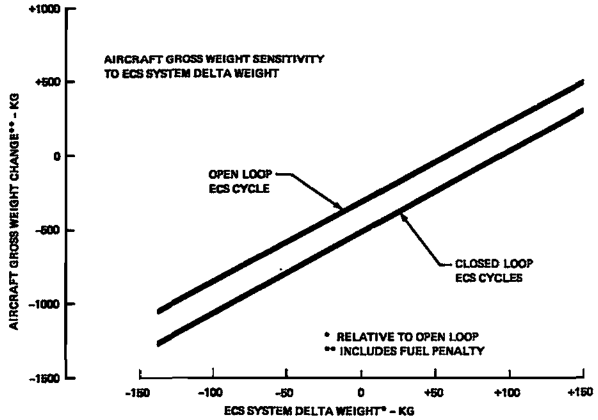


Figure 9. Aircraft Gross Weight Sensitivity

While there are numerous combinations which can be studied in an attempt to improve the fuel penalty, or energy efficiency, it can be summarized that certain key factors and approaches lead to most of the reductions in the overall energy usage. These are also important from airframe and engine integration point of view and involve parameters such as the overall thermal conductance of the fuel tank structure versus fuel management to determine fuel heat sink capacity, mission loads management, engine cooling cycle interface and the relative costs of bleeding air from different compressor stages, or extracting shaft horsepower, and engine inlet duct sizing and design for optimum ram air source. Figure 10 shows the relative energy extraction penalty for a typical current tactical aircraft for the type of concepts discussed.

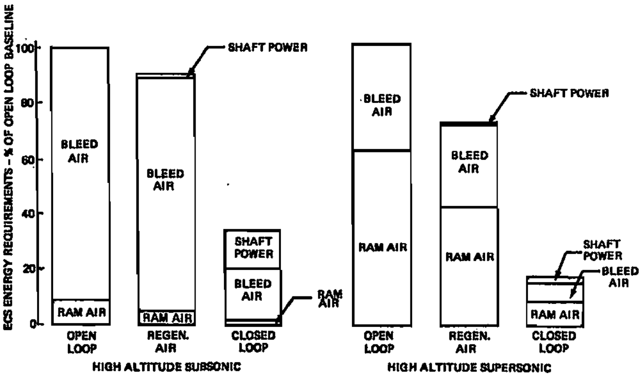


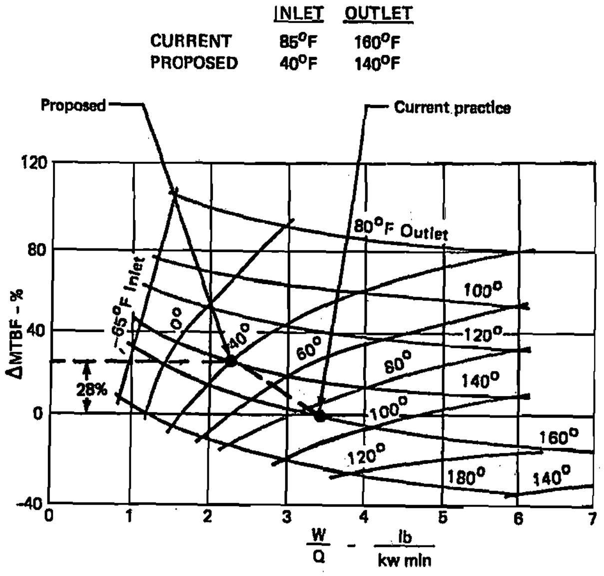
Figure 10. ECS Energy Requirements Comparison with Open Loop ECS Baseline

Temperature Control for Avionic Reliability and Low LCC

The impact of proper selection of air sources, heat sinks and cooling cycles on fuel usage and cost has been explored above. Another major factor to consider in reducing life cycle costs is the capability of ECS to control the coolant supply temperatures within narrow limits and without much fluctuation throughout the wide range of disturbances an ECS is subjected to during normal and emergency mode operations. Examples of these disturbances include variations in bleed air characteristics during engine power transients, load excursions caused by switching of large avionic loads, and variations in ambient ram préssures and temperatures during flight maneuvers. Because of these conditions it is understandable that existing ECS are often unable to maintain stable avionic equipment operating environment in terms of temperature and moisture. Rapid fluctuations in coolant air supply temperatures of 50°C or more are not uncommon. These functuations, within the context of ECS component performance alone, are not intolerable. However, in terms of their impact on the interfacing avionics, they have a severe effect on the equipment reliability. Experience shows that achieved avionic equipment reliability in service is often as low as 15 to 20 percent of predicted value, primarily due to adverse thermal and moisture conditions. The use of advanced temperature control systems can not only be advantageous in improving reliability, but by going to concepts such as centralized digital controls for ECS heat load thermal management, one can design an optimum demand related coolant flow system. This approach, while having the ability to maintain constant supply temperatures, can also lead to minimizing the amount of coolant air used commensurate with the actual load duty cycle demands and thereby further reduce the bleed air energy requirements.

The major environmental reasons for avionic equipment failure are high coolant supply temperature levels, large temperature transients and moisture or other contaminants in the coolant air. Figure 11 shows the typical effect of coolant supply and exit temperatures to avionics in terms of mean time between failure (2). Similarly, industry and service data indicates that lower junction temperatures result in reduced component failure rates.

Temperature cycling over a wide range results in premature thermal fatigue failures of components. Hence, the overall avionic O&S costs attributed to maintenance can be significantly reduced by requiring that the design of ECS controls must have an inherent capability of providing a stable and essentially constant temperature coolant supply regardless of flight maneuvers, avionic loads or engine induced transients in the system.



*From AFFDL-TR-77-68, Volume I, Advanced Environmental Control System, August 1977.

Figure 11. Avionic MTBF Sensitivity to Coolant Temperatures

Low Life Cycle Cost (LCC) ECS

The life cycle cost of a system breaks down into three major categories, the RDT&E costs, the Acquisition costs, and the Operations & Support (O&S) costs. These are shown in Figure 12 along with a listing of elements of cost which are typically included in each category. Figure 13 shows a generalized time profile of LCC for either a system or an airplane. Figure 14 shows typically how the design decisions in the early days of RDT&E program affect the accumulation of the system LCC; for instance, it is likely that some 70 percent of the total LCC is committed through decisions taken in the concept development part of the RDT&E phase, whereas the actual expenditures up to that point in time are in the 2-5 percent range.

With this general background in LCC one can start looking at ECS and interfacing avionic system costs, and in particular the O&S element, which is the predominant part of LCC, Figure 15. O&S costs include two important elements - the fuel costs and the R&M (reliability/maintenance) costs. Obviously, to keep the fuel costs down, one must lower the energy usage or fuel penalty attributable to the ECS, and it has been shown above how this can be achieved. However, the R&M element of the O&S costs needs to be explored a little further. Figure 16 shows a typical distribution of O&S costs for a current technology tactical aircraft. ECS forms a small percentage of O&S costs, and even 50 percent reduction in the maintenance costs of ECS will not greatly affect the overall airplane LCC. However, when one considers the R&M costs of the avionic systems which interface with ECS and whose reliability substantially depends upon ECS performance characteristics, then it becomes apparent that achievement of some 50% reduction in avionics maintenance costs will reduce the overall life cycle costs by a significant amount. Studies indicate that supplying avionics with a constant coolant temperature throughout the mission, say at about 4 to 5 °C, can lead to at least a 25 to 30% reduction in avionic O&S costs. Hence, the controls aspect in the design ECS assumes a great importance and points toward the desirability of expending a strong effort during early phases of ECS design.

RDT&E*	ACQUISITION	OPERATIONS & SUPPORT (O&S)
CONCEPT DEVELOPMENT & SYSTEM TRADES o RESEARCH o DESIGN o DEVELOPEMNT o TEST o EVALUATION	o UNIT EQUIPMENT o COMMAND SUPPORT o ATTRITION o INITIAL SPARES o AGE o FACILITIES o TRAINING o WAR RESERVES o TECHNICAL MANUALS	o REPLENISHMENT SPARES o PETROLEUM-OIL-LUBRICATION (POL) o PERSONNEL PAY o VEHICLE MAINTENANCE o VEHICLE MODIFICATION o AGE MAINTENANCE o FACILITY MAINTENANCE o DEPOT MAINTENANCE

*Research, development, test and evaluation.

Figure 12. Life Cycle Cost Elements

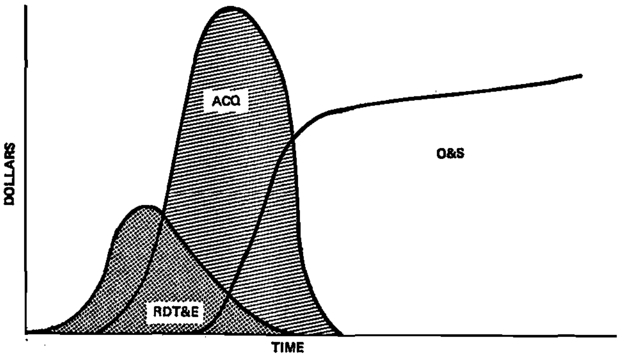


Figure 13. Life Cycle Cost Profile

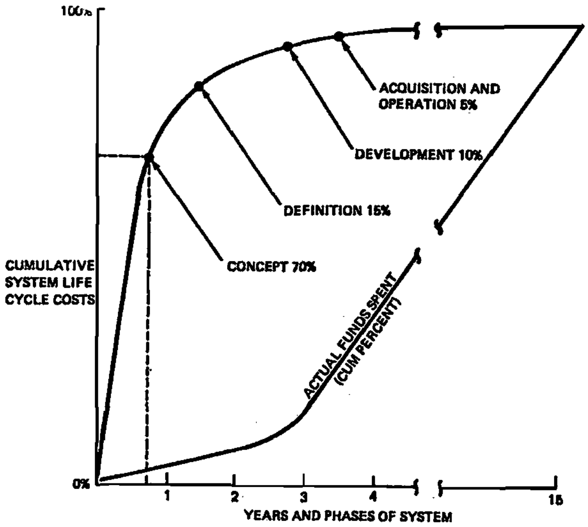


Figure 14. System Funds Committed by Initial Planning Decisions

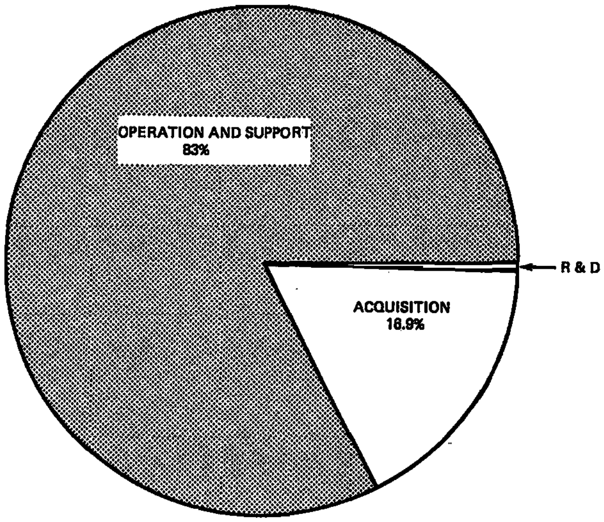


Figure 15. Typical Aircraft Life Cycle Cost (Mature System)

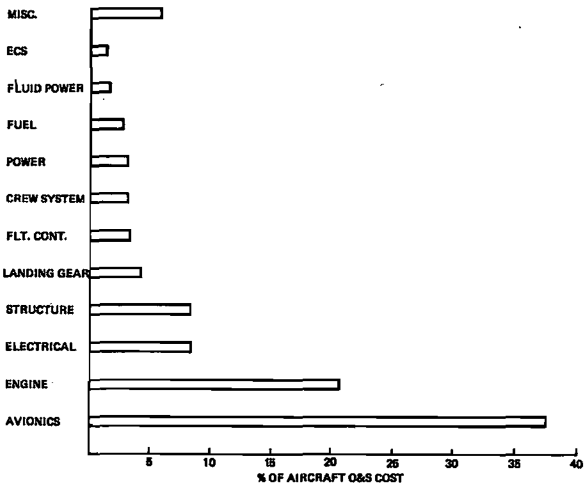


Figure 16. Typical O&S Cost Distribution; Tactical Aircraft, 15 Year Life Cycle

Since avionics may constitute some 70-80 percent of the ECS loads in tactical aircraft, and about 40 percent of the O&S costs, not to mention the high acquisition costs, the importance of well designed ECS, capable of providing stable environment with a minimum expenditure of energy, becomes quite evident. It is apparent that the optimization and design of ECS should not be restricted to this one system by itself, but should be undertaken and evaluated in conjunction with its effect on interfacing systems, in particular the avionics.

In conclusion, it can be stated that the achievement of low LCC and low energy usage environmental control systems demands a truly integrated approach to subsystem development carried out in conjunction with avionics. The potential benefits in energy and cost savings are very large. Also this integrated design effort should be done in the very early phases of the RDT&E program for an airplane or weapon system when, historically, the funds maybe limited, but the leverage in the benefit to cost ratio is the highest.

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