AT&T Technical Journal
Vol. 64, No. 3, March 1985
Printed in U.S.A.

Introduction

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(Manuscript received October 5, 1984)

The transatlantic optical fiber submarine cable system—employing semiconductor lasers and photodetectors and scheduled for service in mid-1988—is the first application of lightwave technology to transoceanic communications. This eighth transatlantic undersea system, known as TAT-8, represents a radical departure from its predecessors. The previous systems used coaxial cables as a transmission medium, with periodically spaced repeaters to amplify the analog signal back up to its original level, thus compensating for the cable attenuation. The technology and components required were well understood from previous use in similar ocean and land-based systems. In contrast, TAT-8 will use pulses of light traveling in glass fibers, with periodic regeneration of the pulse train. This will require the use of state-of-the-art semiconductor lasers and photodiodes for which there is no prior reliability experience for a land-based system.

There are several advantages which motivate this changing over from an analog-coaxial cable to a digital-optical fiber waveguide system. The coaxial cable technology has reached a level of maturity where only modest further cost reductions can be anticipated from future designs, whereas the lightwave technology is still evolving rapidly. Significant increases in repeater spacing and higher bit rates—making possible large cost reductions and increases in traffic capacity and improving the reliability of deep-water repeaters—can be anticipated. Furthermore, a digital submarine cable can be part of an

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all-digital world network, which permits applications not possible if analog links are present. One very important example of such an application is the highly efficient circuit multiplication made possible by digital processing of voice signals. The price of obtaining the advantages offered by this new technology, however, is the use of state-of-the-art components.

The question that we consider in this issue is the following. If a lightwave submarine cable is built, is it possible in advance of deployment to assure that it will perform with no more than approximately three repairs in the desired 25-year system lifetime—a goal dictated by the costs of repairing a deep-water cable, including the provision of alternate transmission service during a period of up to several weeks that it may take to effect a repair. The answer to that question depends critically upon the behavior of the two newest state-of-the-art semiconductor components, lasers and photodetectors. Given that there already exists evidence suggesting feasibility (i.e., at least some individual devices appear to possess the potential for long life), the determination of whether adequately large numbers of lasers and photodetectors have sufficient reliability is conveniently broken up into two stages. Using the available knowledge concerning modes of failure about these and other similar semiconductor lasers and detectors, the first stage involves the design of the most suitable strategies for the timely detection of potential premature device failures. With a tentative best-approach in hand—one subject to alteration as subsequent data analysis might compel—stage two is concerned with determining whether any particular group of devices is adequate in fact.

This two-stage approach is mirrored by the division of papers in this collection. The emphasis in the first group is upon analyses of various reliability assurance strategies, including those proposed by us, as well as the more traditional ones. These analyses serve to critique, organize, and develop methodologies for reliability assessment. The second group of papers focuses upon the implementation of these strategies *and* the results of preliminary studies of unpackaged devices. These results provide compelling evidence for our conclusion that the device designs are consistent with the high-reliability goal and that the strategies which we have employed can provide for the selection of those devices that will meet that goal.

There were several motivations for producing the first group of papers. One was the absence in the literature of a comprehensive and critical discussion of methodologies for reliability assurance. Although the literature on reliability assurance is vast, the focus tends to be on specific failure modes of specific devices or upon mathematical modeling. No prior work provides an adequate organized way of thinking about how to assure the long-term performance of new semiconductor components. While the first group of papers often employs the laser as a particular exemplary device, that group is intended to have potential applications for a broad range of semiconductor devices. It represents the papers that we wished had existed when we embarked upon this project.

Another motivation was prompted by the difference between the approach mandated for the 1988 deployment of TAT-8 and the approach that had governed all previous systems. Historically, the assurance of the high reliability required for submarine cable transmission was predicated upon the use of well-proven device types for which failure modes had been identified in previous systems and for which performance/reliability trade-offs were well understood. The desire to harvest the benefits offered by new technology requires the incorporation of rapidly evolving state-of-the-art components for which there has been no prior use and about which little is known in detail. Substantial emphasis must then be placed upon strategies for the early detection of system-threatening premature failures, which *may* occur. These strategies are based upon a priori considerations, rather than extensive manufacturing and field experience. There has to be as much focus upon the possible as upon the probable failure modes.

A final motivation springs from the observation that certain traditional strategies fail to take full advantage of the character of failure which exists in semiconductor components. For example, it is observed that detectors fail suddenly, without warning. In such an event, traditional population-inference approaches are the best available. It is also observed, however, that mechanisms controlling laser lifetime lead to gradual degradation. In this event, information about the early behavior of an individual laser can be very important in assessing the prospects for longevity of that device. What is needed for lasers is an individual-inference scheme to supplement the traditional population-inference approach; substantially greater reliability assurance is the goal. Such a scheme is discussed at length in the first group of papers.

All of the papers in this collection have a common approach. It is that reliability assurance is to be determined by extrapolation in temperature rather than time. Either one or the other is inevitable when the desired system lifetimes are tens of years; clearly it is unacceptable to wait for 25 years to determine whether a device operating in field conditions will actually live 25 years. For a slowly degrading device such as a laser, both temperature and time extrapolations are possible in principle. A straightforward application of the purely temporal option would involve aging each laser at the use temperature for as long as it took to determine the aging law (e.g., the time dependence of the operating current, $I_{op}(t)$, to maintain a constant optical power output), and then using this law to compute the behavior at the end of the designed system lifetime. Experience with aging long-wavelength (1.3-μm) lasers suggests that the data follow a sublinear aging law that is not universal, e.g., $\beta t^{1/2}$, but which appears to have a universal form,* e.g., βt^m, $m < 1$. Thus, the parameters β and m will be different for each laser. The problem, however, is that even if an empirical aging law were adequately parametrized for the aging-test period (approximately 1 year), the temporal approach offers no assurance that the same law or the same parameters are valid at 25 years. The very nonuniversality of the aging law—i.e., the fact that the law is not, for example, $t^{1/2}$ for every laser—raises the suspicion that each laser is being controlled by different processes. The unsatisfactory nature of the temporal extrapolation is that an empirical law established, however well, in some test period is then assumed to hold for a period of time that is more than an order of magnitude longer than the test period. This is not the approach which we have adopted, because there is *no* basis for any confidence in such a temporal extrapolation.

The approach which underlies virtually all of the work in this collection is that of thermal extrapolation. Semiconductor reliability experiments show that failure can be accelerated by increasing the temperature of the device. It can be said that increasing the temperature makes the internal device clock run faster. The degradation rate (or reciprocal of the lifetime) is often found, and hence usually assumed, to be proportional to $\exp[-E_a/kT]$ where the empirically determined activation energy, E_a, has a reasonably well-defined value for a particular type of device. Proof of the validity of this acceleration factor between test and use temperatures is, of course, an important part of a reliability assurance program. Once E_a is known, it is possible to age devices at elevated temperatures for relatively short periods of time (approximately 0.1 year), which are equivalent to examining the actual behavior of the device for a system lifetime (25 years) at a lower use-temperature. The behavior of a device at the end of 25 years can be determined without waiting 25 years. It is this ability to "crystal ball" the future which makes the temperature extrapolation approach so desirable; temporal extrapolation has no comparable virtue. This does not preclude using observations over a relatively long test period (though still short compared to system life) under use conditions to

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* Aging should proceed sufficiently long so that an empirical sublinear law of the form $\beta \ln(bt + 1)$ could be distinguished from βt^m, $m < 1$. If insufficient aging time were available to make such a distinction, the more conservative form, βt^m, could be chosen.

enhance confidence that the accelerated aging scheme accurately models the behavior of the laser in the system.

For the purpose of guiding the reader through this volume, the remainder of the introduction will be devoted to a brief description of the contents. In the first paper, "Selection of a Laser Reliability Assurance Strategy for a Long-Life Application," critiques of traditional approaches to reliability assurance provide relevant nomenclature and concepts. To overcome the perceived deficiencies of conventional approaches, to deal with anticipated types of particularly deleterious or misleading degradation behavior in semiconductor devices, and to take full advantage of the character of long-term laser degradation, an alternative strategy for providing reliability assurance is proposed. Its regimes are called "stabilization," "purge," and "truncation." As previously noted, lifetime estimates will rely upon temperature extrapolation. Confidence in these estimates would be substantially undermined if the long-term degradation rates measured in elevated-temperature accelerated-aging tests reflected only an initial transient behavior *or* if there existed weakly temperature-activated, suddenly occurring, early (infant) failure mechanisms that might be expected to remain undetected if temperature were the only degradation accelerant used. By overstressing all available driving mechanisms for degradation, purging (a timely identification of infant failures) and stabilization (a rapid driving to completion of transient behavior) are accomplished. The result should be a population of devices whose longevity is controlled exclusively by a gracefully occurring degradation (wear-out). Truncation is the process by which devices are sorted according to their initially measured degradation rates and only those degrading sufficiently slowly are kept for use. The success of the rate-monitoring process to implement truncation depends upon a prior elimination of devices prone to sudden failure and the stabilization of transient behavior.

The starting point in the second paper, "Methodology of Accelerated Aging," is at the end of the stabilization and purge regimes. It is assumed that a long-term thermally accelerable wear-out mode of degradation controls the behavior of all devices; all infant mortalities have been eliminated and all transient behavior has been stabilized. In approximately one-half of this paper, a conceptual framework is presented for understanding the information provided by accelerated aging, using temperature as an exemplary accelerant. Considerable analysis is given on the important distinction which must be made between, for example, a thermal activation energy (all measurements of failure or degradation caused by operation at higher temperatures are performed at a lower reference temperature) and a thermal extrapolation energy (measurements of failure or degradation are performed at the same temperatures at which the failure or degradation occurs). The related discussion makes clear why there can be considerable variations in the experimentally determined values of these often undifferentiated energies. In a given experiment, the amount of degradation is determined not just by the initial and final aging points in time-temperature space, but also by the particular path between these points. As a consequence, it is next shown that the simplest possible model of accelerable degradation is, in mathematical terms, a differential form. Differential-form modeling is developed and used for extrapolation outside the scope of the usual integrated-form models. In the event that the projected device lifetime exceeds that of the system, it is next shown how to achieve a considerable saving in aging time and cost by not aging the device to failure, but only for an *effective* system lifetime, i.e., the equivalent, but shorter in real time, lifetime of a device aged at some elevated temperature. Finally, a procedure is given for assessing the effectiveness of truncation, i.e., a procedure for quantifying the uncertainty in projections based on the initially observed degradation rates.

This truncation-assessment procedure is given a more detailed quantitative formulation in the third paper, "A Statistical Approach to Laser Certification." A statistical "correction factor"—obtained by comparing the *actual* degradation that occurs for a population of devices aged for an effective (i.e., temperature-contracted) system lifetime with the *predicted* degradation based upon observations of initially occurring degradation rates—is important in quantifying the risk associated with a reliability assessment dependent upon initially observed rates.

The group of experimental studies commences with "1.3-μm Laser Reliability Determination for Submarine Cable Systems," whose main purpose, consistent with the temperature extrapolation approach for lifetime estimates, was the determination of the activation energy associated with the long-term (wear-out) degradation and characterization of the aging behavior at elevated temperatures. The lasers used were neither stabilized nor purged. To the extent that the initial degradation behavior displayed undesirable characteristics, the elimination of those characteristics would be the goal of a stabilization procedure. Indeed, a substantial transient behavior (large initial degradation rates) was observed which required approximately 1 kilohour to stabilize even at elevated ambient temperatures (60°C). The more graceful wear-out degradation occurred only after this initial effect had been stabilized. Because of a considerable variation observed in post-stabilization rates of degradation among nominally identical lasers, it was decided to abandon the traditional *isothermal* approach to determining activation energies, in which the median degradation rates of two groups of lasers aged at different temperatures are compared. Instead, a *step-temperature* technique, in which each laser is consecutively aged at two elevated temperatures, was employed to determine an activation energy for each individual laser. All such values were found to lie in the range 0.8 to 1.3 eV. Assuming that failure is defined by a 50-percent increase in operating current, I_{op}, above its initial value, and assuming that the increase in I_{op} is linearly dependent on time, the estimated activation energies were used to predict more than adequate lifetimes at ocean bottom temperatures for the lasers examined. The above assumptions are conservative; other studies have shown that transmitter packages continue to perform adequately,[1] beyond the 50-percent increase in I_{op}, *and* that long-term degradation is actually temporally sublinear[2] over several effective (temperature-contracted) system lifetimes. This conclusion of adequate lifetimes for an unpurged, untruncated population leads to high confidence that a properly screened population will exhibit a comfortable additional margin.

The next paper, "Implementation of the Proposed Reliability Assurance Strategy for an InGaAsP/InP, Planar Mesa, Buried Heterostructure Laser Operating at 1.3 μm for Use in a Submarine Cable," is an attempt to put into practice the reliability assurance strategy described in the first paper of this volume. The most important aspect of this work was the discovery of a regimen in which high currents (250 mA dc) and high ambient temperatures (150°C) could be used to compel a rapid stabilization (10 hours) of a large initially occurring transient degradation phenomenon (referred to previously) that appears to affect many lasers. The unstabilized presence of this transient behavior can lead to erroneously large or small estimates of the activation energy and hence to misleadingly pessimistic or optimistic lifetime predictions. The survivors of the purge-stabilization process were subjected to the truncation process that sorted the aging rates in an elevated temperature (60°C) burn-in operation. The largest observed increase in operating current that occurred in *one* effective system lifetime was a negligible 3 percent, and observations conducted for at least *five* effective system lifetimes showed the degradation to be well behaved and the cumulative largest increase in operating current to be only about 20 percent. These results are in accord with those previously mentioned that predict more than adequate longevity for the subcable lasers.

The final experimental study, "Reliability of InGaAs Photodiodes for SL Applications," is concerned with developing and verifying a purge procedure for photodiodes. Unlike the lasers, which *appear* to have no suddenly occurring failures, such failures, which are not preceded by cognizable warning signs, can occur to a significant extent in InGaAs photodiodes. A conventional elevated temperature (200°C) burn-in can promote these sudden failures but only at the expense of time (approximately 1 kilohour) and some consumption of the useful life of "good" diodes. A high-temperature (200°C), high-reverse-bias (20V) purge lasting 10 hours was developed to eliminate weak devices outright and to identify those devices likely to become early failures. The effectiveness of this purge was confirmed by a subsequent long-term elevated temperature burn-in.

It is to be understood that all of the experimental work presented on components is based upon data acquired in the period mid-1982 to mid-1983, and it represents an early snapshot in a continuing program that is now investigating the reliability and performance of packaged components and subassemblies such as transmitters. Additional work on lasers and detectors is also currently being performed.

Some redundancy will be noted in this collection of papers. This is inevitable and desirable as individual workers strive to refine the perspectives in which new results should be viewed. Minor differences exist in the more speculative conclusions drawn by some of the authors. These are important because they focus attention on work for future study. Particular conjectures may be applicable to the populations studied, but may not be valid for the subpopulations resulting from stabilization, purging, and truncation. Having said all of this, it is well to restate that important conclusion, unanimously supported by the authors, which is that our critical components, the lasers and detectors, have more than adequate reliability for the submarine cable application.

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AUTHORS

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