RELIABILITY AND THE DESIGN PROCESS AT HONEYWELL AVIONICS DIVISION

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ABSTRACT

This paper describes the Honeywell Avionics Division philosophy for "Designed-In" reliability, a summary of selected tasks from the Willoughby "New Look", and a comparison of reliability programs (based on electronics) for space, manned military aircraft, and commercial aircraft. The approach we have taken in this paper will cover the following items, as they relate to Honeywell AvD:

- o Reliability Philosophy and Organization
  - Reliability Interface with Design
  - Reliability Interface with Production
- o MTBF Predictions, Concept Phase through Final Proposal
  - The Laser Gyro - A New Technology
  - Electronics - An Evolutionary Technology
- o Design, Development, Test and Evaluation Phase
  - Semi-Conductor Junction Temperatures
  - Sneak Circuit Analysis
- o Production Phase
  - Production Support
  - Manufacturing Run-In (MRI)
- o Commonality Among Space, Military, and Commercial Avionics
  - Space Electronics
  - Military Avionics
  - Commercial Avionics

INTRODUCTION

This paper has been prepared in response to a request from Dr. A.O. McCoubrey, general chairman for the 1980 PTTI Meeting. As we understand the background of PTTI measurement, some of the concepts and technology are new, even unique. Reliability and Maintainability (R&M) considerations to date may, therefore, be inadequate for the projects of tomorrow. Our purpose in this paper is to present a picture of how our company--the Avionics Division (AvD) of

Honeywell, Inc.--approaches the subject of designing, building, and testing electronics equipment with controlled R&M characteristics.

The breadth of the subject is staggering in terms of a 20 minute presentation. In an attempt to avoid an overly broad-brush approach to the subject, we are making some assumptions. First (and foremost): because the Willoughby "New Look" has gained wide acceptance, we will not review all of the various tasks, tests, and analyses that it prescribes. We believe that R&M people can, in their own operations, perform or lead most or all of the salient tasks inherent in the "New Look". Therefore, this paper will dwell on efforts at AvD that are different--and in one case, unique to our operation.

We recognize that the approach we have chosen might amplify the appearance of disagreement with other people in R&M work--including, perhaps, some of you in the audience. Please, then, keep two things in mind: (1) we undoubtedly have a high degree of commonality in most of the items not discussed in detail here; and (2) the material we are covering represents a view--a series of Engineering judgments--on methods that we consider to have been effective for us.

RELIABILITY PHILOSOPHY AND ORGANIZATION

Honeywell AvD subscribes to a basic reliability philosophy that is common to most organizations where product reliability is of major importance: "Reliability is a 'designed-in' performance characteristic. Testing and inspection verify that the design meets objectives, and that the product, as built, retains the characteristics of the design." While very few people would disagree with any aspect of the philosophy as stated, the methods by which the concept is implemented by various organizations--the actual tasks and organizational responsibilites of the working reliability engineer--are diverse and, at times, seem to contradict the philosophy as expressed. At AvD, our organizational structure and our assigned charter of responsibilites are tailored to fit the accepted basic philosophy. Therefore, reliability engineers are an integral part of the Engineering Department in a service organization.

Reliability Interface With Design

Although our Engineering department is quite large--(more than 500 engineers, 400 of whom are design engineers)--we have found that a central support/ services group gives flexibility to the covering of changing work loads in the various sections of the department. One section of this group is the Reliability and Design Support (R&DS) function, consisting of about 50 engineers. R&DS has responsibility for disciplines that include: reliability, maintainability, system safety, mechanical/vibrational stress analysis, thermal analysis, electromagnetic interference considerations, and electrical/electronic part standardization and specifications. There is a need for interaction within these disciplines and our organization fosters such interaction.

In the design phase of major projects, our experience has seen the assignment of one or two R&M engineers for every 10 design engineers. On recent projects, the ratio has been closer to two-to-10.

Reliability Interface with Production

There are gray areas between Engineering Department control of product performance, and those items of control that belong to the Production and/or Quality Departments. However, we believe (with Mr. Willoughby) that the prudent resolution of such gray areas is almost always in favor of making them the responsibility of the Engineering Department. Specifically, if there is any doubt about the control of the end result of a process by direct measurement of the end-product, then that process should become an engineering specification, under control of the Engineering Change Order (ECO) procedure.

Despite this effort, there are areas of overlap in which items that are not under ECO control can--and do--have an effect on reliability. Therefore, one of the tasks assigned to our reliability engineering function is to interface with engineers from the production and quality departments in order to resolve problems during product build, and for malfunctioning goods that are returned from the field. We title this task FRACA--Failure Reporting, Analysis and Corrective Action. We'll discuss this task again later, as well as some of the major differences between a quantity build (100s or 1000s of the same item) program and a space-oriented product.

Highlights of a Current Program

The remaining portions of this paper, which describe various phases of a particular program, are examples from a current commercial project that brings Honeywell AvD into a new major field of business--inertial reference/navigation for manned aircraft. It may seem strange to choose a commercial product for a discussion of "Hi-Reliability" hardware, but we believe it is applicable to the objectives of this meeting.

MTBF PREDICTIONS, CONCEPT PHASE THROUGH FINAL PROPOSAL

There are numerous R&M tasks that are significant and necessary contributors to this phase of a successful program. We have decided to discuss prediction methods because they are very important to a commercial program (warranties and guaranteed MTBFs), and because our prediction methodology (for solid-state electronics) is unique within the industry. Furthermore, we believe the concepts are also critical for space applications, and a reasonable baseline for tradeoff decisions (relative failure rates) and for projected life/redundancy considerations is needed.

The Laser Gyro - A New Technology

The Ring Laser Gyro (RLG) portion of the subsystem under consideration represents a new technology--one for which we have limited (relevant) reliability data. As the primary motion sensor required to perform inertial navigation, the gyro's failure rate can make-or-break the ability of the system to meet its MTBF and Life Cycle Cost (LCC) goals. Because no comparable instrument exists, we projected the failure rate by the following general approach:

- o Identify failure modes as thoroughly as practical.
- o Review failure modes by (sub)function and comparable (sub)function.
- o Use failure rates for known hardware and comparable function where possible.
- o Analyze and review causes of failure in prototype gyros for compatibility with the theoretical analyses.
- o Factor-in experience during the build process.
- o Total subfunction failure rates, and review and compare those rates with known failure rates for mechanical gyros.

Although the RLG subsystem has many advantages over the gimbaled, rotating gyro mechanization, the most significant item is improved reliability at equal or lower cost. There are two considerations when comparing the new technology with the old-"random" failure rate, and mean life. However, there are no known wear-out or age oriented failure modes in the RLG during the anticipated life of the equipment. Therefore, a sum of the estimated random failure rates of the RLG is compared to the cumulative wear-out and random failure data for the mechanical gyros.

Even though the entire process tends to be better on paper than it does in practice, we have enough confidence in the procedure to use it as the basis for extended warranties and guarantees.

The RLG involved more than 15 years of research and development. The steps for reliability analysis described above, meanwhile, represent an iterative process that started almost with the original idea of a laser sensor mechanism (i.e., a motion sensor with no moving parts). The final, numerical assessment by a reliability engineer only formalizes and quantifies the accepted basic probabilities associated with the new technology.

<u>Electronics - An Evolutionary Technology</u>

Although MTBF projections for new technology items carry the greatest risk, electronics predictions are also critical in the reaching of good decisions at the front-end of a program. AvD has developed a unique prediction methodology for solid-state electronics hardware that is based on extensive data gathered over a period of years. Our largest, most-accurate data base is the record of failures of a digital air data computer (DADC) used in Douglas DC-10 airplanes. Considerable data is also available from AvD flight control electronics equipment on the C5-A and F-14 airplanes, as well as radar altimeters used in most of the Navy's airplanes. That data is limited in scope and accuracy, however. Specifically, the available data suggests two sources of reliability improvement in production-type solid-state electronics:

- o The universally-accepted improvement of a design, and its associated production processes through maturation
- o An aging maturity related only to operational age (average operating hours per unit).

Figure 1 shows a log-log plot of the measured failure rate of the Digital Air Data Computer (DADC) electronics vs. the average age of all equipment in the field. Each data point represents at least 35 failures. The calendar period is superimposed on the axis depicting average operating hours. Further information on this subject is available from the author.*

Based on the data cited earlier, we have developed a simple equation (Figure 2) for predicting electronic failure rates. The equation is based on the assumption that there are two components of the basic failure mechanism, such that:

$\lambda i = KH^{\alpha} + \lambda r$, where

- o λi is the failure rate at any given instant
- o λr is a residual or constant λ, approached as an asymptote
- o The KH^{α} term is the variable λ, very large at infancy and approaching zero as an asymptote. K is a constant, H the operating hours, and α is the slope of the curve.

We recognize that failure rates will vary with temperature and could be affected by other environmental and package-design factors. For AvD purposes, the validity of our prediction is limited to equipment that operates within tight design constraints for temperature and packaging. The actual environment at the piece-part level is then controlled within these constraints. For AvD applications, we believe that the accuracy of failure data does not justify any greater precision than we get with our simple equation.

We are convinced that the data summarized in Figure 1 is a valid indication of the behavior of electronic parts. The explanation we have developed postulates that solid-state electronics have the following characteristics:

- o There are no significant wear-out modes for the operational life of the equipment involved.
- o Some electronic parts have latent defects or flaws that represent a weak link in the chain that could lead to failure.
- o All of the latent defects may still not lead to a failure during the life of the product (10,000 to 75,000 operating hours).

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* "The Effect of Endless Burn-In on Reliability Growth Projections," Alex Bezat and Lyle Montaque, Proceedings 1979 Annual Reliability and Maintainability Symposium.

- o Repair actions for failed parts result in the removal of the weakest part within the population at any given instant. The replacement part is, in all probability, a part that will not fail during the remaining life of the equipment.

Other investigators have arrived at conclusions similar to ours regarding both the cause and shape of the failure rate curve (there is a paper on this subject scheduled for the forthcoming R&M symposium in Philadelphia). However, the explanation must be treated as theory; the failure rate curve represents data at a high level of statistical confidence. Based on the above characteristics, the reliability prediction methods described have been used in the RLG program under discussion in this paper, as well as for all other programs where management risk/cost analyses are needed.

It should be noted, however, that MIL-HDBK-217 is still the only method that government procurement agencies can use on an "apples-for-apples" basis, so our AvD operation uses the MIL-HDBK for all such projects, as required.

Design, Development, Test and Evaluation (DDT&E)

The Willoughby "New Look" applies fundamental engineering design principles and disciplines to the design process, with the objective of attaining "designed-in" reliability at the earliest, most cost-effective phase of the program. We have adopted NAV MAT Instruction 3000.1A as a baseline for preparing a Reliability Statement of Work (SOW) for situations that are incomplete, or inadequate by contract. The checklist at the end of this paper summarizes the "New Look" tasks associated with designed-in reliability, as we applied them on the RLG program.

Semi-Conductor Junction Temperatures (Tj)

At AvD, we believe that design margin is the touchstone to cost-effective reliability. Adequate temperature margin is, in our judgment, the most important of all stress factors that impact reliability. We have found two difficulties in specifying and controlling design requirements so as to keep Tj within desired bounds. The worst of these is the paucity of data on θ_{JC} (the thermal impedance from semi-conductor case to junction). Furthermore, conflicting, often absurd values for θ_{JC} are sometimes found in both the Military Specifications and the vendor data sheets for integrated circuits. We have generated an interim solution for the item by defining θ_{JC} by measuring the forward voltage drop of the substrate isolation diode. Although we feel that our methods are far more accurate for design decisions than our previous attempts to use published data, there remains much to be desired in terms of variables other than those covered. Also, our data is incomplete, but compatible with that from other people who have taken measurements similar to ours.

The other difficulty has to do with improved dissipation of heat from medium- to high-power LSIC (Large Scale Integrated Circuits) mounted on printed-wiring boards (PWB). Thermal planes have been used extensively, but we have found no straight-forward, reasonably-economical methods of improving the heat flow from the semiconductor case to the thermal planes. This problem is not yet fully-resolved, but we have measured significant--and highly reproducible--reductions in case temperature by the use of a silicone compound displacing the usual air gap between the case and the copper of the PWB.

Sneak Circuit Analysis (SCA)

The only item of "New Look" analysis that we by-passed on this program was SCA. We are not sure that SCA is cost effective at a level below the system or major subsystem level, and the subject was explored in detail with our customer. Our experience with SCA is that it duplicates somewhat the parts application analyses, failure mode and effects analysis, and related built-in-test (BIT) analyses for design problems within the black box. However, we believe that an SCA at the system or major subsystem level can avoid interface/interconnection problems, and simultaneously uncover design errors with optimum cost effectiveness.

Honeywell AvD experience with SCA is not comprehensive, being limited to work performed on a subcontract basis on three manned aircraft avionics items, and one manned spacecraft project. We would be highly interested in the experiences and judgments of other people with experience in this field.

PRODUCTION PHASE

Production Support

Operations at AvD are such that the engineering and production functions are in the same building as engineering. The FRACA system represents an important interface among the three departments most involved in the production phase (i.e., production, product assurance (quality), and engineering). The documentation, retention, and retrieval of anomaly (defect, failure, non-conformance, etc.) data is the responsibility of the Quality Department. The automated retrieval system is so mechanized that failure trend data is rapidly available by sorting against a variety of items (i.e., defect code, part types, part number, assembly/subassembly numbers, etc.). The FRACA system is applied either on a 100 percent basis for all anomalies, or on a selective basis by using the automated trend analysis output, working closely with production and quality engineers.

For this program, closed-loop FRACA will be used for 100 percent of all anomalies that occur during final acceptance testing, for 100 percent of manufacturing run-in on the first 50 units, and selectively for all other anomalies. The number of anomalies that are to be investigated in the detailed procedure called FRACA will be reduced with the maturity of the design and production processes. (The FRACA procedure is, of course, used extensively throughout the DDT&E phase for all failures that occur during Qual test, Rel-Development tests, etc.)

Manufacturing Run-In (MRI)

MRI (or burn-in) has been used at AvD for almost all of our avionics during the past 10 years. It is a natural outgrowth of our failure rate concept regarding the improved product reliability associated with operating age. Three factors are considered important in the MRI screening process: (1) 100 or more operating hours at elevated temperature, (2) power cycling in excess of mission requirements, and (3) 10 or more temperature cycles. Our internal standard is an MRI elapsed time of one week, four temperature cycles per day (temperature extremes beyond mission requirements, but no overstressing allowed), with power-on during the elevated-temperature portion of the cycle.

Power is cycled four times per hour during the elevated-temperature operation. A random vibration screen precedes the operational portion of the screen, and the last three temperature cycles must be failure free. The RLG program we have reviewed will use the AvD internal standard described here.

COMMONALITY AMONG SPACE, MILITARY, AND COMMERCIAL AVIONICS

Honeywell AvD has extensive experience in design and production of equipment used in military aircraft of all kinds, manned and unmanned space programs, and commercial jumbo jets of today and tomorrow. In terms of cost effectiveness, in our judgment, the essential principles of the "New Look" are just as applicable to military and commercial avionics as they are to manned space. This is particularly true for the DDT&E phase. We have found some minor differences in the production phase.

Space Electronics

The design, process, and build maturity must be nearly instantaneous for space electronics; "field" results must be at the desired reliability levels with the first unit. It is self-evident that corrective action in the field is usually impractical or impossible. Therefore, "S" level parts and extremely costly tests and screens can be cost effective for space applications. Furthermore, each failure at any level of build and assembly justifies a complete, thorough analysis for cause, as well as high-visibility decisions on corrective action (i.e., FRACA) throughout the total production build. The MRI prior to final acceptance testing should, we believe, be comprehensive to an extent that would be prohibitive for non-space applications. The AvD concept of reliability growth of electronics through operational age suggests that run-in of at least 1000 hours might be a practical requirement for space electronics. Based on our experience with APOLLO, it is reasonable to believe that little or no equipment left the ground with less than 1000 operating hours, and 3000 operating hours prior to flight was not unusual. We believe that extended testing contributes to reliability by growth-through-aging, as long as maintenance actions are not destructive.

Military Avionics

Typical military avionics can be repaired after installation. Therefore, there is a viable tradeoff between increased maintenance cost for manned aircraft avionics and the ultimate reliability built into space equipment. This factor has been misused in the past as a license for shoddiness. The AvD compromise approach has been to use FRACA extensively in the early production systems. For example, an extended MRI can be used with 100 percent failure analysis (i.e., FRACA) for the first 20 to 50 units. This type of effort is treated as an extension of "Rel-Development" testing.

Subsequent production systems can then be evaluated for trend failures or any unusual anomaly events, and the FRACA procedure is superimposed on the quality anomaly reporting system as the problem-solving vehicle. Generally, the design-and process-oriented problems can be resolved quickly and effectively with this approach. As the product matures, the proportion of failures that are analyzed declines from the 100 percent range, to as low as five percent with fully matured systems. Typically, the trend analysis becomes the "spotter" for lot-oriented part problems that sift through the inspection screens at the piece-part level, and can only be detected under the simulated operational conditions of MRI.

Electronic parts for military applications are usually specified to the MIL-STD levels (MIL-M-38510, level B for integrated circuits) where available. Non-standard parts are purchased to an AvD "Spec Control" drawing that imposes the more critical controls equivalent to the MIL-SPECS for generically similar parts. Although we have found that Government source inspection does not guarantee that parts are really tested, such MIL-STD parts appear to be generally cost effective. There is, however, one glaring exception: we believe that the added costs of MIL-M-38510 controls on standard integrated circuits cost more than they are worth. We find that reasonable specification control drawings, using mostly vendor-level requirements of MIL-STD-883B (with 100 percent hi-low temperature testing at receiving inspection) are more cost effective. The subject of parts specification and control would require a full paper of its own, so these comments will have to suffice.

Commercial Avionics

Honeywell AvD has found that R&M inputs are cost effective at essentially the same levels for commercial aviation programs as for the military. A typical three-year warranty in a commercial jet will involve 10,000 to 15,000 operating hours, which is usually equivalent to more than the full life of avionics for military fighter aircraft. A military transport (C5-A) may go as many as 1000 hours per year--or perhaps a 20,000- to 25,000- hour total life vs. 50,000 to 75,000 hours for commercial. Because we see no wear-out failure modes in solid-state electronics, the only difference beween commercial and military avionics is the elapsed time to attain full maturity, which is much more rapid for the commercial.

Parts specifications and controls for commercial avionics at Honeywell AvD are the same as for the military, with one exception. Integrated circuits are usually purchased to Spec Control drawings and MIL-STD-883B, and MIL-M-38510B parts are used only when commonality and quantity-buy for the military makes them cheaper.

SUMMARY

There are a few significant points that we would like to emphasize. Most important, perhaps, is the idea that the "New Look" is just as applicable to commercial and "ordinary" military projects as it is to space hardware. The check list appended to this paper is not a shopping list--it represents the significant items associated with an effective R&M program.

Again remember that the items we have covered in detail herein were not chosen as having the highest priority--only that there are, perhaps, greater variations in how to handle them.

We mentioned that "design margin" generates a reliable product, but the importance of controlling the build process may not have been stressed adequately. It is obvious that the world's best design can be murdered by shoddy practices in the factory--or repair facility--if precautionary measures are not used.

Finally, we believe that all of the controversial items covered have a sound basis in fact. We are, however, anxious to correct our ways when better information is available; this better information often comes from people like you, with experiences in new technology. We would like to hear from you.

CHECK LIST FOR "RELIABILITY BY DESIGN"

- o Mission/environmental profile definition
- o Design alternative studies
- o Numerical allocations and reliability growth analysis
- o Conservative derating criteria
  - $110^{\circ}C$ maximum junction temperature, worst case
  - $60^{\circ}C$ to $85^{\circ}C$ maximum junction temperature, normal operation
- o Part stress analysis
- o Thermal analysis
- o Thermal testing/measurement
- o Structural analysis
- o Worst case tolerance analysis
- o Failure modes and effects analysis
- o Parts and materials selection and control by technical baseline documentation
  - Screening to "hi-rel" levels: JANTX: MIL-STD-883B, etc.
  - Detailed part characteristics controlled to fit application
  - Parts teardown analyses to 883B visuals
  - 100% hi/lo/room temperature tests of key electrical characteristics
- o Design reviews
- o Reliability development test (test analyze and fix test - TAAF)
- o Design limit qualification test
- o Manufacturing run-in screening with random vibration
- o Failure free reliability verification/acceptance testing
- o Failure reporting, analysis, and corrective action
  - Design and development tests
  - Qualification tests
  - Reliability development tests
  - Production manufacturing run-in (MRI)
  - Failure free reliability verification/acceptance tests
  - Returned goods

- o Technical baseline documentation control of production processes that impact reliability and maintainability as well as the classical "form, fit, and function"
- o Adequate staffing and involvement of reliability, maintainability, and manufacturing in the design process.
- o Receiving inspection screening of electrical and electronic parts.

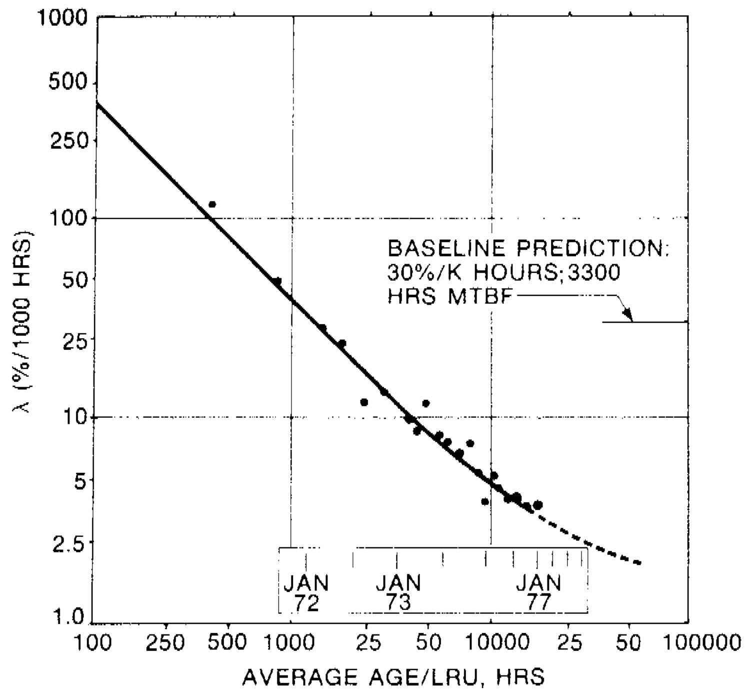

Figure 1. DADC Electronics Failure Rate

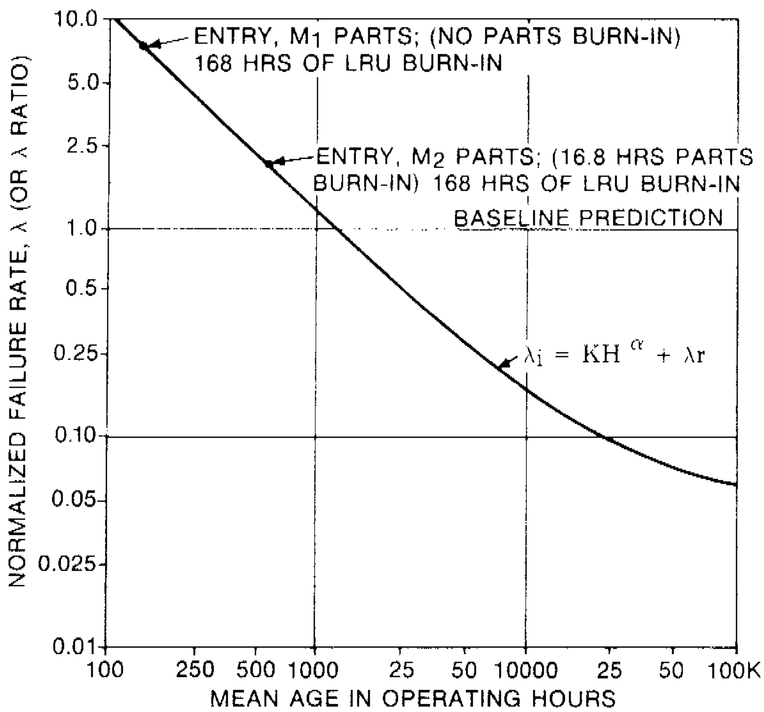

Figure 2. Honeywell Reliability Prediction Curve

QUESTIONS AND ANSWERS

DR. CARROLL ALLEY, University of Maryland

This is the first paper the term "sneak circuit analysis" was used, but I am intrigued by what that really means and it hasn't been explained.

MR. BEZAT:

Let me read it to you. I passed up discussing sneak circuit analysis. I didn't have time. I should mention that on this particular program, the ring laser gyro program for the Boeing 767-75-7 airplane, we went into considerable review of the possible application of sneak circuit analysis.

We went into it with our customer and our own analysis. We have had sneak circuit analysis done by Boeing-Houston because it is a mechanized approach and I believe General Dynamics is also doing it now.

Let me read to you what is in the work statement very quickly. "The sneak circuit analysis for hardware looks for sneak paths; that is to say energy flow on unexpected routes. It looks for sneak timing, energy flow on expected times. For sneak labels; that is to say that information and undesirable stimuli. That information is available to the pilot or what have you."

A sneak circuit for the software is virtually identical except for energy flow. You want to talk about logic flow. They also do similar things to what we would do for design margin considerations, but those are sort of an additional output.

Now, our preliminary conclusion about sneak circuit analysis in terms of its usefulness -- and I certainly don't want to talk as though we were experts on this entire subject -- our preliminary conclusion is that it is probably cost-effective at a major system or total system level because much of what would be discovered by this kind of an approach has to do with interface of equipment that is designed in different areas.

If you have a big enough subsystem, that same problem can occur. Generally we have found in our past experience, those areas where we have had sneak circuit work done -- things that were found internal to the box -- our people had found with the normal analysis. I don't know if other people agree with that approach.

DR. STOVER:

In several earlier papers, the point was made that the parts vendor couldn't really be trusted to produce reliable parts. And in your paper, you make the point about junction temperature data not being quite adequate. Does this imply that there is a place here for the independent testing organization to get involved? Some kind of organization that doesn't exist to date.

MR. BEZAT:

You need to provide an objective basis of comparison.

DR. STOVER:

Right. Where there is not the bias of being the vendor.

MR. BEZAT:

Those organizations do exist. I mentioned the Defense Electronics Center, the RADC. However, I am not sure that they are able to cover all the subjects, but particularly I believe, they could not impact the adverse that Mr. Willoughby is talking about in respect to parts and parts quality, parts reliability. We have indeed found exactly the same thing Mr. Willoughby talked about. I don't have the numbers that are anywhere near as accurate as what Mr. Willoughby indicated; we can't quantify it quite that well.

But indeed the parts are bad. I should say, though, that the data that we got from the supplier was, in general, about -- seven out of ten suppliers we contacted was much better in regard to the junction temperature coefficients than what we found from the other sources -- than any other sources including the military.

DR. STOVER:

This really applies more to previous papers than to yours, but from this standpoint of each doing their own inspection and verifying and maybe doing the same thing -- every organization doing the same thing. If some independent testing organization would do this type of failure testing and publish the results for different vendors, would not the free market -- the competitive market forces force us into more reliability?

MR. BEZAT:

I don't know that I can answer that question. I have some opinions about it from a straight economic standpoint which would say no. Simply because the total quantity of parts that are used, where we need this relatively high reliability and where it is cost-effective to have it, is such a small proportion of the total number of parts that are used.

Therefore, it would appear that the mass production method which I think will probably move upward in quality and reliability on a competitive basis as you were pointing out, but not on a quantum jump basis. The cost of screening is ever so much lower than the cost of actually building to that high reliability at the present time. That is an opinion and I could not support it with data.

DR. STOVER:

Thank you.

CHAIRMAN WINKLER:

Thank you very much. Before we close, I would like to make just one comment concerning this section. I think, at least for me, it has been a most interesting session. Each of these papers leaves a number of suggestions behind, what to do in our specific cases. I hope you share that impression.

One thing came back very strongly to me, and that is that there is no such thing as a material failure, that all of these failures are failures of the man in one way or another; failures of our intellect to recognize the properties, to recognize the hidden problems in design, and failures, of course, in the manufacturing process. So, what we have is a much, much lower random failure level than we would have assumed until now.

The last paper has reinforced this opinion that you really are talking about weeding out the faulty components and then you have not yet reached the purely random failure rate, the Poisson distribution. For many devices you will never reach that level because in the case of cesium beam clock you end up running into the end of life phenomena, likewise the rubidium lamp problems which come up after a number of years. So, maybe it is a wrong position to take to believe that there is such a thing as a material failure. These are failures in our intelligence recognizing what is going on.

That, of course, brings me to a second point. That is, maybe a useful change in attitude, in one's own intellectual attitude, would be to remember that our ideas of characterizing a module or an atom by fixed properties may break down at the level of very complicated systems. Its actual properties change because it is exposed to a different environment which you had not foreseen.

I consider that a very general attitude and it has made me more cautious and maybe less ambitious. But again, I enjoyed that last session very much and I am sorry to see it come to an end. It is something which has been very important in precision timekeeping. Thank all of the contributors to this session.