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### Abstract

The purpose of this paper is to describe the importance of thermal management in electronic equipment design and illustrate how Computer Aided Design (CAD) technology may be used to improve thermal management programs for electronic equipment. The Aeronautical Systems Division is establishing a program called the Electronic Equipment Thermal Management (EETM) Program which is a portion of the recently introduced aircraft system level Thermal Management Control (TMC) Program. The system level TMC program establishes the process by which we thermally integrate the airframe Environmental Control System (ECS) and the electronic equipment in such a manner as to optimize system reliability by minimizing system Life Cycle Cost (LCC). Minimizing LCC is accomplished by allocating available cooling capacity to individual equipments based on the benefits that will be derived. TMC was introduced to take advantage of existing technologies being applied through the latest CAD techniques and the known relationship between electronic part operating temperatures and the resulting part reliabilities. When this relationship is fully utilized, the thermal design and packaging of the equipment can be optimized for improved equipment reliability at lower operating temperatures. In addition, reliability improvement techniques such as selective derating, part selection, etc., can be concentrated on those parts that have been identified by the thermal analysis to be drivers in equipment unreliability. Concentration of effort is placed at the part level. After all, "systems do not fail, parts do!"

### Introduction

As we move toward the next generation of aircraft such as the Advanced Tactical Fighter (ATF) we are quickly realizing that some of the problems associated with cooling avionics equipment in the past have been magnified. The introduction and continued drive toward higher functional densities in microelectronic devices coupled with higher thermal densities has complicated the processes of removing heat from the individual electronic parts to the ultimate heat sink. At the same time we are becoming increasingly more aware of the need for product assurance at both the system and subsystem levels which is directly related to readiness and force multiplication through higher sortie rates. On the other side of the coin, the difficulty and penalties associated with providing the required cooling for both the crew and the avionics equipment are increasing drastically and there are now even concerns about the availability of potential heat sinks in high performance aircraft. Increased emphasis must be placed on improved equipment reliability, availability, supportability and sustainability if we are to get the job done. CAD can integrate the tools for accomplishing this important task.

In order to carry out the overall system level

TMC program as indicated in Figure 1, certain verified details about the design of the electronic equipment are required. The basic required information is in the form of an analysis that establishes the relationship between changes in cooling provisions for the equipment and its impact on the predicted failure rate and projected LCC of the equipment. To accomplish this, one must conduct good thermal/reliability analyses on the equipment, validate the final thermal model and run numerous conditions where cooling capacity and/or ambient temperature are varied and the reliability and LCC analyses are calculated based on the resulting part junction temperatures.

It is not intended that this analysis be used to predict equipment failure rate as much as it is to provide a tool to evaluate the predicted change in failure rate and LCC as one varies the amount of cooling for the equipment. Temperature is, of course, only one of many contributors to failure rate. However, it is a major contributor and one that has been verified by test. Once these relationships are established, one can make a technical (rather than general rule-of-thumb or "good design practice") decision on the best level of cooling that should be provided.

### Background

Cooling considerations and provisions play an important role in the design and operational performance of electronic equipment. There are two primary reasons for supplying cooling to equipment and equipment bays. The first is to provide at least a minimum amount of cooling so that the internal equipment part junction temperatures are kept cool enough to ensure that they are operating within their performance limits. The second is to provide additional cooling beyond this minimum level in an attempt to achieve some additional life for the equipment. This premise is based on the fact that the failure rates of many electronic parts, more or less depends on the operating temperature of the device and increases approximately exponentially with increasing temperature. Because the amount of cooling capacity required to achieve the desired additional life exceeds that required to barely meet initial performance requirements, it is the reliability requirements that should dictate the equipment cooling requirements. However, this is not the case reflected in the present situation. Seldom, if ever, does anyone know the relationship between cooling and the equipment reliability. Cooling capacity is normally allocated based on the electrical load of the equipment, not the reliability requirements.

It is interesting to note that the amount of cooling allocated to cool avionics is not determined by the equipment designer based on need, but by the ECS engineers based on the equipment heat load (thermal dissipation). This is unfortunate since only the equipment designer who has the ability of knowing what the part operating temperatures are and

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# THERMAL MANAGEMENT CONTROL PROGRAM

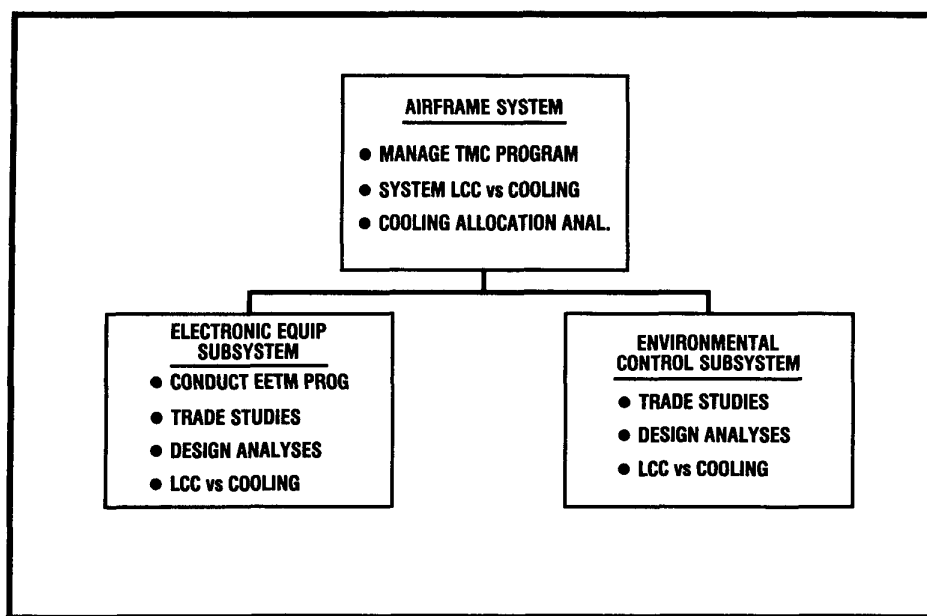


FIGURE 1

what impact these temperatures will have on the equipment reliability.

The EETM concept places emphasis on more up-front involvement at the sub-system level during the equipment design process in order to attain a better and more cost-effective product in the field. It is well recognized within the Department of Defense that increased emphasis must be placed on equipment reliability, availability, supportability and sustainability. An area that stands out as having one of the highest potential reliability improvement benefits and dollar savings potentials is the avionics subsystems. An electronic circuit cannot be any more reliable (logistically) than the least reliable part within the circuit. A failure in a redundant circuit even though improving mission reliability, still needs to be fixed. Each and every part plays a role in the overall reliability of the equipment and each part should be treated individually in early design analyses to determine its contribution to the overall equipment failure rate. The failure rate problems which plague electronic equipments are real and the potential savings associated with identifying and minimizing the influence of the major failure rate contributors can be tremendous. However, we need to understand the cause of the failure before we can attempt to fix it. This means we need to develop the tools to provide this capability. CAD is the technique that can be used to incorporate these required design tools into the early design process.

## The EETM Philosophy

There are numerous reliability enhancement options that can be employed in the design of electronic equipments. Some of these options can be

agreed to and applied prior to starting the design process, such as; establishing part derating criteria, screening criteria and quality requirements, etc. Other options can be included in the actual circuit design and layouts such as controlling part power dissipations, locating parts on circuit boards, minimizing part operating temperatures, etc. And still other options can be employed after the equipment design is finalized such as conducting qualification tests, reliability tests, burn-in tests, test-analyze-fix testing and other reliability growth techniques.

The EETM program initially concentrates on the initial design of the equipment although it remains in force throughout the testing phases. The main goal is to optimize the reliability of the equipment by minimizing its LCC. This is accomplished during the initial design by applying the following philosophy:

- o Minimize the thermal resistance between parts and the equipment heat sink as long as it can be justified based on LCC improvement.
- o Maximize reliability rather than minimizing part temperatures as long as it can be justified based on LCC improvement.
- o Rank parts based on failure rate so that further derating, component selections, etc. can be applied on a selected basis to the reliability drivers to improve reliability at the minimum cost. Note that general derating criteria would still be applied as it is today.

As an illustration of the above three points, see Figure 2. Consider a simple circuit board design

## CURRENT THERMAL PRACTICE

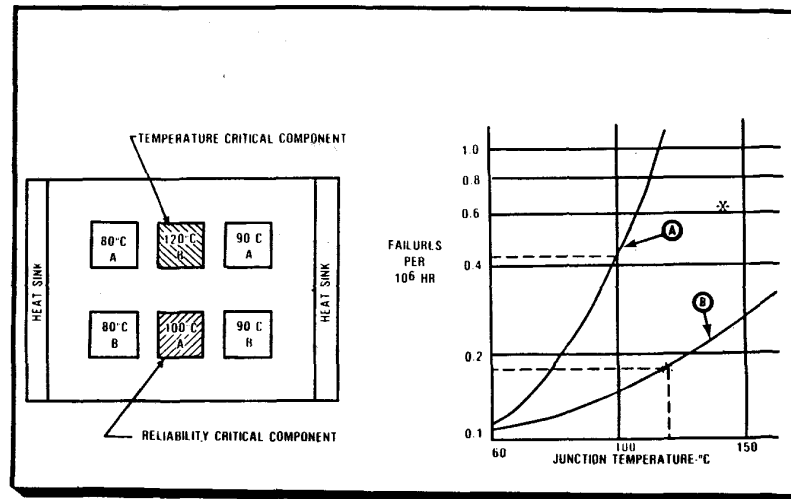


FIGURE 2

with heat sinks on either side. Suppose that mounted on the circuit board are three identical part "A's" and three identical part "B's". Suppose that each part has failure rate versus junction temperature relationship as indicated.

It is assumed that the thermal resistance between the heat sink and the parts was minimized during the initial layout and circuit board design. Therefore, the initial efforts to optimize the initial cooling concept is not discussed in this illustration. The junction temperatures are assumed to be the results of operating at specific operating conditions.

For this initial baseline condition then, and referring to Figure 3, CASE I, failure rate ( $\lambda$  BASE) is:

$$\begin{aligned}\lambda \text{ BASE} &= \lambda A(80^\circ) + \lambda B(120^\circ) + \lambda A(90^\circ) + \\ &\quad \lambda B(80^\circ) + \lambda A(100^\circ) + \lambda B(90^\circ) \\ &= 0.196 + 0.19 + 0.245 + 0.13 + 0.43 + 0.14 \\ &= 1.331 \quad (1)\end{aligned}$$

If we attempt to apply "good design practice" and limit these parts to the 110°C maximum junction temperature limit, we quickly see that part "B" at 120°C exceeds the design limits and corrective action is required. If part "B" at 120°C is switched with part "A" at 80°C (see Figure 3), and if the resulting operating temperatures both go to 100°C (see Figure 4), we have accomplished our desire to meet the reliability goals of not exceeding the 110°C limit. However, if we re-calculate the new "improved" reliability we find that the failure rate has increased by 15% rather than decreasing. This emphasizes the problem of minimizing temperature as a design criteria rather than maximizing reliability.

Going back to our baseline configuration, Figure 3 and applying our new criteria, i.e., maximizing reliability or minimizing failure rate, we see that part "A" at 100°C is the reliability driver and is the area we should be concentrating on. As indicated in Figure 5, if we switch part "B" at 80°C (lowest failure rate) with "A" at 100°C (highest failure

rate) we end up with a decrease in the base failure rate of 13% for the whole circuit board. Also from Figure 5 it is easy to see that there are two "A" parts at 90°C that are now the reliability drivers. Since apparently neither can be moved closer to the heat sink to minimize the part to heat sink thermal resistance, other alternatives can be considered. Potentially better thermal conductors could be used to further reduce the thermal resistance. If we conduct an analysis and determine that the cost of the conductors exceeds the LCC benefits obtained from lowering the part temperatures any further, it is possible that "selective derating" could be applied to just these two parts. It is assumed that the parts could be further derated so now they are part "A" in lieu of the original "A". A 50% improvement in failure rate for "A" would result in a final 21% improvement in the circuit board reliability above the baseline. (Figure 6).

This illustration, although very simplified, provides an overall general approach to the EETM philosophy. Depending on the example and situation, the results can be more or less dramatic. Although not discussed, the evaluation of the different thermal design techniques for lowering the resistance between the part and heat sink can lead to even more impressive failure rate reductions. Depending on the parts and operating conditions, a microelectronic part reliability will typically decrease by approximately 10% for every 2°C temperature rise.

### Application Of Computer Aided Design (CAD) Programs

The tedious process of conducting a detailed thermal analysis to determine the operating junction temperatures of each part was considered to be technically overwhelming and costly in time and money in the past, and therefore, was only used in the few cases where the thermal impact on reliability was suspected to be a potential problem. The trial and error method of the test-analyze-fix approach to design was the only practical design approach that could be employed. With the advent of CAD techniques much of the tedious process is eliminated and the realistic analytical approaches and capabilities have

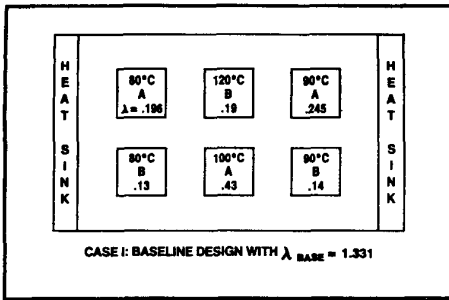


FIGURE 3

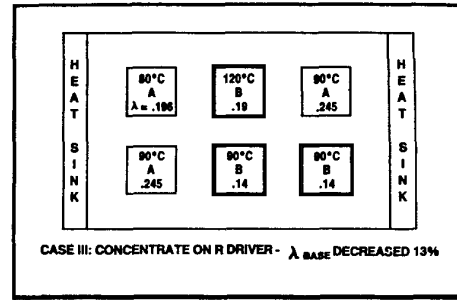


FIGURE 5

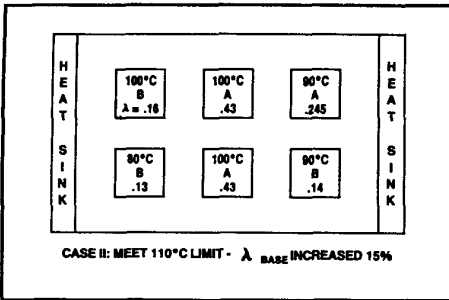


FIGURE 4

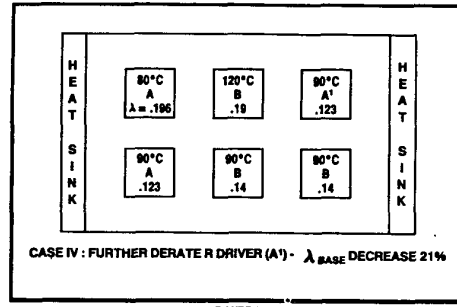


FIGURE 6

mushroomed.

There are many individual heat transfer thermal analysis programs available on the open market. Perhaps one of the best sources for obtaining these programs is the Computer Software Management and Information Center (COSMIC). COSMIC, located at the University, Athens Georgia, was established by a grant from the National Aeronautics and Space Administration (NASA) to function as a collection, evaluation and dissemination center for computer programs developed through federal agencies.

Extensive development has gone into producing the large selection of thermal analysis programs using both nodal analyses employing finite-difference numerical methods, as well as finite element analyses. Many of the individual airframe prime contractors and subcontractors have developed in-house unique programs for conducting required analyses on their particular equipment. However, many programs are commercially available and can be tailored to the design and analysis of electronic equipment.

The introduction of CAD technology has made it possible to integrate circuit design engineering with the circuit board packaging and the reliability engineering to attempt to optimize the packaging of the equipment. The new initiative by the Air Force Flight Dynamics Laboratory to develop the Integrated Thermal Avionics Design (ITAD) is one such attempt. This initiative is one that is intended to provide industry with the tools necessary to carry out the objectives of the EETM programs. It can and should be tailored to the individual effort. Many companies may either want to add to or substitute company CAD codes to ITAD. Individual companies are attempting to establish their own CAD programs tailored to their particular needs.

#### The Electronic Equipment Thermal Management (EETM) Program

It is significant to recognize that the proposed approach is not just a "nice-to-do" analysis but one that if not developed and applied could very well

lead to a major thermal problem. The time is here where those companies not standing up to the challenges of the computer age will be unable to produce the required product, and therefore, will no longer be able to compete in the market place. The high thermal densities for new part technologies such as the Very Large Scale Integration (VLSI) and Very High Speed Integrated Circuit (VHSIC) devices are such that thermal considerations are critical. The thermal design will have to become an integral part of the design process and can no longer be left to chance. The problems which can be identified from the test-analyze-fix approach will more than likely not be able to be corrected with simple quick fixes but may require major modifications to the total cooling concept involving a major redesign.

The technology and capability currently exist to conduct thermal analyses down to the part junction temperature level and then to convert these temperatures to predicted failure rates for those parts. Such a process would identify to the designer which parts have the most influence on the overall failure rate of the equipment and which are the parts where application of reliability improvement techniques could be the most beneficial and cost effective. However, many electronic equipment manufacturers do not take full advantage of the reliability information that is available for designing their equipment. This information is usually applied using an "across-the-board" approach rather than identifying and directing the effort to those electronic parts most influencing the equipments reliability. "Across-the-board" approach is used here to describe the application of general derating criteria to all parts in a particular equipment in order to initially improve the reliability of that equipment. Consequently, with the "across-the-board" approach the cost of attempting to design in reliability is much higher than if they were applied to just the parts which most influenced the overall equipment reliability. Of course, a ranking of parts as to their contribution to the overall equipment failure rate would be required. Specifying minimum general

derating guides, implementing general part screening requirements, specifying the across-the-board use of high reliability parts, and establishing maximum allowable junction temperature limits are all examples of techniques applied to all parts, whether they have significant impact on overall equipment reliability or not. This is not to imply that this approach is not effective or acceptable because, as we all know, its use has shown to be very effective in improving the reliability of our equipment and should continue to be used. The disadvantage of this approach is that parts that exhibit the highest reliabilities are treated the same as those that exhibit the lowest reliabilities rather than concentrating on just those with the low reliabilities. If we identified which parts were driving the equipment reliability, a concentrated effort to further derate these parts, or consider the use of higher reliability parts would directly result in an improvement in equipment reliability at a minimum investment cost. Using existing techniques in combination with the EETM program will provide a basis of evaluating the cost benefits of using the across-the-board techniques and to what level they should be applied.

#### MIL-STD-785B EETM Tasks

The tasks which define the EETM program are currently in the process of being coordinated for incorporation into MIL-STD-785B, Notice 1. Each task is intended to establish a set of objectives to be accomplished at specific stages in the design process. These tasks can apply to all electronic equipments, no matter how they are cooled or where they are installed.

The new MIL-STD-785B, Task 106, "Thermal Management Control (TMC) Program Plan" establishes the overall TMC program at the system level and defines the required tasks that must be accomplished by the system prime or integration contractor. At the subsystem level, there are three distinct tasks that are levied on the equipment manufacturer but are still under the cognizance of the system prime or integration contractor. First, Task 210, "Thermal/Reliability Design Trade Studies" addresses the required trade studies that need to be conducted as early in the design process as possible. Emphasis is on looking at different thermal design concepts and selecting the one which results in the least LCC. Emphasis is placed on maximizing reliability rather than minimizing temperatures. Task 211, "Thermal/Reliability Design Analysis" is basically an expansion of the analyses conducted under Task 210 with emphasis on analyses down to the part levels and changing part temperatures to failure rates based on MIL-HDBK-217 type data. Task 305, "Thermal Design Validation Test (TDVT) Program" includes those tests that should be conducted to validate the thermal/reliability models established under Task 211. In all cases, CAD techniques should be used to the maximum extent to simplify the overall process and enable the analysis to influence the initial design of the equipment.

#### Summary

The EETM program is based on the premise that designing reliability and integrity into a product will result in lower LCC and improved readiness for the total weapon system. Both of these are major goals in today's weapon system acquisitions.

Too much of the overall reliability emphasis has been placed on verification and not enough on up-front design efforts. This is not to say that less effort should be placed on verification, because this

is definitely not the case. The message is that drastic improvements can be made in the way we do business and how we apply reliability technology to up-front electronic equipment design. The introduction of CAD technology makes it possible to efficiently and effectively conduct thermal/reliability analyses and to optimize the thermal design of electronic equipment and thereby produce a much more reliable and cost effective product. Additional efforts need to be concentrated in this area and the proposed EETM program is an important step in that direction.

#### Conclusions

The technology exist today to put product assurance in its rightful place in the acquisition process. The Electronic Equipment Thermal Management Program applies this technology directly to designing reliability into today's electronic equipments. To meet the new challenges, we (both government and industry) must be willing to do the necessary up-front design effort. Inspecting or testing in quality cannot be used as a substitute for good initial design. Redesign to eliminate design deficiencies or inadequacies are normally less effective and more costly than designing out the problem in the initial design. The reliability problems which plague electronic equipment are real and the potential LCC savings associated with applying new as well as existing computer aided design techniques can be truly significant. Actions and techniques developed today will help us work around the technological problems of the next generation of microelectronics facing us tomorrow.

An attitude of cooperation is required to effectively utilize and share the wealth of information available in the thermal management area. Cooperation will improve the products we produce which in turn will benefit us all. This program requires continued support and inputs from industry to truly succeed and your continued interest is solicited.

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#### Biographies

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Mr. Berger is currently Chief of the Environmental Equipment Branch within the Directorate of Flight Systems Engineering which is responsible for aircraft and missile air conditioning, pressurization and bleed air systems. In addition, the branch within the past two years has accepted the responsibility

for the thermal design of electronic equipment. This latter responsibility has resulted in an initiative to establish the Thermal Management Control (TMC) Program currently defined in MIL-STD-785B. The Electronic Equipment Thermal Management Program is a subset of the TMC Program.

Mr. Berger is a 1967 graduate of Ohio University (BSME), a 1972 graduate of the University of Dayton (MSEM) and a 1977 graduate of the Air War College Seminar Program. He is currently serving as Honors and Awards Chairman of the Dayton-Cincinnati Section of AIAA and is a registered Professional Engineer in the State of Ohio.

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Mr. Jenkins is currently a project engineer with the Environmental Equipment Branch. Presently he is the lead engineer for the Electronic Equipment Thermal Management Program.

Mr. Jenkins is a 1978 graduate of University of South Carolina where he received a bachelor of science degree in mechanical engineering (thermal systems). He is currently a member of American Society of Mechanical Engineers.