New Technological Considerations That Improve Avionic Reliability

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Significant avionic reliability and aircraft flight performance increases can be utilized as a result of employing the improved aircraft environmental control system (ECS) technology. This technology improvement, which can realize better weapon systems, has resulted in improved integrated aircraft flight envelope operations combined with the onboard electronics. This integration is a direct result of a better understanding of the impact of different environmental stresses on electronic failures and more effective and efficient use of the onboard ECS. This paper discusses the efforts under way to exploit the emerging new technological directions with advances in ECS.

Introduction

AVIONICS has emerged as the most pervasive technology within a modern aircraft system. The functions performed by modern avionics have grown from the radio in the 1940s to flight controls, weapons systems fire controls, electronic countermeasures, among others. Despite continuing reductions in size, weight, and power consumption for specific electronic functions, the percentage cost of avionics in a modern fighter/attack/interceptor aircraft continues to increase. (In 1940, it was about 1%; it is now about 10%.) The spread of electronics into every corner of a modern aircraft has led to the observation that "Airplanes are merely a form of truck in which to carry electronics around the sky."[1]

Today, avionics is being used for flight-critical flight safety systems, such as flight controls, ground-following radars, and electronic countermeasures. The failure of any one of these systems could mean the loss of the aircraft or the inability to complete the mission; thus, the importance of reliable avionics is growing. The Air Force has identified this need by initiating programs such as R&M 2000, Avionics Integrity Program (AVIP), and Unified Life Cycle Engineering (ULCE).[2-4]

The deployment reliability of avionics depends heavily on the internal thermal design and the performance of the onboard cooling system, which are designated as the environmental control system (ECS). This system has been designed to provide the appropriate environmental conditions for long life of avionics. This paper will present the view that the "appropriate environmental conditions" for long life of avionics is changing in response to changes in the nature of electronics and the better understanding of what causes failures in today's deployed systems. In the next section, changes in the understanding of what causes failures in deployed avionics systems will be discussed. This will be followed by a discussion of ongoing developmental efforts to demonstrate an improved ECS, which will address changing avionic needs and improvements in ECS technology, in which microprocessors are used to provide on-demand cooling with improved impact on aircraft performance and avionic reliability and a reduction in maintenance costs.

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Background

Over the years, many different investigators have examined avionic failures to identify the mechanisms that contribute significantly to the occurrence of avionic failures.[6-9] Unfortunately, the results of studies of failures in one system, however interesting in their own right, are often seen as of little benefit when applied to other avionic systems. This view is reinforced by the cavalier and widely held belief that the problems associated with a particular type of electronic device or family of devices will be overcome by using the latest state-of-the-art electronic technology.

Another major contributor to this viewpoint is that avionic equipment historically fails, and is expected to do so, during operational usage. Other aircraft systems, however, such as structures, engines, and hydraulics, are designed to be failure-free during operational usage.[3] Thus, the expected-failure-rate projection is the accepted norm unless the number of avionic failures becomes excessive. This difference in expectations develops out of the philosophical base and relative maturity of the technology involved. System designers for structures, engines, hydraulics, etc., consider a failure to be a caused event, while avionic designers consider a failure to be a random event. The rate of occurrence of these random failures can be influenced by the environment into which the equipment is installed, the quality of the components, etc. Despite extensive research to develop an understanding of the various failure processes, there is an apparent acquiescence to the view that avionic failures are random events. This acquiescence, though not openly stated, is reflected in the form and structure of the analytic tools used to support the system design process.[5]

This acquiescence extends into another area in which environmental factors significantly contribute to avionic factors. There is no question that the temperature level at which a component is operating strongly influences the available useful life of avionic systems. The importance of temperature is reflected in the form of MIL-HDK-217 reliability prediction models. These models, however, only identify one environmental factor, temperature, as contributing to the component failure rates. The effects of all the other environmental stress factors are lumped into the environmental π factor. Thoughtful and careful consideration of the influences of other environmental factors, such as thermal cycling, vibration, moisture, shock, and dust, have been neglected in most avionic designs. Generally, these environmental effects are tested after the design is complete by testing methods from MIL-STD-883 and/or MIL-STD-810.

The net result of this preoccupation with temperature levels is that the reliability benefits of paying more attention to these other environmental effects are not realized. This neglect is reflected in the fact that the environmental stress conditions found to be most effective in provoking failures in just-produced equipment are environmental stresses other than temperature level.[10] These environments are so detrimental to reliability that exposure to less than 20 stress cycles and 10 min of random vibration manifests failures that would have occurred in deployment if the equipment was deployed without being first exposed to these stresses.[11] This approach has been called environmental stress screening (ESS). The use of a postproduction test to cause failures quickly did not begin with ESS. A similar type of end-of-the-production-line process was called burn-in which, as the name implies, exposes the equipment to temperature levels to provoke failures. Over the past several years, this test has been replaced by ESS. This trend suggests that the equipment design process produces equipment that is compatible with the anticipated deployment temperature levels, while still sensitive to dynamic environmental conditions. This perspective is consistent with the nature of an electronic assembly and its failure processes. This will be discussed in the next section.

Defect/Failure

Electronic assemblies and components consist of many dissimilar materials, which have been bonded or joined together to obtain the desired electronic functions.[12] It is reasonable to assume that every electronic component and assembly contains latent defects or flaws. This assumption is reasonable because it takes extreme care just to make a nearly defect-free perfect crystal, let alone build a defect-free assembly of many parts and dissimilar materials.[13] The discipline of failure physics emerged to identify failure mechanisms, latent defects, etc., that significantly contribute to the occurrence of an electronic failure.[14]

Unfortunately, for the reasons cited earlier, in many quarters, failure physics has been thought of as electronic autopsy, whose results are of value to the equipment being analyzed but of little transferable benefit to different avionic systems. Capitano and Feinstein[15] have taken issue with this perspective by stating:

> If an assessment is made of the construction techniques and the component parts used to produce electronic systems, one can conclude that all electronic systems are essentially the same. That is, they are manufactured with the same family of components, i.e., transistors, resistors, etc., purchased from the same QPL sources who supply parts throughout the USA. Since the majority of system failures result from component part latent defects many of their failure modes are common and therefore they may be eliminated by similar means.

A major component of the methodology for defect elimination described by Capitano and Feinstein is the use of random vibration and thermal cycling to drive latent defects to failure before defective components are used in electronic assemblies. Additionally, Capitano and Feinstein recognized that though avionics systems may look different, they are essentially the same in terms of their response to environmental stresses.

At first glance, it appears that the assertion by Capitano and Feinstein is not supported by a recent study of different avionic systems used in modern aircraft. This study could not find a common subset of latent defects or failure mechanisms that accounted for the majority of the experienced field failures. But for any one system, it was possible to identify which failure mechanism or latent defect types accounted for most of the problems experienced by that system.[16]

Unfortunately, such studies do not take into account the significant influence that environmental stresses have on failure frequency and types. One study examined equipment deployed in several aircraft types and found that the failure rate for the avionics in bombers and transports was 2–4 times lower than for similar or the same avionics in trainer and tactical aircraft.[17] Laboratory tests have shown that avionic equipment exposed to different simulated flight environmental stress profiles had significant differences in failure frequency and type, even when the temperature range and maximum vibration amplitudes were the same.[18] The differences in the environmental stress profile consisted of stress change rates, dwell times at given temperature levels, and environmental sequences.

Detailed studies of individual electronic devices or assemblies have shown that there can be as many as a hundred different ways for failure to occur.[14] For any specific application, however, only a subset of all the possible ways of failing will be activated since the deployment environment is bounded and does not contain all possible environmental stress factors.

One way of conceptualizing this is to consider the diagram shown in Fig. 1. Circle I contains all the possible ways an avionics system could fail. Circle II covers those failure modes that are activated by the environmental stress conditions experienced by the avionic equipment of interest in a specific application. Using the equipment in a different application means that a different combination of environmental stress conditions will be experienced, activating a dif-

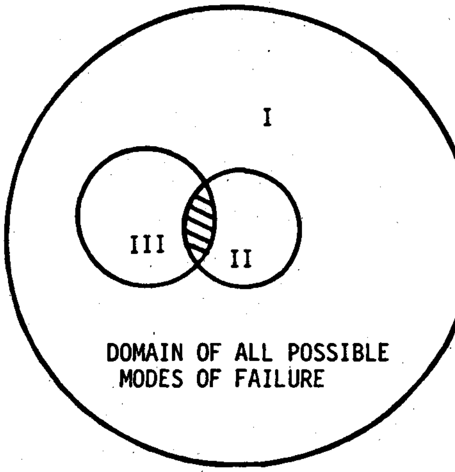

Fig. 1 Each application environment activates only a subset of all possible modes of failure.

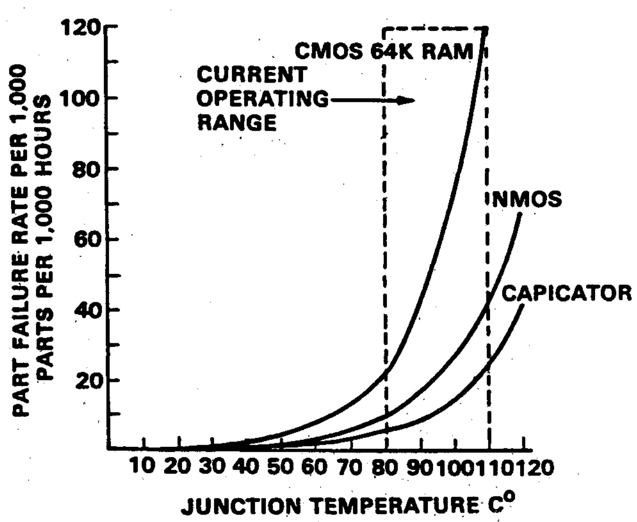

Fig. 2 Junction temperature effects on avionic equipment failure.

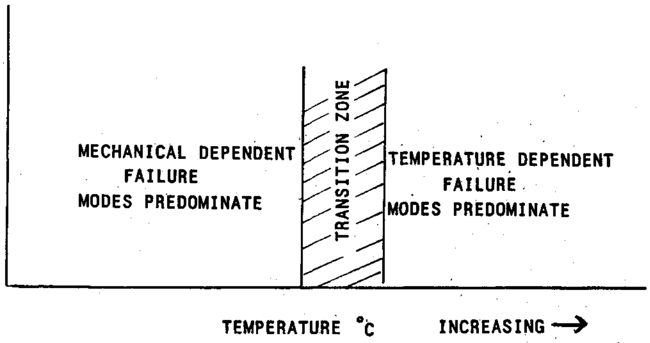

Fig. 3 Domains in which specific failure modes predominate.

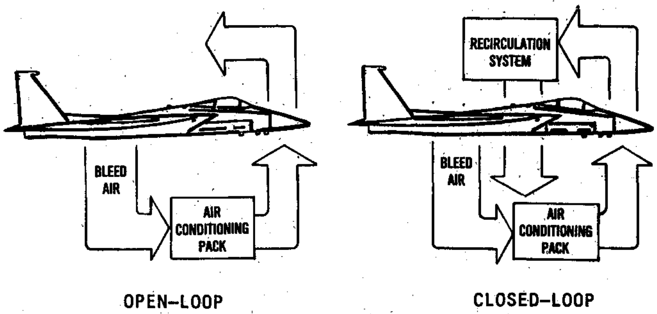

Fig. 4 Environmental control system (ECS).

ferent subset of modes of failures, as indicated by circle III. In general, there is some, but not complete, commonality of failure modes that are activated by both sets of environmental conditions, represented by the overlapping area between circles II and III. Exposure to a wide variety of environmental stresses should result in the identification of the entire set of failure modes. Several investigators have suggested that all avionic failures can be considered as one or a combination of the following processes or changes: chemical, mechanical, metallurgical, and electrical overstress.[19-22]

Avionic Failure as a Process

Detailed consideration of each of these processes identifies different environmental stresses or factors necessary for each process to occur. For example, a mechanical type of failure needs mechanical stresses and strains that either exceed the strength of the materials or are of a cyclic nature so that fatigue can be initiated. Chemical processes need materials in close proximity that can interact chemically. Also, the time spent at elevated temperatures is critical since the rate of a chemical reaction is related exponentially to the temperature level. Metallurgical processes require an appropriate stress/strain condition and metallurgical structure and an elevated temperature to speed the process like that caused by diffusion or grain growth. Electrical overstress can cause nearly instantaneous burnout of an avionic system or precipitate transport phenomena due to excessive current densities in small conductor paths. Two of the four processes, chemical and metallurgical, are strongly related to time at temperature, since temperature level exponentially influences the rate of reaction. Mechanical effects are temperature influenced but not in an exponential manner. Electrical overstress is influenced scarcely, if at all, by temperature level. Thus, temperature level, which is considered the primary component of the operational environment that influences the occurrence of failures, is not necessarily the prominent driver for all failure mechanisms.

The contribution of each process category to the total number of failures experienced by an avionics system is a function of the anatomy of the failed system and the nature of the environmental stress profile experienced in usage. Without knowing the exact level of contribution of each process category for a given system, some generalized observations can be made. It is reasonable to expect that at higher temperature levels, the failure processes that depend heavily on temperature would be the predominant modes of failure; while at lower temperature conditions, those failure modes that are not so dependent on temperature will become more significant or predominant. Unfortunately, this can lead to errors when the result of higher-temperature testing is used to project behavior at lower temperatures. As discussed by Turner,[23] even if the assembly contains only temperature-dependent failure mechanisms, it is difficult to project behavior at lower temperature levels from high-temperature failure data. This is because the lower activation energy mechanisms, which are masked at higher temperatures by the more prevalent higher activation energy failure mechanisms, become significant modes of failure. Without compensating for this, the predicted failure rate will be higher than that actually experienced in deployment.

A review of the literature shows a consistent warning that the use of prediction relationships developed from data collected under one set of stress conditions cannot be used to estimate the behavior under another stress condition unless the same failure modes are activated.[24-26] This problem occurs whenever overstress or accelerated testing is done to compress time as discussed in Ref. 27. Analysis of specific devices has found that:[25]

> ...it appears certain that valid extrapolations of the acceleration curves can be made at least over one or two orders of magnitude in time, provided that great care is taken to ensure that the accelerated failure mechanisms at high stress levels are the same as those which dominate at the lower stress levels.

Despite these limitations, the reliability prediction models of MIL-HDBK-217 display interesting trends. Figure 2 shows the decreasing influence of junction temperature on failure rate as the temperature is decreased. This behavior has led one investigator to conclude:[28]

> ...in most components there is a leveling off of failure rate to an extent that further reduction in temperature has little or no beneficial effect on failure rate.

A recently developed reliability prediction model for microcircuits from Finland shows a similar type of reduction in the influence of temperature on failure rate as the temperature is reduced.[29] Palo points out that the curve flattening at low temperatures (30–50°C) is due to package-related mechanical factors.[29] The temperature at which this occurs depends on the electronic technology of the specific component. Experts have stated that the ideal junction temperature is room temperature, 25°C.[30]

These data suggest that the dependency of component failure rate on temperature is not always exponential in nature. This means that over one temperature range, the failure rate is established by failure processes not strongly coupled to temperature and, over another temperature range, the failure rate is established by failure processes strongly coupled to temperature. In terms of the failure processes identified earlier, the low-temperature domain is where mechanical processes predominate, and the high-temperature domain is where chemical and metallurgical processes predominate. This is shown conceptually in Fig. 3. The transition zone between the two domains is not rigidly established since the bounds of each domain depend on factors such as the type of electronic components, component quality, and the nature of the experienced environmental stress profile. By the appropriate selection of electronic components and good quality and level of environmental control in the design process, it appears feasible to shift the transition zone such that significant reliability gains are possible.

As indicated above, there is evidence that suggests that cooling should be kept constant and controlled at the component level. The current practice of just controlling the inlet air temperature to an aircraft bay full of electronic equipment may not be acceptable in future aircraft. In the next section, technological considerations, currently under development, integrating microprocessor control and ECS concepts will show how to handle the localized stability requirements while providing improvements in aircraft performance with reduced maintenance requirements.

Background: Microprocessor/Environmental Control System

The ECS onboard existing aircraft is designed to provide the avionic cooling requirements defined at the inception of an aircraft development with an approximate growth margin of 25% in cooling requirements expected due to avionic growth after the aircraft is in service.[31-33] Even though the system as a whole performs as expected, the cooling of individual avionics boxes can be such that one could be undercooled and another overcooled. In order to achieve desired high levels of avionic reliability, junction temperatures should be reduced below current accepted values and their temperatures stabilized. This section presents the view that the ECS can be designed, using microprocessor advances, to integrate the ECS with the avionic system to 1) provide on-demand cooling to life-critical avionics even to the component level and 2) use test technology built into the ECS system to effect a gradual reduction in operational capability. In this process, failed components are bypassed as the system is reconfigured to allow normal operations of avionics, with the ECS in integrated concert with all other systems in the aircraft.

The capability to provide on-demand cooling, while including built-in test (BIT) with gradual degradation of avionic equipment, is now made possible with the tremendous advances in solid-state technology. Use of this technology to act as smart signal interfacers as well as signal selectors and/or decision makers is now very attractive for military subsystems. Tremendous advances have been demonstrated in the use of this technology in the B-1, F-15, F-16, and the advanced avionics systems for multimission application (AASMA).[34] The application of this technology to form an integrated system involving the ECS and avionics has been suggested.[33]

A background on ECS is now provided prior to discussion of how the ECS can be impacted by microprocessor technology. A simplified schematic of the conventional open-loop ECS is shown in Fig. 4. Bleed air is drawn from the jet engine of the aircraft. This hot bleed air is cooled by heat exchangers and then supplied to the air-conditioning pack, where it is compressed and expanded. Dust and water separators purify this air, which is passed into the crew cabin and avionics bay and then discharged overboard.

Currently, there is substantial interest within the Air Force in the closed environmental control system (CECS) concept shown in Fig. 4. In CESC, the air is not discharged overboard but is recirculated back into the air-conditioning pack. This concept has been evaluated since 1975 by the Vehicle Equipment Division of the Flight Dynamics Laboratory (FDL). A study has shown that the advantage of CECS over the conventional open-loop ECS is an approximate 6% reduction in takeoff gross weight (TOGW).[31] Air Force in-house studies have shown that a 10% improvement in range is possible if the 6% reduction in TOGW is replaced by additional fuel. The studies performed relate to a F-15 type of fighter configuration. One can easily project improvements in the reliability of avionics equipment simply by comparing the closed-loop system to that of the open loop.

Two benefits that are less costly to achieve in operation than in an open-loop system are immediately evident just in the process of closing the loop by recycling the conditioned air within the ECS. First, the open-loop ECS depends on the ambient atmospheric conditions since the environmental air is "dumped" into the atmosphere external to the aircraft. As a result, the avionics bay cooling can be subjected to large thermal transient conditions if the atmospheric conditions in particular pressure change during aircraft maneuvers (i.e., a fighter power dive from altitude to terrain-following conditions). Air recycling makes the ECS relatively independent of atmospheric conditions, significantly improving the possibility of maintaining a constant environment within the avionics bay and improving the possibility of the constant conditions within the avionics equipment at the component level. Second, the use of water/dust separators or any filtration systems to extract chemicals (i.e., fuel fumes or currently projected chemical/biological influences) must provide pure dry air based on only one pass through the open-loop system. As a result, all current Air Force aircraft employ the open-loop system and have major problems with moisture and dust relative to the avionics equipment.[6] On the other hand, the conditioned air in a closed-loop system is

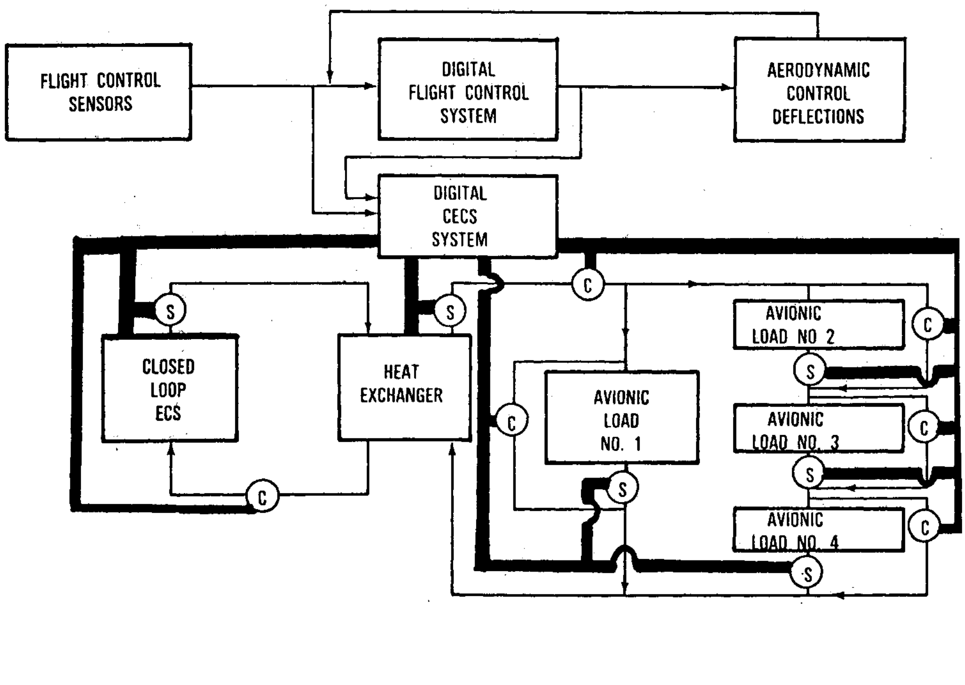

Fig. 5 Microprocessor-controlled environmental control system (CECS).

"cleansed" on each recycle of the reconditioned air, and a significant reduction in moisture, dust, and chemicals is achievable. In this type of system, it is less expensive to achieve cleansed air results than in the open-loop system. The impact of this on improved avionic equipment reliability is obvious.

In 1980, the CECS concept was shown to be attractive because it used less fuel than the open-loop ECS concept.[32] The study showed that approximately 6000 lb of fuel could be saved per flight mission for a penetrating manned bomber (PMB) if CECS was used instead of a conventional open-loop ECS. The penetrating mission considered consisted of a 5000-n.mi. range of 12-h duration flight for an approximately 400,000-lb. aircraft. The 6000-lb savings in fuel is even more significant when projected out for 200 aircraft operating for 400 flight h/yr between 1985 and 2005.

As a result, an industry survey was made in 1981 to assess whether the vapor cycle system was sufficiently advanced, technologically for transition into the advanced tactical fighter (AFT). The results of the survey suggested that a ground demonstration, with particular emphasis on vapor cycle maintenance and survivability, followed by an appropriate flight test, would suffice for proving the maintainability of this technology for use in the next-generation aircraft, as well as the 6% savings in TOGW or the 10% increase in range discussed earlier.

Consequently, the Environmental Control Branch within the Vehicle Equipment Division in FDL planned and instituted a program to demonstrate CECS on the ground in a laboratory environment. Emphasis was placed on demonstrating maintainability and reduced life cycle costs (LCC), with the use of an efficient digitally controlled CECS, as well as the 6% TOWG reduction or 10% increase in range discussed earlier. Further, evaluation of avionics LCC were a major part of the study. Thus, savings in fuel expenditures were to be demonstrated while providing a clean, low temperature, and constant temperature heat sink for the avionics. The goal, in terms of impact on improved avionic life, was to achieve a 20% reduction in avionic LCC.

Contract F33615-85-C-3401 with the Garrett Corp. of Canada Ltd. was initiated in 1985 to investigate all the concerns discussed earlier. The demonstration of the benefits includes the use of a ground-based facility that reflects a full-scale CECS cooling system with capabilities of cooling all F-15 heat loads through a real-time F-15 mission profile. It is of particular interest that the fuel system is simulated in real-time with real-sized tanks and a fuel simulant in the tanks so as to assess whether the total heat load generated as a result of the crew, avionics, and other requirements (i.e., hydraulic heat loads) can be totally absorbed by the fuel heat sink. The effort consists of three phases: 1) analysis and concept definition; 2) analyze, design, and build the test CECS; and 3) testing to demonstrate all CECS benefits projected over those achieved with the open-loop ECS. The results of the phase I study were completed and presented to industry and government personnel on November 18, 1986.[33] These results showed that all goals were achievable, particularly the 20% reduction in avionic LCC.

This program was launched with consideration to fuel costs and savings relative to fuel costs as projected in 1980.[32] Current projections using linear analysis and 1986 fuel costs simply suggest that the cost of fuel might be as low as $1.10/gal in 1992. This implies that the cost savings to the government in regard to the PMB study conducted in 1981 is $96 million. These fuel savings are significant even with the adjusted cost of fuel based on 1986 automobile costs at self-serve gasoline pumps. It is more important to current mission success that a 10% improvement in range is achievable for strategic military systems while maintaining avionic benefits. Currently, range considerations far outweigh considerations of fuel savings. It must be emphasized that closed-loop systems are projected to provide either a 6% decrease in TOGW, with accompanying improvements in avionic reliability, or a 10% increase in range, with accompanying improvements in avionic reliability.

Cooling on Demand—ECS

The technological considerations of both microprocessors and ECS are now integrated so as to illustrate a system that adapts, through the use of microprocessors, to mission requirements.

It is possible to control the coolant supply temperature of the CECS to low temperatures with smaller thermal-cyclic temperature fluctuations than currently exist with conventional controls and open-loop systems. This will be illustrated by a feasibility demonstration that has been ongoing[33] to assess the appropriate control laws to be used when incorporating microprocessor technology into the CECS concept. Because of the potential of dynamic interactions between various loops, an integrated (centralized) controller could give superior performance over individual controllers. Furthermore, gain scheduled optimal controllers (GSOC) could show better control capability than the best proportional plus integral (PI) controllers. At the same time, a distributed (decentralized) controller design may be superior, from the point of view of reliability and survivability. Therefore, the use of a microprocessor-based control system requires an assessment of the appropriate control laws to be used in incorporating microprocessor technology into the CECS. The target date for completion of the ICECS effort is the fiscal year (FY) 1988. Thus, industry as well as the Aeronautical Systems Division (ASD) will have direct access to unbiased conclusions regarding the use of CECS, as well as microprocessor controls.

Now, cooling-on-demand can be provided to the avionic suite through the use of microprocessor technology coupled with the use of a CECS to cool the avionics equipment appropriately. A simplified schematic of such a system is given in Fig. 5. The concept is seen as an integrated system with other subsystems in an aircraft. Thus, the program described in Ref. 33 is termed an integrated closed-loop environmental control system (ICECS). Now, Fig. 5 indicates how the microprocessor control system might be integrated with only the flight controls, one of many systems in an aircraft, to provide on-demand cooling to the avionic pack. The idea is to maintain a constant temperature for those parts of the avionic package (i.e., the parts are represented as either avionic load 1, 2, 3, or 4) that require optimum cooling capacity for the avionic systems for the mission profile at hand. The sensor (S) and controllers (C) are directed by the digital CECS to control the cooling provided by the CECS and to cool the appropriate avionic heat load controlled by an appropriately located temperature sensor. In Fig. 5, the dark heavy lines connecting sensors and controllers reflect the digital control network, while the lighter lines connecting the avionic loads reflect the ECS and its ducting. The sensor is installed at life-critical locations projected by a mean-time between failure (MTBF) analysis at both avionics line replaceable unit (LRU) level, as well as at the component level of either the avionics system or ECS. Avionics not in use may not need momentary cooling, and further fuel savings might be achieved than already indicated.

In this example, a pilot could process appropriate buttons in the digital flight control system in readiness to go into a terrain-following mode which may require full use of electronic counter measures (ECM). This signal might be used to activate appropriate control laws of the digital CECS controller, activating appropriate channels of the environmental cooling system. The controllers could then direct the appropriate cooling to the proper avionic components so as to keep their temperatures constant. Cooling could then be provided *a priori* to prevent temporary overheating of the components.

This example reflects integration with the flight control system. There are databus systems reflecting each of the

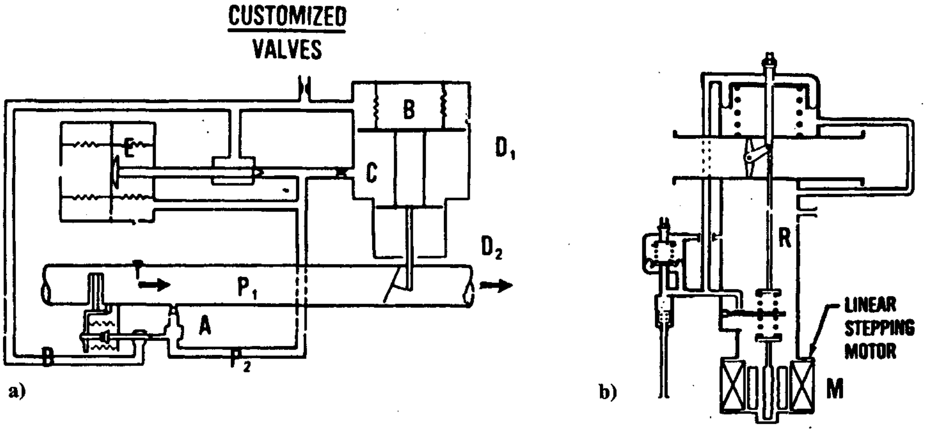

Fig. 6 Impact of microprocessor control on valves: a) typical electropneumatic controller (simplified schematic) and b) the "all-purpose" valve concept.

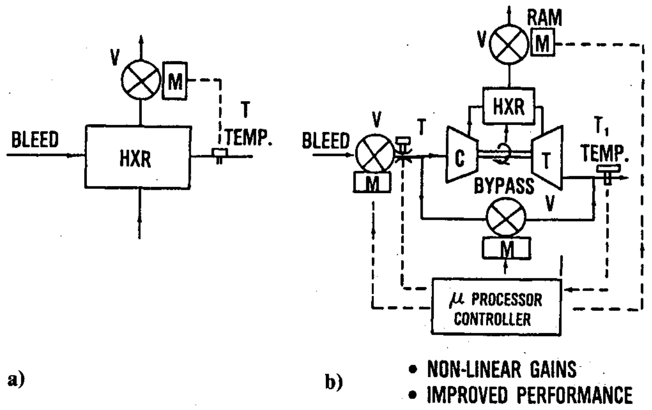

Fig. 7 ECS/CES controller—past, present, and future: a) single-input/single output and b) multi-input/multi-output.

other major and minor subsystems in an aircraft which could be used to extract relevant information for use by the CECS to provide the appropriate cooling to the avionics. An example of systems that make databus signals available to the ECS-microprocessor control system are the engine electronic control system (EECS), digital engine control system (DECS), and all digital information displayed to the pilot, as well as all flight control/instruments actuated by the pilot.

Reliability/Adaptability

Many valves in current ECS, whether pneumatic or electropneumatic, are complex, heavy, inflexible, costly, and often the least reliable parts of the system. The complexity of such valves is illustrated in Fig. 6a. This design consists of a temperature sensor, pressure valves, diaphragms, and springs. For example, pressure valve A acts on the differential between pressure P_1 and P_2. If $P_1 > P_2$, pressure valve A opens and flow traverses through channel C providing pressure on D1 forcing the butterfly valve to close. On the other hand, if temperature T exceeds a certain value, flow traverses through channel B and provides pressure on side B of the diaphragm D1 forcing the butterfly valve open. System E provides damping and further control of the overall system. Further explanations are required to understand fully how all these parts work in concert. Suffice it to say that the explanation provided so far illustrates the complex nature of these valves. Once the design is fixed, it is inflexible. Many different valves are needed in an ECS system leading to high developmental costs.

These valves are hard to analyze. Dust and other impurities, such as ice from moisture in the servo air, modify the frictional and stiction characteristics. Long periods of inactivity in an impure environment can result in erratic operation. Thus, there is the potential for improved reliability through simplification.

The use of microprocessors permits simplifications in valve design. With the control logic in the microprocessor, the valve is required merely to position the butterfly valve in response to an electrical signal. The dynamic requirements (slew rate, bandwidth, etc.) are not stringent. Thus, it should be possible to derive a relatively simple design which, with the appropriate sensor, could act as a temperature, pressure, or flow controller. Such an "all-purpose" valve is shown in Fig. 6b. Stepping motor M moves rod R up and down, and the signal is amplified to move the butterfly valve V. The reason for the all-purpose designation is that the control logic can be changed simply by modifying the programming in the microprocessor to realize significant savings in development costs. Additional comments regarding adaptability and its impact on avionic reliability follow the discussion regarding ECS controllers.

The manner in which the microprocessor can significantly improve the conventional open-loop ECS or CECS is illustrated in Fig. 7: the single-input/single-output controller in Fig. 7a and multi-input/multi-output controller in Fig. 7b.

The single-input/single-output controller shown controls the temperature of the air issuing from the heat exchanger HXR. Even though such a system is outdated relative to current aircraft, it does serve as an example for the point to be made here. Hot bleed air is taken from the jet engine and cooled in the heat exchanger. If temperature sensor T indicates that the temperature of the air is too hot to be passed into the avionics, motor M opens valve V to increase the flow of ram air into the heat exchanger. This action increases the cooling provided to the bleed air, and the temperature T then decreases. If T becomes too low, valve V is closed, reducing ram airflow. Of importance here is that no provisions are made to minimize the bleed-air usage to minimize the use of fuel. For example, we saw earlier that bleed-air usage penalizes aircraft performance through impact on TOGW. This system does not minimize ram air usage. The use of ram air penalizes the aircraft performance, that is, reduces range through an increase in aerodynamic drag.

The multi-input/multi-output controller shown in Fig. 7b is a system far superior to the one discussed earlier. Bleed air is again taken from the jet engine and the temperature monitored by the control system. The air is compressed in compressor C, cooled through heat exchanger HXR, and then expanded through turbine T to result in temperature $T1$. Ram air is again used to cool the air as it passes through HXR and a bypass valve V is included. All the flows, temperatures, and pressures are directed by the control unit. This permits the control of bleed-to-ram air to meet crew compartment and avionics requirements (heating, cooling and ventilation) at minimum penalty to the airplane. Now, multi-input/multi-output control can be achieved through the use of an analog controller. These systems, however, are currently constant-gain systems or have simplified representations for nonlinear gains.

There are many off-design operating conditions that an ECS/CECS (open or closed) operates at during mission profile. The large memory capability of the microprocessors permits total monitoring of all necessary flow, temperature, and pressure conditions and the use of nonlinear gains. This permits optimum operation for all design conditions that may be encountered during flight. In addition, the control laws could be designed so as to maintain temperature *T*1 as constant as possible in the avionics bay, in an LRU, and even at the avionic component level. Sufficient memory exists in state-of-the-art microprocessor(s) to do this.

These discussions regarding improved valve reliability and ECS efficiency through integration of microprocessor control are good from an aircraft reliability, developmental cost, and overall vehicle savings point of view. Of note is that the introduction of microprocessor technology not only makes the ECS more reliable but also adaptable. For example, the avionic suite installed in the first aircraft off the assembly line undergoes many changes and improvements and, in fact, grows during the lifetime of the aircraft. For the future, it is therefore essential that the ECS be adaptable so that its on-demand cooling capabilities can be modified/tailored to address changes in LRU's even down to the component level. This can be easily done with an ECS controlled externally with microprocessed control laws and made adaptable internally through all-purpose valves as shown in Fig. 6 and with microprocessed control of the sensors S and controllers C in Fig. 5. New on-demand cooling requirements are simply achieved by recoding the software of the appropriate microprocessed control loops.

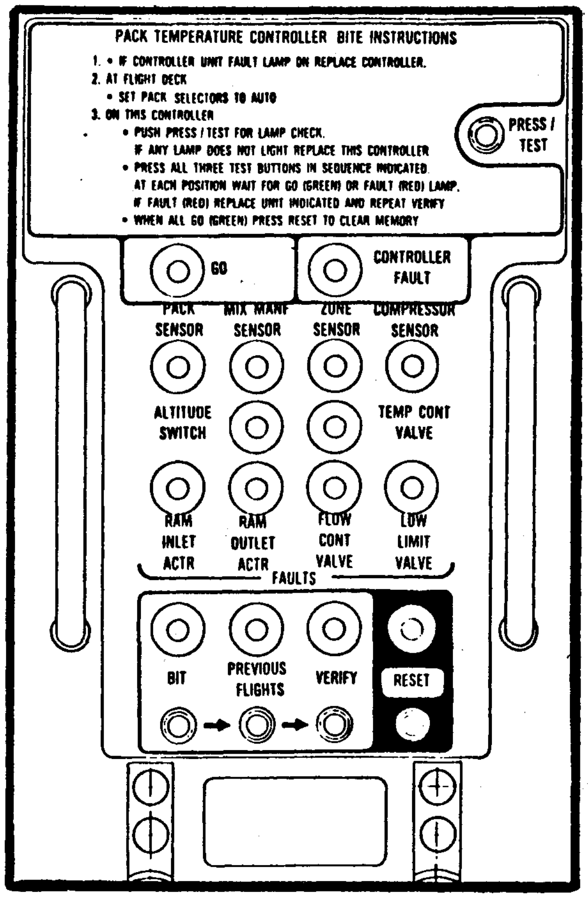

Fig. 8 ECS fault isolation (Boeing 757/767).

Gradual Degradation of Avionics

Fault isolation and tolerance in the development of aircraft systems is one of the most important considerations since it directly impacts the reliability, survivability, vulnerability, and maintainability of the system, as well as the flight safety and probability of mission success. Fault tolerance starts with the mechanism by which a fault condition is detected in the overall aircraft system, including the avionics. The fault is isolated in a specific unit, and some action is initiated either by replacement of the defective unit during ground maintenance or by a microprocessed reconfiguration of life-vital systems during flight. The latter permits operation without the defective unit signals but at a reduced gradually degraded capability.

Fault isolation and tolerance, to be effective, must consider all elements of the system: computers, software, interfaces, data communications, sensors, hardware, avionics, and power distribution. Means must be provided to allow the condition of each element to be monitored by self-test, online monitoring, voting, or a variety of other tests. The logic required to isolate a particular failure and to adapt the system to continue near normal operation or a gradual degraded state, can be achieved through a combination of hardware and software techniques. The particular mechanism chosen is highly dependent on the complexity vs the verification and validation of software performing this function.

The Boeing 757/767 has the microprocessor fault isolation capability shown in Fig. 8.[34] This technology was developed by the Garrett Manufacturing Corporation of Canada Ltd., under contract to Boeing. This unit is a microprocessor "brain," which keeps track of the "health" of the 757/767 Boeing ECS. Appropriate elements of the ECS are checked continuously during each flight. The health histories of these components are stored in the unit for 10 flights. The data records are updated so that only the latest previous 10 flight records are retained in the microprocessor memory of the unit.

In the future, maintenance crews will be able to evaluate the health status of the aircraft and avionics during inspection through units such as this, or advanced "health monitoring" capabilities, faults in the total avionics system and ECS can be uncovered readily and replacements made. The flight history stored in the fault isolation system can then be used as a diagnostic for uncovering the reasons for the failure.

In future operations, faults during flight can be tracked, failed components/avionics can be bypassed, needed parts identified, and this knowledge transmitted automatically to the home base. This could significantly reduce maintenance time and improve Air Force effectiveness if all needed replacements are identified and brought to the affected aircraft immediately upon landing.

Conclusions

One way to achieve higher levels of avionics reliability demanded from future systems is to reduce the junction temperatures and amount of thermal cycling experienced in usage. This can be accomplished by the use of an ECS, which is closed-looped, microprocessor-controlled, and has gradual degradation. While providing the needed improved avionics thermal environment, this system provides major improvements in the basic performance envelope of the host aircraft. Studies have shown this to be as much as a 6% decrease in TOGW or a 10% increase in range. Likewise, the closed-loop ECS provides the ability to protect against contamination, such as dust, chemical/biological agents, excess humidity, with fewer penalties than the open-loop system.

In addition to the avionics reliability and host aircraft performance envelope improvements, this ECS technology provides opportunities to reduce the amount of electronic circuitry dedicated to overhead functions, such as gradual avionics degradation and bit checking, and to use this circuitry for performance gains. Avionics and ECS maintenance costs will be reduced because deferred maintenance allows use of reduced skill levels of maintenance personnel involved. These benefits are achieved because of the integrated ECS and avionics built-in test, gradual degradation capabilities of both the avionics and ECS systems, and more precise identification of failure locations within either the avionic system or ECS.

References

[1]Augustine, N., "Augustine's Laws & Solution 9," *Military Science and Technology,* Vol. 3, June 1982, pp. 14–17.

[2]"United States Air Force Reliability and Maintainability (R&M 2000) Action Plan," Feb. 1985.

[3]Haplin, J.C., "AVIP Air Force Thrust for Reliability," Proceedings of the Institute of Environmental Sciences 31st Annual Technical Meeting, May 1985, pp. 206–218.

[4]Burke, H. and Copolla, A., "Unified Life Cycle Engineering," *Proceedings of the 1987 Annual Reliability and Maintainability Symposium,* IEEE, Philadelphia, PA, Jan. 27–29, 1987.

[5]Burkhard, A.H., "Deterministic Reliability Prediction," *Proceedings of the 1987 Annual Reliability and Maintainability Symposium,* IEEE, Philadelphia, PA, Jan. 1987.

[6]Dantowitz, A., Hirschberger, G., and Pravidlo, D., "Analysis of Aeronautical Equipment Environmental Failures," AFFDL-TR-71-32, May 1971.

[7]Burkhard, A.H., Earls, D., and Prather, D., "Environmental Effects on Reliability and Maintainability of Air Force Avionics Equipment," AFFDL-TR-74-113, Aug. 1974.

[8]Swett, B.H., "Avionics Reliability, Part 1 and 2," *Journal of Environmental Sciences,* Vol. 18, Sept./Oct. 1975, Nov./Dec. 1975.

[9]Edward, E., Flint, S., and Steinkirchner, J., "Avionics Environmental Factors for MIL-HDBK-217," RADC-TR-81-374, Jan. 1982.

[10]Anderson, J., "Environmental Burn-In Effectiveness," AFWAL-TR-80-3086, Aug. 1980.

[11]"Institute of Environmental Sciences," *National Conference and Workshop Environmental Stress Screening of Electronic Hardware Proceedings,* San Jose, CA, Institute of Environmental Sciences, Feb. 28–March 2, 1979.

[12]Howard, R., "Packaging Reliability—How to Define and Measure It," *IEEE Transactions on Components, Hybrids, and Manufacturing Technology,* Vol. CHMT-5, Dec. 1982, pp. 454–462.

[13]Burkhard, A.H., "Evolution of Emerging Environmental Testing and Evaluation Techniques," *Journal of Environmental Sciences,* Vol. 29, No. 2, pp. 38–42, 1986.

[14]Stojadinovic, N.D., "Failure Physics of Integrated Circuits—A Review," *Microelectronic Reliability,* Vol. 23, No. 4, 1983, pp. 609–707.

[15]Capitano, J. and Feinstein, J., "Environmental Stress Screen (ESS) Demonstrates Its Value in the Field," *Proceedings of the 1986 Annual Reliability and Maintainability Symposium,* Las Vegas, Jan. 1986, pp. 31–35.

[16]Kallis, J.M. et al., "Latent Defect Life Model and Data," AFWAL-TR-86-3012, March 1986.

[17]Kern, G., "Operational Influences on Reliability," RADC-TR-76-366, Dec. 1976.

[18]Burkhard, A.H., "CERT Evaluation Program—Final Report," AFWAL-TR-82-3085, Dec. 1982.

[19]Dicken, H., "What Can Happen to an IC in Your System," *Evaluation Engineering,* Nov./Dec. 1978, pp. 46–47.

[20]Doyle, E.A., "How Parts Fail," *IEEE Spectrum,* Oct. 1981, pp. 36–43.

[21]Doyle, E.A., "How Parts Fail," *IEEE Spectrum,* Oct. 1974, pp. 36–44.

[22]Swanson, T.R., "How Reliable Are Military Components?" *Electronic Products,* Oct. 15, 1986, pp. 49–55.

[23]Turner, T., "Forecasting IC Failures," *Machine Design,* Nov. 26, 1981, pp. 85–88.

[24]Stitch, M., Johnson, G., Kirk, B., and Brover, J., "Microcircuit Accelerated Testing Using High Temperature Operating Tests," *IEEE Transactions on Reliability,* Vol. R-24, Oct. 1975, pp. 238–250.

[25]Nelson, W., "Graphical Analysis of Accelerated Life Test Data with a Mix of Failure Modes," *IEEE Transactions on Reliability,* Vol. R-24, Oct. 1975, pp. 230–237.

[26]Mackintosh, I.M., "The Reliability of Integrated Circuits," Microelectronics and Reliability," Vol. 5, 1966, pp. 27–37.

[27]Lahtonen, D., "Microcircuit Reliability Assessment Through Accelerated Testing," *Electronic Packaging and Production,* July 1977, pp. 288–293.

[28]Blanks, H.S., "The Temperature Dependence of Component Failure Rate," *Microelectronics and Reliability,* Vol. 19, 1980, pp. 297–307.

[29]Palo, S., "Reliability Prediction of Microcircuit," *Microelectronic Reliability,* Vol. 23, No. 2, 1983, pp. 283–294.

[30]Arsenault, J., and Roberts, J. (eds.), "Reliability and Maintainability of Electronic Systems," *Computer Science Press,* Potamac, MD, 1980.

[31]Midolo, L.L., "The Use of Positive Displacement Air Cycle Machine in a Closed-Loop Environment Control System," *ASME 9th Intersociety Conference on Environmental Systems,* July 1979.

[32]Tsujikawa, G.S. and Rajpaul, V.K., "Closed-Loop Environmental Control Systems (CECS) Study," Vol. 1, AFWAL-TR-80-3149, Jan. 1981.

[33]"Integrated Closed Loop Environmental Control System," *Systems Design Review,* Nov. 18, 1986.

[34]Kurylowich, G. and Lloyd, A.J.P., "Aircraft Vehicle Equipment Improvements Via Microprocessors," SAE Paper 82 0868, July 1982.