CLOCK PERFORMANCE, RELIABILITY AND COST INTERRELATIONSHIPS

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ABSTRACT

Clock manufacturers have encountered major difficulties in attempting to supply reasonably-priced, reliable clocks for critical aerospace applications. The basic problems arise from the inherent technical difficulties of designing and fabricating equipment to provide performance at the limits of the state-of-the-art in demanding environments, but the difficulties are compounded by inconsistent and unstandardized specification practices, and by an emphasis on initial acquisition costs, rather than on life-cycle-costs. Conventional parts-stress analyses, which do not provide a useful indication of the reliability of a clock, lead to increased parts costs for high-performance aerospace clocks without commensurate benefits in improved reliability or performance. The characterization of clocks in term of the mean-time-between-resynchronizations, facilitates the estimation of life-cycle costs and provides a means to evaluate clocks in a realistic fashion for specific systems applications.

INTRODUCTION

There is concern in our industry, users as well as suppliers, over the reliability and the acquisition costs of high-performance clocks and frequency standards. Such concerns can be related to the complex interaction between cost, performance and reliability in the design and fabrication of clocks. Certainly there are similar relationships in all technologies; but there are unique aspects to the clock problem, particularly with the respect to a useful definition of clock reliability. Although our primary interest here is with instruments intended for long-term operation in spacecraft, the same considerations are applicable to a wide range of environments and applications, from standards laboratories to oil-exploration rigs, in which uncompromising performance and reliability are essential.

A pragmatic approach is to carefully examine the impact of certain categories of customer specifications and requirements on the cost, reliability and performance of clocks. The issues of parts selection and parts stress analyses, "qualification", nonstandard interfaces, and operation or "life-cycle" costs are of particular concern in any discussion of cost, reliability and performance tradeoffs. The situation is further complicated by the extreme difficulty of abstracting clock specifications from the system design. A clock which may be quite adequate in one system may be considered inadequate in the context of a second system, even in instances in which the missions of the two systems are identical.

PARTS STRESS ANALYSIS

Mean-time-between-failure (MTBF) estimates based on electronic parts stress analysis are a valuable tool in the reliability engineer's kit. Used with care and understanding, and in conjunction with failure mode and effects and worst-case analyses, MTBF calculations are an aid to a complete understanding of the operational characteristics of an item of equipment. But because the MTBF estimate is relatively simple to calculate, and provides a single unambiguous number as the result of the calculation, the MTBF tends to be given a great deal more attention than it deserves. A review of the basics of parts stress reliability predictions may help to clarify the limitations of the parts-stress MTBF estimate.

MTBF Calculations

Failure rate models have been established for the heavily-used electronic parts: integrated circuits, transistors, resistors and capacitors. The models and the corresponding experience factors are compiled in a military handbook, MIL-HDBK-217.[1] From this handbook, the failure rate model for a discrete semiconductor device in failures per 10^6 hours is

$$\lambda p = \lambda b \; (\Pi_E \times \Pi_A \times \Pi_{S2} \times \Pi_C \times \Pi_Q) \qquad (1)$$

where

Π_E is the environmental factor
Π_A is the application factor
Π_{S2} is the voltage stress factor
Π_C is the complexity factor
Π_Q is the quality factor

The voltage-stress factor and the quality factor are cost-sensitive; that is, tradeoffs are possible between cost of the device and the failure rate.

An example is instructive. Table I lists the appropriate factors for a NPN silicon transistor used in a benign ground environment (a laboratory or similar protected environment). The transistor will be operated at a collector voltage of 40% of V_{CBO}.

TABLE I

MEAN-TIME-TO-FAILURE EXAMPLE

NPN SILICON TRANSISTOR

$\Pi_E = 1$ Ground Benign Environment, 25°C
$\Pi_A = 1.5$ Linear amplifier application
$\Pi_Q = 0.2$ JANTXV quality level
$\Pi_{S2} = 0.48$ Voltage stress level $= 0.4 \times V_{CBO}$
$\Pi_C = 1.0$ Single transistor complexity

$\lambda p = 0.0014$ Failures per 10^6 hours

All factors from MIL-HDBK-217B

Once the failure rates of the individual parts are determined, the failure rate of the equipment, λ_{EQUIP} can be computed by summing over all parts,

$$\lambda_{EQUIP} = \sum_{i=1}^{m} \lambda_{pi}$$

where

m is the number of parts in the equipment

and

λ_{pi} is the failure rate of the i^{th} part.

As examples of the results of such calculations, the following results were obtained for two typical frequency standards:

a.) Precision 5 MHz Crystal Oscillator: λ_{EQUIP} = 470,000 hours
(Ground Benign, 25°C)

b.) Cesium Beam Frequency Standard: λ_{EQUIP} = 68,000 hours
(Ground Benign, 25°C)

It should be noted that these estimates include all electronic piece parts, but exclude the precision quartz resonator and the cesium beam tube resonators. This exclusion will be discussed in greater detail later.

Parts Cost Considerations

The voltage stress and the quality factors were earlier indicated to be cost-sensitive items. The calculated part failure rate can be reduced by selecting derated parts and by chosing high-quality parts. All other things being equal, a higher-voltage rated capacitor will be more expensive than a lower-voltage device and similar arguments apply to transistors and resistors. In most instances, the economic impact of derating is moderate and the effect on equipment reliability is substantial and cost effective. Note, however, that there are pitfalls to an undisciplined attempt to achieve low failure rates through part derating. Transistor voltage stress level is an excellent example - the selection of a device with a high V_{CBO} rating may sacrifice other desirable characteristics such as switching speed and result in an overall lower equipment reliability in practice. The cost impact of higher quality parts can be very high, however. Table II is a listing of the purchase price of typical Established-Reliability capacitors, in single unit quanties, as a function of the failure level of the device. Prices of established reliability parts have been volatile recently, so that only the relative prices should be considered.

Parts, including Established Reliability types, used in equipment intended for critical applications are generally required to be rescreened - tested by the equipment manufacturer upon receipt from the factory or distributor. Rescreening costs can be considerable, often greater than the purchase price of the parts themselves, and difficult to accurately predict. The actual costs of the electrical and mechanical screening tests and of the required destructive physical analyses (dissection and microscopic examination of samples of each lot) are only a portion of the total costs attributable to rescreening. The loss of entire lots of parts due to excessive failure rates in either electrical, mechanical or destructive testing, may require the procurement of from three to ten times the quantity of parts normally required.

TABLE II

ESTABLISHED-RELIABILITY PARTS COST EXAMPLE

Capacitor: Solid Tantalum, 22MF, 50VDC ± 10%
Type CSR13G226M

Failure Level	Failure Rate Factor (Π_Q)	Price
L	1.5	----
M	1.0	$10.28
P	0.3	13.15
R	0.1	21.80
S	0.03	30.45

Limitations of Parts Stress Analysis

It should be reemphasized that parts stress analysis is only one of a number of sophisticated analytical techniques available to the reliability engineer. Taken by itself, a parts stress analysis does have certain value. It can illustrate the reliability improvements possible by replacement of lower quality parts by higher quality parts and the tradeoff of part costs versus increased MTBF. Perhaps the most important use of parts stress analysis is to provide a quick and simple means for estimating the relative failure rates of competitive equipment all other things being equal. A simplified technique, parts count reliability prediction, can be used for this purpose before the circuit design has even been completed, if the approximate parts count in each generic part category (resistor, capacitor, relay, etc.) can be estimated.

Parts stress analysis, however, cannot be used to compare equipment of varying complexity. In fact, noncritical application of parts stress analyses in these cases can be misleading. A multistage-stage transistor amplifier of marginal performance is a simple illustrative example: an additional stage of gain will improve the reliability of the amplifier in the commonly understood sense of the word. The parts stress analysis taken alone, however, indicates a decrease in the MTBF.

The extension of this concept to clocks and frequency standards is straightforward. Stated simply, the MTBF estimates do not indicate the relative reliabilities of different clocks, or different types of clocks, when applied in real-world systems. The precision quartz crystal oscillator, discussed earlier in this section, with a MTBF of 470,000 hours, is not necessarily more reliable than a cesium beam frequency standard with a MTBF of 68,000 hours. If a system specification requirement is that a frequency shall be maintained to within 1 x 10^{-10} of an inital value, then the quartz oscillator will "fail" within a matter of days or weeks due to its frequency aging, whereas the cesium beam frequency standard could operate satisfactorily for about 7 years.

There is another, perhaps more fundamental, limitation of the application of parts stress analysis to state-of-the-art clocks and frequency standards: the inadequate reliability data base for the resonators; precision quartz crystals, rubidium cells and lamps, and cesium beam tubes. Parts-stress MTBF estimates are statistical data based on many millions of hours of user experience with a large number of electronic piece parts. It is not meaningful to factor into these estimates failure rates for resonators based on a limited sample of a few dozen to a few hundred parts. The examples shown above assumed that the MTBF was not limited by resonator failure; an adequate treatment of the subject, although admittedly of utmost importance, is beyond the scope of this paper.[2]

QUALIFICATION

Military and aerospace equipment is normally "qualified"; validated by test and analysis to survive and operate in a specified environment. Qualification is an expensive and time-consuming process, justified by the expectation that the qualified equipment can be deployed with confidence.

There is an unfortunate corollary to the concept of a qualified item of equipment; unless the specific test and analytical sequences are completed, the unit is unqualified. This fact has become a powerful inhibitor to the use of existing or previously developed clock and frequency standards in new systems. Each system or platform has its own specification and corresponding environmental and performance requirements. The resulting design changes dictate further qualification testing, adding to the cost spiral without signifigantly improving either performance or reliability.

In addition, different and incompatible requirements for similar space vehicles or for different portion of the same payload are not unusual. The lack of standardization, however, may go beyond objective requirements of the actual environmental conditions; test requirements are sometimes specified in conflicting and incompatible terms, even in cases in which the actual physical conditions are similar or identical. Shock and vibration requirements are particularly subject to requirements proliferation. Shock testing for example can be specified in terms of hammer blows, pyrotechnic simulation spectra or time-domain pulse shapes and it is often difficult or impossible to analytically verify that a clock which has been qualified to one set of shock criteria will prove satisfactory under a different set of test conditions.

The major casualty of the proliferation of specifications and the non-standardization of requirements is the "off-the-shelf" high-reliability clock or frequency standard. For the reasons outlined above, clock manufacturer cannot prequalify the instrument and offer it as a standard item. It follows, therefore, that production runs are always short and that clock prices reflect the inability of the manufacturer to amortize development, documentation and project management costs over a large number of units. Furthermore, reliability inevitably suffers when only a small number of items are fabricated. The normal product maturation process (learning curve) by which design and workmanship problems encountered in the early production units are corrected in later production runs never has a chance to operate.

SPECIAL INTERFACES AND FREQUENCIES

The primary purpose of a system clock is to provide a stable, reliable and precise time or frequency reference. This challenges the clock manufacturer if the requirements of the system specification are at or near the limits of the state-of-the-art and new or unique interface requirements such as special output levels, multiple outputs, "TTL-compatibility", special ground isolation, or operation from non-standard supply voltage are an additional, and often costly, burden.

When a special or non-standard interface is specified, the clock manufacturer must incur not only the engineering costs associated with the development of new circuitry and mechanical packaging, but documentation, reliability engineering and qualification testing expenses as well. Even if the basic frequency control circuits and resonators are proven and reliable, the qualification legacy may be lost because of the addition of the special features.

The specification by a user of a non-standard or unusual frequency for a high-performance clock presents the clock manufacturer with a difficult measurement problem, one that may be unique to our industry. If state-of-the-art performance is required, the manufacturer is usually instrumented to measure frequency stability and phase noise spectra at a few commonly used frequencies such as 5.000 or 10.23 MHz. The only feasible technique for certain measurements at non-standard frequencies may be the fabrication of additional units or of special test systems. Therefore, certain specification requirements may not be economically feasible at all for a small production order.

CLOCK COST EXAMPLES

It may be useful to examine two illustrative examples of some of the relative cost elements of high-performance clocks for spaceflight applications. The examples are composites and are not intended to represent the pricing of any specific instruments. The relative costs in both cases are for small production quantities and the parts and parts screening costs reflect the distortions caused by minimum lot-size procurements. The per-unit parts cost would be considerably less for larger production quantities.

Precision Quartz Crystal Oscillators

Table III shows a composite relative cost breakdown for a quantity of four space-qualified crystal oscillators.

All electronic parts in this example are to be ordered to JANTXV or to Established Reliability Level "S" and subjected to rescreening and a sampling DPA.

TABLE III

PRECISION CRYSTAL OSCILLATOR COST EXAMPLE

Parts		44%
Purchase	19%	
Rescreening and DPA	25%	
Manufacturing and Test		8%
Qualification Test		4%
Program Management		30%
Design and Development		14%
TOTAL		100%

Atomic Frequency Standards

A second example, shown in Table IV, is a quantity of four space-qualified atomic frequency standards. The parts are to be selected to the same standards as in the previous example.

TABLE IV

ATOMIC FREQUENCY STANDARD COST EXAMPLE

Parts		28%
Purchase	14%	
Rescreening and DPA	14%	
Manufacturing and Test		15%
Qualification Test		7%
Program Management		30%
Design and Development		20%
TOTAL		100%

A moderate amount of engineering effort, primarily reliability and parts selection oriented, has been assumed. Major changes in the basic design, such as any of the interface characteristics, would require substantial increases in the design and development costs.

It should be noted that a very signifigant fraction of the costs shown are unrelated to the specific technology of the clock but rather arise from the reliability, testing and management aspects of the program. Since these cost elements tend to be similar for equipments of roughly the same complexity, the cost differentials between high-reliability, high-performance clocks based on different timekeeping systems can be expected to be much smaller than for the respective commercial counterparts. Flight-qualified cesium and rubidium frequency standards, for example, are roughly equivalent with respect to initial acquisition costs.

RELIABILITY AND LIFE-CYCLE COSTS

The previous discussion has been primarily concerned with the acquisition costs of clocks. In most cases, however, the operational costs of the system far exceed the procurement costs and the total life-cycle costs must be considered in the selection of a clock or frequency standard for a particular system application.

It is difficult to treat adequately the subject of life-cycle costing without a more careful consideration of the performance and reliability of the system clock. In general, the mission of any system can be accomplished over a wide range of system clock performance capabilities. With less stable or less precise clocks, the system must be resynchronized more often than with more stable and precise clocks but, in principle at least, mean-time-between-resynchronizations (MTBR) can be traded off directly for system clock performance. Neglecting systematic errors, a precision quartz crystal oscillator requires resynchronization at 1-day (approximately) intervals to maintain one-microsecond time accuracy. A rubidium frequency standard requires resynchronization about every 10 days for the same accuracy, and cesium frequency standard about every 100 days. The resynchronization process may require frequent travelling clock trips or additional radio-frequency channels and may be difficult or expensive because of security or operational considerations, but the principle is still valid. It is interesting that the MTBR, which is derived from the performance of the clock and the requirements of the system is also a useful measure of the reliability of the clock in the specific application. The probability of outright failure of the clock cannot be neglected, but in those cases in which the MTBR is much less than the MBTF, the MBTR number must be considered to be a primary indicator of clock reliability.

The lifetime cost of resynchronization; the total life of the system divided by the MTBR and multiplied by the cost per resynchronization, can be computed readily for a large variety of systems. For example, at the Deep Space Network, operated by the Jet Propulsion Laboratories, preliminary estimates have been made of the tradeoff of operational costs for network time synchronization by simultaneous radio telescope observations of quasars versus the cost of acquiring and operating improved atomic frequency standards.[3] The improved clocks extend the MTBR by approximately a factor of ten and for network operational costs of $500 to $1000 per hour per tracking station, the life-cycle costing excercise favors the use of the improved standards, even at very high acquisition cost levels.

Although it is not possible to generalize broadly from this example, it appears that for multi-user, continuous-duty applications such as spread-spectrum communications systems and navigation satellite systems, operational costs dominate the life-cycle-costing estimates. In these instances the acquisition costs of the system clock is a secondary consideration and the primary concern of the system designer should be the MTBR.

CONCLUSION

The ability of the clock manufacturer to supply reasonably priced clocks and frequency standards for high-reliability applications would be greatly enhanced by the standardization of clock frequencies, interfaces and environmental requirements. Conversely, the cost of clocks for aerospace applications is inflated by the very small production quantities required for most systems and the consequent small base over which development and management costs can be amortized.

Stable, high-performance clocks improve the reliability of systems as measured by the mean-time-between-resynchronizations. Therefore, there does not exist a one-to-one relationship between clock complexity and reliability, in contrast to the conventional parts-stress analysis of failure rates. It also follows that the total operational costs of a system are inversely proportional to the MBTR and that the system designer must include resynchronization costs as well as procurement costs in the life-cycle-cost estimates.

Finally, the focus on the electronic circuit performance clocks without an equivalent effort of obtain data on the resonators may be misleading to the designer as well as the user.

REFERENCES

(1) "Reliability Prediction of Electronic Equipment" Military Standardization Handbook MIL-HDBK-217B. US Government Printing Office, 1976,

(2) D.B. Percival, G.M.R. Winkler, "Timekeeping and the Reliability Problem", Proceedings 29th Annual Symposium on Frequency Control, VS Army Electronics Command, Fort Monmouth, N.J. pp 412-416 (1975). Copies available from Electronic Industries Association, 2001 Eye St, NW, Washington, D.C. 20006

(3) E. Thom, private communication, 1979

QUESTIONS AND ANSWERS

QUESTION:

I liked it very much, but I wish you could have included some idea of how often these costs are not typical of contract by delivery price. You never once mentioned the fact that so many manufacturers count on delivery and then you have people sitting around with nothing to do because some other supplier has not given them or has a good excuse for not delivering.

DR. LEVINE:

My experience has been that everybody working on a system is hoping and praying that somebody else will come in late.