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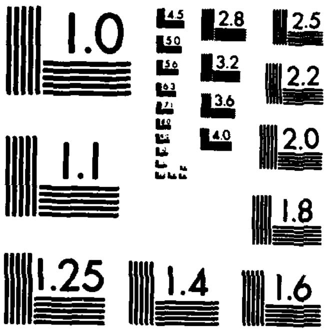

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AD-A134 350

An Assessment of the Benefits of Using Infrared Thermography to Measure the Temperature of Discrete Electronic Components Operating in a Vacuum

a report to the

Naval Research Laboratory
Washington, D.C. 20375

under

Contract No. N00014-81-C-2048
Data Item A003

prepared by

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1.0 PURPOSE AND SCOPE

The purpose of this memorandum is to document the results of an assessment of the potential use of infrared (IR) thermography to measure the temperature of discrete electronic components operating in a vacuum. The assessment specifically considered the cesium beam frequency standards (modules) being developed by Frequency Electronics, Inc. (FEI), Frequency Time Systems, Inc. (FTS) and Kernco, Inc., for use in a spacecraft environment. This memorandum completes the requirements of data item A003 under the subject contract.

2.0 BACKGROUND

Under NRL Contract N00014-81-C-2048, Arthur D. Little, Inc., has provided NRL with an assessment of the thermal design of three cesium beam frequency standard modules being independently developed by FEI, FTS and Kernco, for use in space. The operating temperature level of electronic components is a significant stress factor needed for the prediction of system reliability. Typically, the operating temperature level of all discrete electronic components is not measured in a flight hardware program. Therefore, infrared thermography was utilized to qualitatively survey the temperature of those electronic components of each clock which could be readily viewed while they were operating in a laboratory environment. A more realistic test would be to survey the temperature of the same components while they were operating in a vacuum as this would eliminate the cooling effects of natural convection. This memorandum discusses the benefits and difficulties of conducting infrared measurements of electronic components and what thermal design and packaging guidelines would need to be established to allow wider use of IR thermography in future clock systems.

3.0 SUMMARY

The benefits of using infrared thermography to assess the operating temperature of electronic components are

1. The predicted temperatures of all components used in the system reliability analysis can be verified and recorded, and

2. Unanticipated hot spots can be detected in the circuit. The unanticipated hot spots could be associated with either a component or a connection in the circuit.

The three basic difficulties to overcome, to make infrared measurements of the electronics of a frequency standard operating in a vacuum, are:

1. The electronic components of a frequency standard are typically cooled via conduction paths to the base plate of the standard. The disassembly required to expose the components to the view of a IR imaging system could break the conductive heat flow paths, resulting in component temperatures in excess of their true operating values. To be able to utilize IR thermography to assess the operating temperature level of all components in a frequency standard will require that the heat rejection path of each component not be altered or that an alternative heat rejection path be provided if the hardware is disassembled for IR viewing purposes. IR thermography may be done at the submodule level prior to final assembly if the submodules can be suitably powered.

2. The infrared image of an assembly of operating electronic components requires an analyses to be able to determine the temperature of individual components. Because the infrared image is a measure of the emitted flux in a particular wavelength band, it is required that the emittance of each surface be known in order to be able to predict its temperature. A uniform emittance coating, e.g., a conformal coat or black paint, could be applied to a printed circuit board (PCB) to simplify the derivation of its temperature from its infrared image.

3. The standard infrared imaging systems, utilizing cooled detectors, are not designed to operate in a vacuum so that viewing of the electronics may have to be done from outside the vacuum chamber through appropriate window materials. Magnavox claims that their Pyroelectric Vidicon camera system will operate in a vacuum with appropriate heat sinking.

The mechanical/thermal design of each of the three cesium clocks was briefly reviewed to determine the potential for using IR thermography to measure the temperature of all electronic components. The specific results of this assessment are contained in the three appendices. The assessment was aided by a visit to each of the clock manufacturers to record the infrared image of as many components as possible while the partially disassembled clock was operating in a laboratory environment. A Probeye® IR viewing system was utilized for the measurements and colored photographs of the recorded images were provided to the Naval Research Laboratory.

The difficulties involved in modifying a vacuum chamber to permit IR viewing of test hardware from the exterior of the chamber appear amenable to engineering solutions, i.e., choice of window material as well as size, thickness and mounting hardware.

If the cesium clock has to be partially disassembled to permit viewing of its interior parts, then the location of their parts in the vacuum chamber with respect to the viewing port(s) is important. Techniques such as using several viewing ports, providing mirrors inside the chamber, putting the cesium clock on a rotating turntable, or running several tests with the clock in a different position for each test are potential solutions. A set of cables to electrically connect the disassembled but operating subassemblies will also be required if the full clock system is to be operated. An alternative approach would be to power each subassembly from a supply that was not a part of the clock module.

Computer programs in existence today can predict the temperature of electronic components, however, additional effort will be required to be able to predict the infrared image as displayed by a particular IR imaging device given the predicted component temperatures. The measured, IR radiant flux from discrete electronic components on a PCB can then be compared with the predicted image (flux). If they agree, then a prediction of system reliability can be performed based on the predicted and verified component temperatures. A disagreement between predicted and measured fluxes would lead to further analysis of the operating temperature and predicted IR image of the affected components to understand the cause(s) for the differences.

4.0 TECHNICAL DISCUSSION

4.1 Component Temperatures

The thermal design of electronic systems for use in space is based on the need to satisfy the reliability requirements of the system. As defined by MIL-HDBK 217D, an analysis is required to predict the environmental stresses, e.g., voltage, vibration, temperature, to which each part will be subjected. The part failure rate, λ_p, typically expressed in failures per 10^6 hours, is expressed as a product of a base failure rate, λ_b, and a number of multipliers which account for such factors as environmental stresses other than temperature and different quality levels of components. The base failure rate includes temperature level effects. Figure 1 shows the variation in base failure rate as a function of ambient temperature for a silicon, PNP transistor as defined by MIL-HDBK 217D. Noting that Figure 1 is a semi-log plot, an increase in ambient temperature from 20°C to 30°C increases the base failure rate by 45% while an increase from 50°C to 60°C increases the base failure rate by 121%. Therefore, a rather precise knowledge of component temperatures is required to be able to accurately predict system reliability.

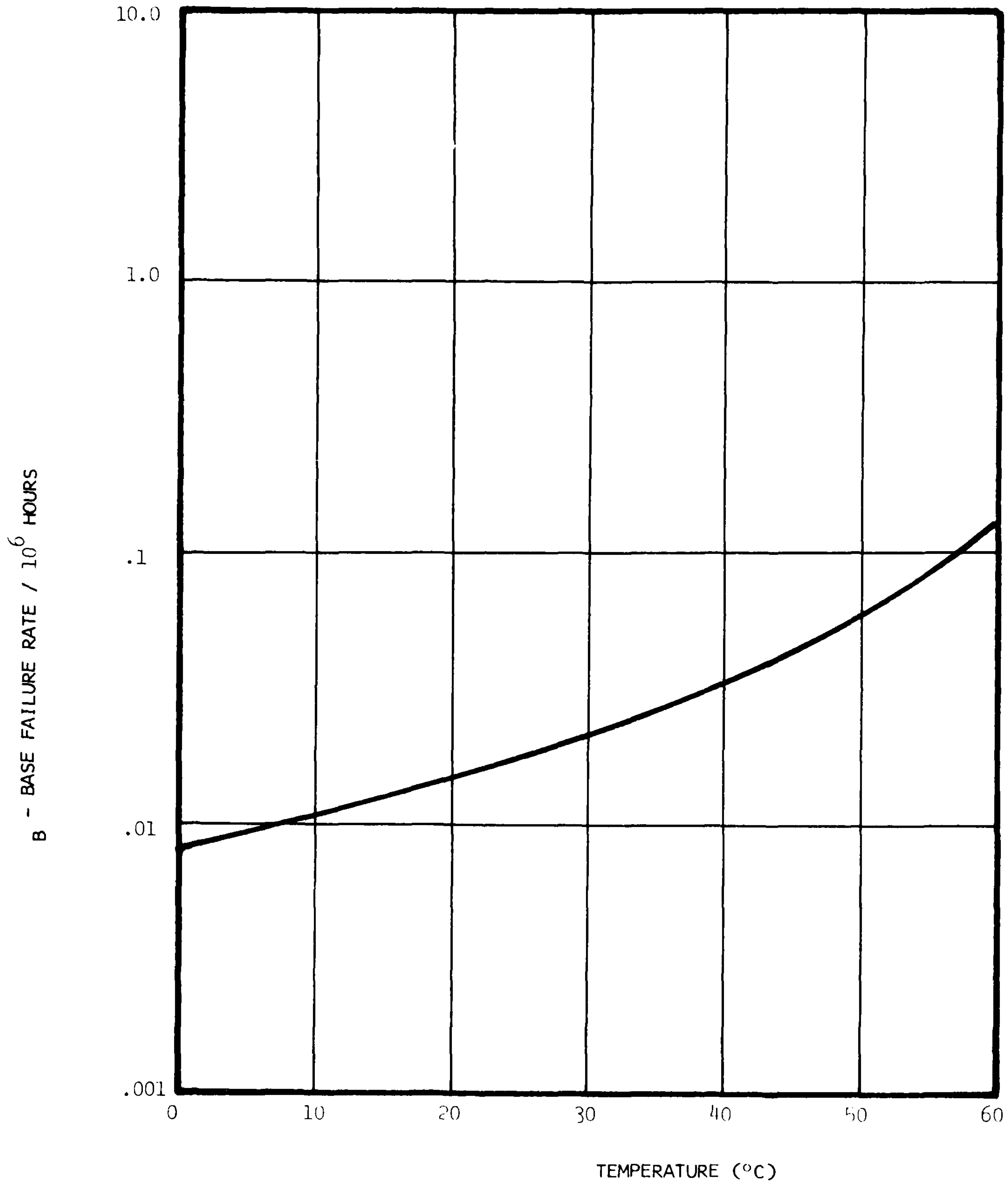

FIGURE 1 BASE FAILURE RATE, λ_B, FOR A SILICON, PNP TRANSISTOR AS A FUNCTION OF CASE (AMBIENT) TEMPERATURE (°C)

SOURCE: MIL-HDBK 217D (5.1.3)

The thermal design of electronics basically comprises the installation of well-defined heat flow paths between those components having significant power dissipations and the heat sink provided by the spacecraft. The thermal conductance of the radiative and/or conductive heat flow paths need to be sufficient to ensure that the components will have operating temperature levels consistent with their specified requirements for reliability. Because of the large number of discrete components in an electronic system, verification of the predicted temperature of all components by test, is typically not done. (The use of an IR imagery system is claimed, by one manufacturer, to be equivalent to using 300,000 thermocouples without touching the PCB.) The temperature of discrete components having significant power dissipation may be measured; however, these components are also typically well heat sunk. Infrared thermography, therefore, provides a technique where a survey of the emitted radiant flux (temperature) of a large number of components can be made resulting in a verified operating temperature level for all of the components.

An electronic module being operated in a laboratory environment will be cooled by natural convection in addition to any specific cooling system provided, e.g., conduction to a cold plate. Natural convection is a process whereby the heat transfer coefficient varies directly with surface temperature so that any local hot spots will automatically develop more cooling capacity. In the vacuum of a spacecraft environmental these same local hot spots could operate at a considerably higher temperature than in the laboratory. The measurement of component temperatures in the laboratory, therefore, is only a qualitative assessment of their operating temperatures in space if the components are not well heat sunk by a solid conduction heat flow path. A component which is well heat sunk by conduction will have an operating temperature level which is relatively independent of any natural convection effects. A component which rejects its power dissipation via a radiative heat flow path is typically a low powered component and its operating temperature in the laboratory will be affected only if the temperature of the local air is different from the effective temperature of its radiative environment.

In addition to making the infrared measurements of the operating electronics, one also has to be able to interpret the recorded images to obtain component temperatures. The infrared radiation leaving a surface comprises both emitted and reflected components. The emitted radiant flux is a function of both the temperature and emittance of the individual surfaces being viewed.

$$q = \varepsilon A \sigma T^4 \qquad (1)$$

Therefore, to be able to determine the temperature of a specific component requires both a measurement of the emitted flux as well as knowledge of the surface emittance.

4.2 Viewing the Infrared Image

4.2.1 Printed Circuit Boards

The use of infrared thermography has applications in the design and development of space hardware electronic systems from the time of the initial bread-board up through fabrication and testing of the flight hardware. In the initial phases of a program, the use of infrared thermography can provide a quick assessment of unanticipated heat spots, leading to a better thermal design, and/or a reassessment of the predicted power dissipations of the affected components. Thermography can also provide checks on the thermal effectiveness of any bonded interfaces, e.g., in a hybrid circuit. As the hardware evolves to the prototype stage, the continued use of infrared thermography provides an on-going assessment of the state of the thermal design of the system, thereby minimizing the opportunity for a thermal surprise after packaging of the prototype or flight hardware is completed.

To be able to view the infrared images of all components requires that the operating components be accessible without disrupting the thermal control system. The difficulties of viewing current designs typically stem from conduction heat flow paths which block the line-of-sight to selected components. A circuit board may also be mounted with its components facing a solid metal bulkhead of a frequency standard so that, as the PCB is mechanically attached to the bulkhead, conductive thermal paths are also established. In these cases, an equivalent conductive heat flow path would need to be established to the selected components when the PCB is removed from the bulkhead. Flexible copper braid could be used to connect the affected components to a temperature controlled heat sink inside the vacuum chamber. If the radiative exchange between low-powered components on the PCB and the bulkhead is important, then a temperature controlled viewing tunnel may be necessary between the PCB in the vacuum chamber and the viewing optics of the IR imaging system. In both cases, an additional electrical cable may be necessary to connect the PCB to the clock module so that the components can be powered during observation. It may be possible to power a PCB from a separate power supply, however, the feasibility of this approach could only be assessed by the electrical designer of each specific board.

A general thermal design approach whereby the majority of the components on a PCB are heat sunk by conduction to the perimeter of the PCB would minimize any blockage of the view of the components. The boards would then be clamped at their perimeters to a metal bulkhead of the frequency standard to complete the conductive path to the baseplate. It is not obvious that one can add a layer of copper cladding to a flight hardware PCB for thermal reasons because of the requirements for the inspection of the many soldered connections. The optimum location for this thermal layer is, of course, on the exterior surface of the board directly underneath each component. An internal layer of copper would also enhance the lateral thermal conductance of the PCB but would be less effective than the surface layer primarily because of the additional thermal resistance between discrete components and the internal layer of copper.

A third thermal design approach currently in use is to mount discrete thermal conductive devices, e.g., copper or aluminum bars or heat pipes, on the surface of the boards so that the higher powered components, mounted to these devices, can conduct their heat towards the perimeter of the board.

In summary, by designing the individual printed circuit boards so that the heat dissipated by discrete components is first conducted to the perimeter of the board, before being transferred to the housing of the frequency standard, blockage of the view of the operating components will be minimized. To operate the boards in a vacuum will then require a temperature-controlled board mounting fixture so as to provide a conductive heat sink equivalent to that of the frequency standard.

4.2.2 Hybrid Circuits or Other Packaged Devices

During the course of fabrication and assembly of a frequency standard there will be some subassemblies which will be potted and/or enclosed in an IR opaque housing. The operating temperature of the discrete components or integrated circuits within these devices should be verified prior to final assembly. This implies that the closing-out of the housing, i.e., bolting on the final cover, should not significantly affect the thermal design of the assembly. Because the subassembly unit will typically be bolted to the metal structure of the frequency standard, an equivalent heat sink in a vacuum chamber could be a relatively simple, temperature-controlled mounting plate oriented so that the operating subassembly can be easily viewed from the IR imaging system.

4.3 Infrared Vacuum Equipment

There are a number of manufacturers providing equipment to measure the IR radiant flux emitted by an object. Table No. 1 is a listing of a number of suppliers with a brief summary of the characteristics of their devices. Infrared measuring devices typically operate in either the 2-5μm or 8-14μm wavelength bands (corresponding to the transmission windows in the atmosphere). For device temperatures typical of components on a PCB the 2-5μm wavelength band will provide better temperature resolution while the 8-14μm band will provide more signal strength. If one were to view very small devices, e.g., an integrated circuit, the shorter wavelengths would provide better spatial resolution due to diffraction limit effects.

The viewing equipment typically involves rotating mirrors which perform a line scan of the object. The analog signal from the detectors can be digitized, stored, manipulated and displayed as a colored

Table 1

SUMMARY OF MANUFACTURERS OF INFRARED VIEWING EQUIPMENT

Manufacturer	Imaging	Detector	Wavelengths (μm)	Cooling Technique
1. AGA Thermovision	yes	InSb/HgCdTe	2 to 5.6/8 to 14	LN_2
2. Barnes Engineering, Inc.	yes	InSb/PbSnTe	1.8 to 5.5/8 to 12	LN_2
3. Barr and Stroud, Ltd.	yes	HgCdTe	8 to 13	J.T. (N_2)[1]
4. Hughes Aircraft Company	yes	InSb	2.0 to 5.6	J.T. (Argon)
5. Inframetrics	yes	HgCdTe	3 to 5/8 to 12	LN_2
6. Magnavox	yes	pyroelectric	8 to 12	not required
7. IRCON	no	Si	various narrow ranges	water
8. Standard Equipment Company	yes	-	1.2 to 6.0	T.E.[2]
9. UTI	yes	HgCdTe	8 to 14	LN_2

[1] Joule-Thomson expansion

[2] Thermoelectric

image. A consideration in the specification of an IR viewing instrument is the spatial resolution which is obtainable with the detecting and image processing system. A pixel of the final color image, as stored and displayed, represents an area of the object with an associated averaged radiant power. If the resolution capability of the detecting and processing system is relatively low, then the emitted flux from a local hot spot on a PCB will be averaged with the flux from a surrounding cooler region and peak temperatures will not be seen. As an example, a 1/8 watt carbon resistor is approximately 0.145 inches long and has a diameter of .062 inches. Viewed from a distance of 1 foot the length of the carbon resistors subtends an angle of 0.7° (12μmrad) and its diameter subtends an angle of 0.3° (5μmrad). The emitted flux information contained in one pixel of the processed image should, therefore, come from an area of the object (PCB) which is of the same size as the smallest component whose temperature is to be measured.

An additional, useful capability on an IR imagery system is the ability to permanently store an image. The UTi CCT-9000 thermal imaging system, for example, has an optional disk storage unit for storage of a viewed image. The stored image can then be "subtracted" from the image being currently viewed so that only the differences are seen. The capability to store a predicted IR image, on disk, would provide the capability for a quick assessment of the difference between the predicted and measured images, thereby making the job of verifying predicted component temperatures easier.

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