THE BELL SYSTEM
TECHNICAL JOURNAL

Volume 47 | October 1968 | Number 8

Step Stress Aging of Plated Wire Memories

By I. DANYLCHUK, U. F. GIANOLA, and J. T. SIBILIA

(Manuscript received February 5, 1968)

A rate of 0.3 failures per billion hours or less is desirable for memory components in large integrated arrays. This unusually stringent requirement complicates the determination of lifetime from accelerated aging studies. The value and limitations of step stress aging techniques are discussed in terms of experimental results obtained using plated wire memory arrays designed to withstand the high ambient temperatures required for accelerated aging. Step stress aging measurements alone are insufficient for confident lifetime prediction. Therefore, longer term measurements at lower temperatures must also be made to establish the validity of the lifetime extrapolations. It is essential to protect the plated wires against corrosion. Given proper protection a shelf life in the hundreds of years is forecast. The importance of duty cycle on lifetime in exercising the memory is discussed and the results of aging under extreme pulsed magnetic field stress conditions are reported. Criteria for wire selection, with long term stability in mind, are discussed.

"And in short measures life may perfect be"—Ben Jonson

I. INTRODUCTION

In spite of their advanced state of development, there is still uncertainty concerning the long term stability of magnetic film memories. As early as 1958 E. N. Mitchell showed that the anisotropy of permalloy thin films could be modified by a magnetic anneal at moderate temperatures.[1] Chang, Gianola, and Sagal subsequently pointed out that such a phenomenon could be detrimental to the lifetime of a magnetic film memory element, and that in the case of plated wire intolerable changes in magnetic anisotropy and coercivity occur in freshly plated films.[2] These changes result in an increased minimum digit current for reliable writing along with a serious decrease in the digit disturb level. The result is a monotonic reduction in operating margins that, in time, can lead to a complete loss of range.

It was, however, also shown that the magnitude of the rate of change of magnetic properties could be substantially reduced by following electrodeposition with a stabilization anneal in an easy direction field.[2, 3] From a practical standpoint, a stabilization anneal has been found essential and is now in general use in plated wire fabrication. It is worth noticing that a post-deposition anneal is automatically provided in vacuum deposited magnetic films, since the latter are deposited on a hot substrate which is allowed to cool in the vacuum system.

From a simple physical viewpoint the effectiveness of the stabilization anneal should increase with annealing temperature and annealing time. However, Chang, Von Neida, and Calbick have shown that detrimental changes can also occur in electro-deposited films even when annealed in an easy direction field, thereby setting effective limits on the maximum annealing temperature for a given annealing time.[3] These limits were shown to correlate with discontinuous grain growth in the film. Grain growth, however, may have been complementary rather than causative to the increased dispersion in magnetic anisotropy noted. Copper diffusion from the substrate wire into the permalloy film has been shown not to be a primary contributor to the aging mechanism.[4]

These early studies showed that the post-deposition anneal extended the mean lifetime of the plated wire memory element to years or decades. Subsequent studies, however, have shown that a clear prediction of lifetime is complicated by a distribution of aging rates between individual bit elements in a large capacity memory, reflecting both nonuniformity in initial element properties as well as the distribution expected of a stochastic process. Since in a highly integrated large memory system the time to occurrence of the first few failures is of greater interest than the mean time before failure that is commonly used to define the lifetime of discrete components, the distribution of failures is of prime importance. The aging phenomenon in magnetic films is also field dependent, being accelerated by hard direction fields (word fields) and retarded by easy direction fields (digit fields).[2] Therefore, since hard and easy direction fields are applied intermittently in an operating memory system, an added complication to useful lifetime prediction is the need to establish the average field environment that a memory element experiences over years or decades of use.

Earlier work has primarily been concerned with changes in dispersion and skew produced by a magnetic anneal, thereby delineating the magnitude of the aging phenomenon, but falling short in that a clear relation between skew and dispersion and the functional memory parameters of interest was not simultaneously established. Rabinovici and Renton subsequently examined the effect of aging on the functional parameters directly,[5] but, while a step in the right direction, the sample population used was insufficiently large to permit lifetime predictions at low failure levels.

To estimate the problem, consider some of the current thinking about high speed memories for which the plated wire is well suited. To achieve an economical system, a compact construction with a minimum number of interconnections, is desirable. We estimate that a suitable module size is about 4×10^5 bits; for example, 4096 words $\times$ 100 bits. Such a store operating as part of the central processor in an electronic switching office would be unacceptable if it were necessary to rework a single spare word or digit line once a year. On this basis then, if each bit in the memory is considered an independent device (not a fully justified assumption since failures are often grouped), an accelerated aging technique capable of predicting with some accuracy one failure in greater than 3.5×10^9 device hours (0.3 FIT) is needed.*

Clearly, it is impractical to build, age, and test large stores for the extended periods needed to derive statistically significant aging data under normal operating conditions. To overcome this difficulty, we have examined the possibility of adapting step stress accelerated aging techniques to magnetic memories in order to estimate lifetime at normal operating temperature. Such techniques are commonly used, particularly for determining the reliability of semiconductor components,[6] but have not been applied previously to memory arrays. This paper attempts to define the value and limitations of the tech-

* 1 FIT = one failure in 10^9 device hours.

nique based on exploratory step stress aging studies of typical plated wire memory arrays.

II. STEP STRESS AGING

It is well established that the aging process in thin magnetic films is thermally activated, and a reasonable starting assumption is that the aging process can be described by a characteristic time constant τ, which is governed by the Arrhenius rate equation. More specifically, it is assumed that the average behavior of a device parameter of interest $P(t)$ can be adequately represented by $P(t) = P_0 + F\ (t/\tau)$, where P_0 is the average initial value. For the present purposes $F\ (t/\tau)$ need not be defined, the only assumption necessary is that it be a continuous monotonic function, albeit a complicated one. In addition, although a number of different rate mechanisms enter into the aging process we postulate a single time constant only. That condition, in fact, must be satisfied if the lifetime extrapolation is to be valid as discussed later.

The Arrhenius rate equation relates the aging time constant to the aging temperature, as follows:

$$\tau = \tau_0 \exp q/kT.$$

Where τ_0 is a characteristic time constant, q = activation energy, k = Boltzmann constant, and T = absolute temperature. This equation describes many of the mechanisms responsible for device degradation; for example, interatomic diffusion, chemical reactions, and crystallite growth.

The procedure followed in step stress aging is first to define a pass-fail criterion, defined by limits on one selected device parameter. In testing memory arrays a convenient device parameter is the output signal, which may be required to exceed a set discrimination level for a given set of operational write, disturb, and read current levels. All bits which give outputs exceeding the discrimination threshold pass, all others fail.

Such a pass-failure criterion is equivalent to setting $P(t_f)$ equal to a predetermined constant P_f at the time of failure t_f. Consequently, the value of $F\ (t_f/\tau) = P_f - P_0$ and therefore t_f/τ are in turn predetermined constants and the Arrhenius rate equation can be used to relate the time of failure to the temperature at which aging is being carried out as follows:

$$\ln t_f = \frac{q}{kT} + \ln \tau_0 + \ln F^{-1}(P_f - P_0).$$

In other words, $\ln t_f$ is inversely proportional to T.

The first step in a step stress aging measurement is to stress (that is, anneal) the sample population at an elevated temperature T_1 for a prescribed time t_1, and then retesting at ambient temperature to determine the number of failures produced, if any. The sample is then once more stressed for the same period (t_1) as before but at a higher temperature ($T_1 + \Delta$). The temperature increment Δ is such that any failures produced are large compared to those accumulated at the lower stress temperature.

Experiment has shown the aging process to have an activation energy of about one electron volt. Therefore, a 20°C increment is appropriate. After aging, the sample is retested to determine the cumulative number of failures. This procedure is continued at successively higher temperatures using approximately the same temperature increment each time until the entire population has failed according to the original test specifications. This series of measurements provides a distribution of failures as a function of temperature for a given exposure time. Figure 1 shows a hypothetical distribution plotted as a function of inverse stress temperature. For the particular exposure

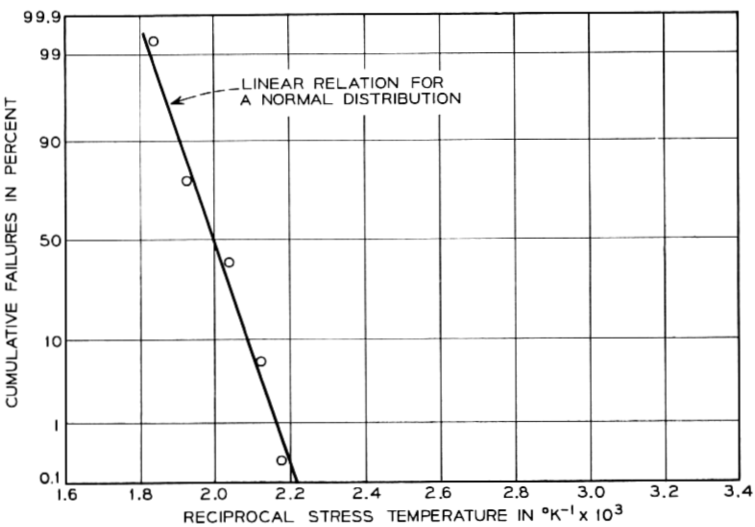

Fig. 1 — Hypothetical step stress aging data.

time chosen, no failures are observed to temperatures up to 200°C, and 1, 10, 70, and 100 percent cumulative* failures are obtained after stressing at 200, 220, 240, and 260°C, respectively.

The distribution of failures in temperature will depend upon both the initial distribution of P_0's and the statistical variations expected of a thermally activated process. If these were random, a gaussian distribution of failures after aging might be expected as suggested in Fig. 1. However, such a distribution is virtually precluded by an initial selection criterion that truncates the distribution of P_0's. If that were not the case, the initial sample population would contain that percentage of bad bits expected of an initially random distribution. This complicates the extrapolation of aging measurements based upon a small sample population. To reduce the uncertainty, the predictions of a step stress aging experiment must ultimately be confirmed on larger sample populations.

The distribution of failures in temperature may be converted to a distribution of failures in time. To do this, a second set of step stress measurements are obtained using a second sample population as identical to the first as possible, but in this case stressed at an exposure time t_2 that is approximately an order of magnitude larger than t_1. The failure distribution in this case will be centered at a lower temperature as illustrated in Fig. 2, which plots the logarithm of time to a given percentile failure versus the inverse stress temperature. A straight line extrapolation through points of equal failure in Fig. 2 provides an estimate of the time required to reach that level of failure at normal operating temperatures, for example, $\leqq 50°C$. The slope of the linear relationship is determined by the activation energy (q).

Figure 3 illustrates the difficulties encountered if aging is not the result of a simple thermally activated process. If it is assumed, for example, that two distinct and independent processes exist, then, depending upon the relationship between the τ_0's and q's, a lifetime extrapolation from an accelerated aging measurement may or may not be valid. If the τ_0 for the high q process is larger than that of the low q at all temperatures then the extrapolation will be valid. If, however, the high q process has the shorter τ_0, it may dominate at the temperatures used in step stress aging, thereby leading to an invalid life prediction because at the operating temperature the low q

* Averaging of the number of failures would provide an improved fit at the lower and upper ends of the distribution, but is not justified by the small statistics in the measurements reported here.

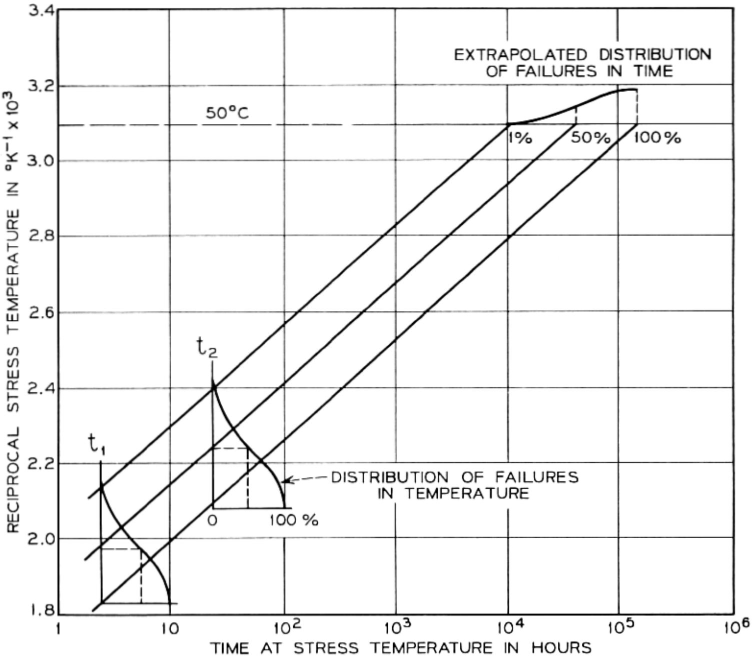

Fig. 2 — Translation of distribution of failures in temperature to distribution in times at lower temperatures.

process will be dominant and will produce earlier failures. It follows that there will always be some uncertainty regarding the validity of such extrapolations unless it can be positively established that a single aging mechanism is dominant up to and including the temperatures used in accelerated aging. In order to reduce this uncertainty as far as practicable, the results of the step stress aging measurements should be confirmed by longer term aging experiments at lower temperatures.

III. AGING PLATED WIRE MEMORY ARRAYS

The essential structure of the conventional plated wire memory consists of plated wire pairs used as digit lines intersected by orthogonal word solenoids to form a regular memory array.[7] The sample populations used for the step stress aging experiments described in this paper each consisted of a 32 word × 31 bit array (992 bits). The test planes used had word solenoids on 50 mil centers with plated wires on 25 mil centers. A 2 mil thick permalloy overlay was used to

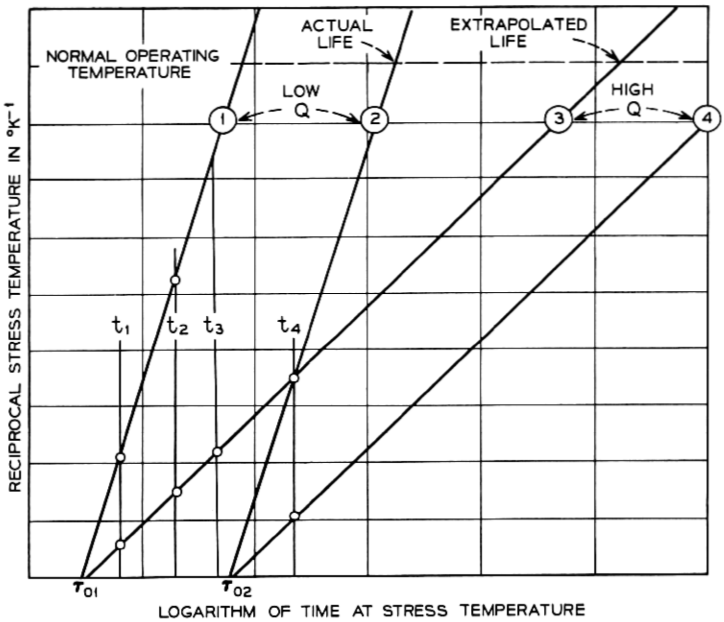

Fig. 3 — The effects of several aging processes on step stress aging extrapolations. If both low Q-high τ_o and high Q-low τ_o processes (2) and (3) are present, step stress measurements made with exposure times less than t_4, (for example, t_1, t_2 and t_3) will lead to longer extrapolated lifetimes than will actually be obtained. If τ_o for the low Q process is lower than for the high Q process—for example, (1) relative to (3) or (4)—the extrapolation will be valid or pessimistic.

provide shielding, enhance the word field, and limit word to word interaction.

In order to withstand the high temperatures used in the aging experiments the memory substrate was made of a slotted ceramic block and the word solenoids were Teflon insulated as illustrated in Fig. 4. Normal substrate materials and insulators are unsatisfactory at the higher aging temperatures. As shown, the plated wire is used in the shape of a hairpin. This construction has two important advantages; first, any uniform skew existing in the plated wire is nullified, second, since one end of the digit structure is free to move, the plated wires are not stressed by differential thermal expansion between the wire and memory plane. For most of the experiments the plated wire consisted of a 3500 angstrom thick, nominally nonmagnetostrictive, permalloy film on a 5 mil diameter conducting wire substrate preplated with a micron of copper. The wires had passed a functional on-line,

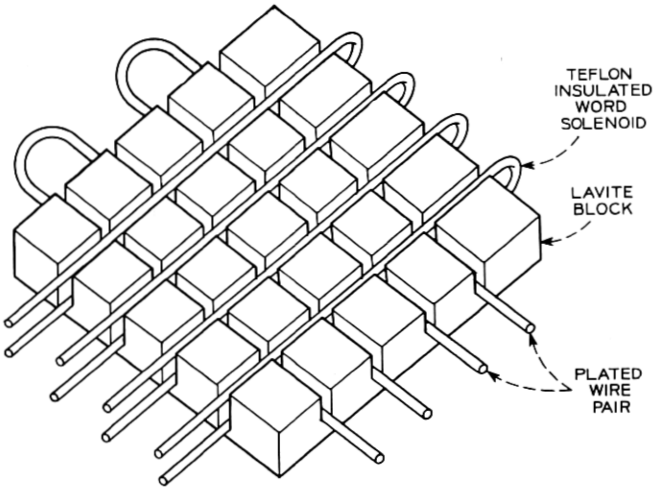

Fig. 4 — Structure of memory planes used for accelerated aging measurements at high temperatures.

destructive readout memory test and had received a stabilization anneal at 350°C for approximately one minute. During the course of these experiments wires from other sources were examined also; but, apart from differences reflecting different operating points and uniformity resulting from different processing details, no substantial difference in aging characteristics was found.

A functional test of normal destructive readout operation with adjacent word interaction using the following program was used to evaluate test planes. (*i*) Write zero in the test location using nominal word current and maximum digit current. Repeat 250 times. (*ii*) Write one in the test location using nominal word current and minimum digit current. (*iii*) Write zero in one adjacent address using nominal word current and maximum digit current. Repeat 10^5 times. (*iv*) Write zero in the other adjacent address as in step *iii*. Repeat 10^5 times. (*v*) Read the test bit and determine whether it has passed or failed. This program provides a worst case memory history that biases the test location towards minimum outputs.

A ±20 percent operating range on digit current was used to ensure a worst case test. It is assumed that a ±10 percent range will be more representative in actual system operation. The center values of currents used varied with the source of available wire. However, the following was typical for the wire used in most of the measurements: word current equal to 800 ma with 40 ns rise time and 200 ns duration; digit current equal to 25 ma with 10 ns rise time and 200 ns duration. The word and digit pulses were overlapped by approximately 100 ns. The threshold level for pass was set at 2.5 mV corresponding to approximately one half the nominal output.

Test results were recorded using an xy plotter to show the failure locations in the array. Figure 5 is a typical map for a plane that has been aged to a 22 percent failure level. It clearly illustrates the tendency for failures to cluster in particular locations along the digit line, and demonstrates a marked variability in number of failures from wire to wire. By mapping failures for both digit senses (that is, 0's and 1's) the cause of failure can often be diagnosed. A negative correlation between failures for the two senses at corresponding locations indicates skew induced failures, while a positive correlation indicates either failure to write adequately or a low disturb threshold. Further diagnoses can be obtained by noting correlations produced under modified test programs.

Aging measurements were performed using several different ambiences: (*i*) air atmosphere, zero applied field; (*ii*) hydrogen reducing atmosphere, zero applied field; and (*iii*) hydrogen reducing atmosphere, pulsed hard direction field.

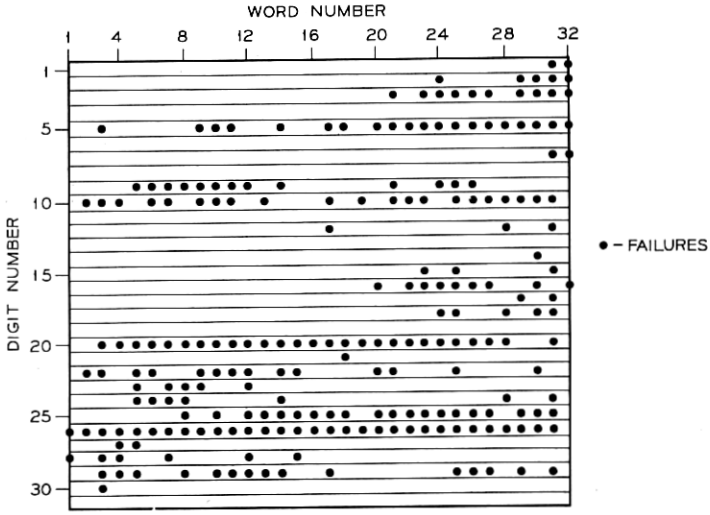

Fig. 5 — Typical distribution of failures in an aged memory plane.

IV. AGING UNPROTECTED WIRES IN AIR

Figures 6 and 7 show the result of step stress aging of unprotected plated wires in air for exposure time of 2, 20, and 200 hours at temperatures up to 320°C. In this experiment the onset of failures was so abrupt that the earliest failures were not observed in using a 20° stress temperature increment. Instead, Fig. 6 shows the last temperature at which no failures were obtained as 0.1 percent failure points for each of the exposure times. The 0.1 percentile represents the first measurable point in the test population of 1,000 bits. Notice that the percentage cumulative failures are plotted on a logarithmic scale. As pointed out previously there is no reason to expect a normal distribution of failures in temperatures, nor is one obtained.

Equal percentage failure points interpolated from the data of Fig. 6 are plotted in Fig. 7 on a $1/T$ vs $\log_{10} t$ graph. A good approximation to the linear relationship called for by the simple thermal activation model is obtained, and leads to extrapolated lifetimes for 0.1 percent failure at 50 and 25°C of 2 and 20 years, respectively. This extrapolation is additionally supported by a constant temperature aging experiment run at 80°C for several thousand hours using another similar 1,000 bit plane. The results of that experiment are also plotted in Fig. 7 and show excellent agreement with the step stress

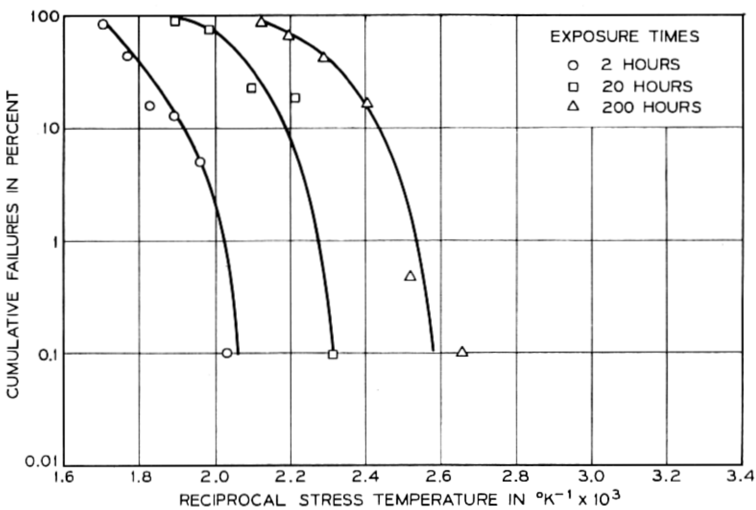

Fig. 6 — Distribution of failures in temperature for unprotected wires aged in air.

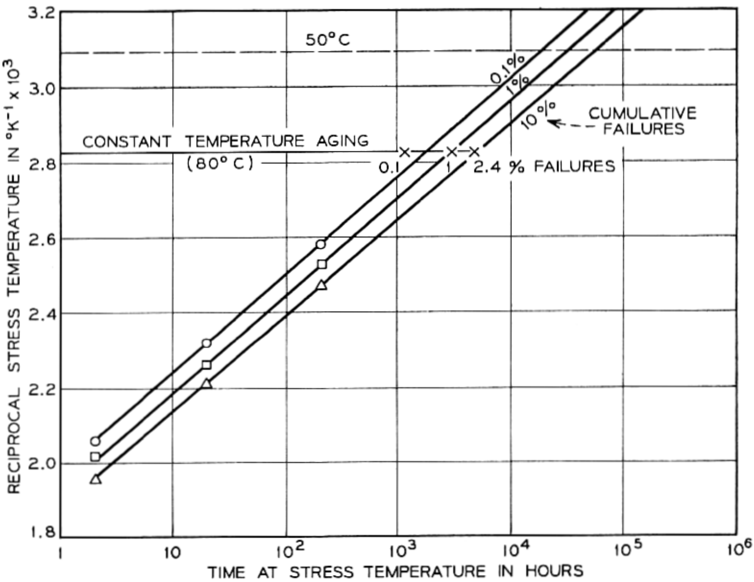

Fig. 7 — Loci of constant percentile cumulative failure in time and temperature for unprotected wires aged in air.

prediction for the 1 percent failure point. The agreement with the 0.1 percent failure point is not unreasonable in view of the large experimental inaccuracy in determining the first failure in a population of 1,000 bits. These results lead to extrapolated lifetimes at normal operating temperatures that are marginal for large memory systems.

Physical examination of failed wires in these studies showed that corrosion of the substrate wire with a resulting eruption of the magnetic film at pinholes appeared to be a primary cause of failure. Indeed, the activation energy of 0.84eV derived from the slope of the $1/T$ vs log t relation is consistent with the value for the oxidation of copper (0.87 eV).[8] These observations, together with the results of the following experiment, lead to the conclusion that chemical passivation or protective encapsulation of the plated wire is essential if adequate lifetimes are to be obtained.

V. AGING PROTECTED WIRES

A dramatic reduction in failure rates is obtained if the wires are protected either by chemical passivation or through the use of an inert or reducing atmosphere. Figures 8 and 9 show the result of step stress aging protected wires. The distribution of cumulative failures versus inverse absolute temperature is seen in Fig. 8 to be better behaved than when corrosion occurs. The 0.1 and 0.2 percent data points in this experiment were obtained experimentally, so that extrapolation to 0.01 percent failure is reasonably justified. The extrapolation of equal percentile failure points on a $1/T$ vs $\log_{10} t$ relationship in this case yields lifetimes to early failures in the many thousands of years at normal operating temperatures.

The validity of the step stress extrapolations is well confirmed by a constant temperature aging experiment carried out at 140°C that has been in progress for 5600 hours with no failures observed in a population of 1,000 bits as indicated in Fig. 9. The slope of the $1/T$ vs $\log_{10} t$ relationship in this case yields an activation energy of 1.3 electron volts in reasonable agreement with the value 1.25 electron volts that we estimate from the grain growth data of Chang, Von Neida, and Calbick.[3] Therefore, it appears that crystallite growth, or a common causative phenomenon, is responsible for the aging observed in protected wires in the absence of applied magnetic fields. Complementary measurements indicated that the prime functional cause of failure was a reduction in the digit disturb threshold as

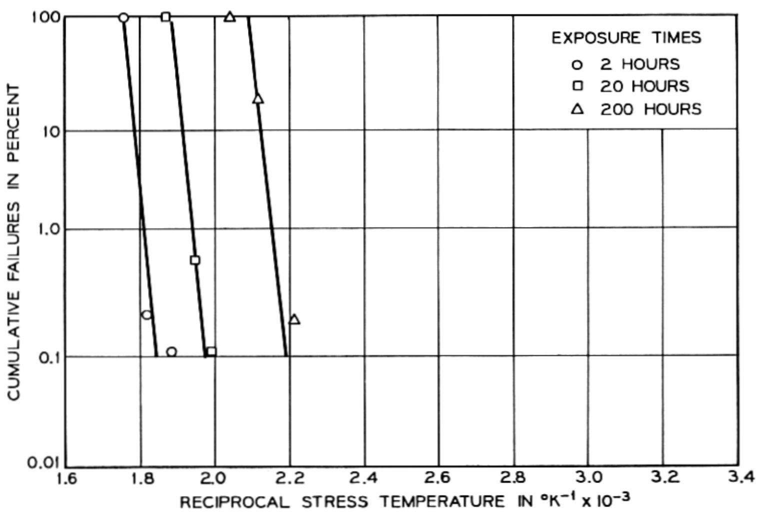

Fig. 8 — Failure distribution in temperature for protected wires.

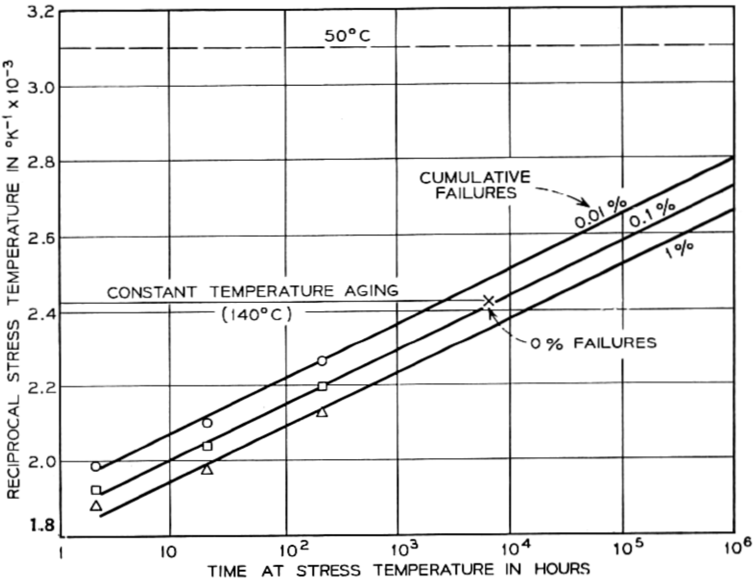

Fig. 9 — Loci of constant percentile cumulative failure in time and temperature for protected wires.

would be expected from the monotonic reduction in coercivity that occurs in permalloy as a result of a strain relief anneal.

The results of this experiment show that properly stabilized wires protected from corrosion should have an adequate shelf life.

VI. EFFECTS OF MAGNETIC FIELDS ON AGING

Hard direction fields produce a rotation of the uniaxial anisotropy in a magnetic film memory element. This result is a natural consequence of the well known magnetic annealing properties of the permalloys.[9] The sensitivity to hard direction fields is substantially reduced by the stabilization anneal discussed previously. In a memory environment the individual magnetic film memory elements are subject to aperiodic pulsed magnetic fields so that measurements of the effect of dc hard direction fields are not simply applicable.

To further complicate matters, the magnetic anisotropy is not uniformly affected by an applied field, but in first approximation it appears to have a relatively stable component in addition to an easily rotatable component. The magnitude of the latter is considerably reduced by the stabilization anneal. This situation can be described in terms of a simple model that assumes that the rotatable component of anisotropy experiences a torque proportional to a function of the angle between the anisotropy and the direction of magnetization, and that the rotatable component relaxes towards the direction of magnetization under a characteristic time constant. Under these circumstances, the rotatable anisotropy component relaxes back towards the easy axis direction established by the stable anisotropy component in the interval between word field pulses.

An analysis based upon this simple model is given in the Appendix. It shows that the worst case effect of hard direction field pulses applied at *low* duty cycles is to induce a skew that is approximately proportional to both the duty cycle and the ratio of the rotatable to stable anisotropy components. Such a growth in skew with a dependence on duty cycle has been verified experimentally, although there is as yet insufficient data to provide the exact form of the dependence over a wide range of duty cycles.

One problem, then, in designing a meaningful field aging experiment is to decide upon a representative duty cycle. In a 4,000 word memory with a ratio of cycle time to word pulse duration of 5, no one memory element would be subject to hard direction fields for more than 0.005 percent of the time if the memory were exercised in a completely random fashion. On the other hand, it would not be out of the question for any one memory word to be interrogated once every 10 instructions over substantial periods. In that case some memory words will be subject to hard direction fields 2 percent of the time. On the other hand those same memory words would be unlikely to be exercised continuously over many years of operation. In the absence of any definitive data, it is suggested that a representative worst case duty cycle will be about 0.1 percent.

Figures 10 and 11 give the results of an exploratory step stress aging measurement under pulsed field stress. In this experiment *every* bit in the test population was subject to hard direction fields under a 1 percent duty cycle to determine the effect of extreme aging conditions. It will be clear from the previous arguments that this is an unrealistically severe test which, however, serves to illustrate the problem of making extrapolations from aging measurements under pulsed magnetic field stress.

The test program used was the same as described previously, except that a ± 14 percent digit current range was used. Unsatisfactory extrapolated lifetimes were obtained for the ± 20 percent margin used in the previous experiments. This was not surprising since a ± 20 percent

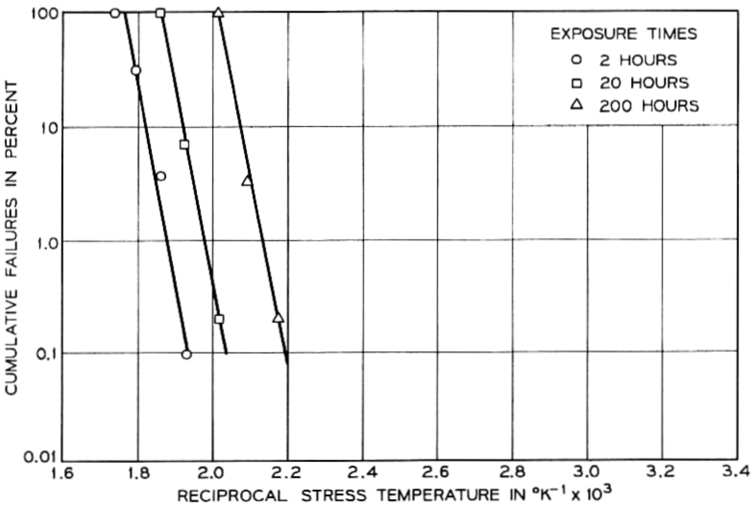

Fig. 10 — Distribution of failures in temperature for protected wires subjected to pulsed field stress during aging.

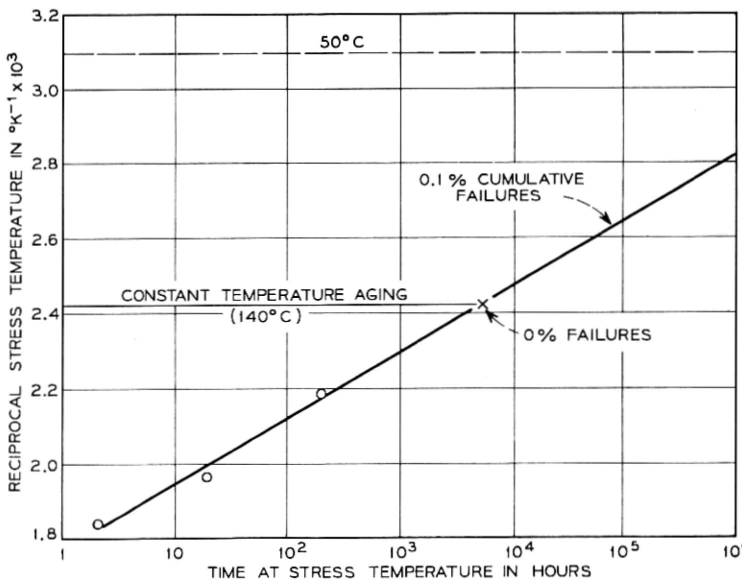

Fig. 11 — Loci of constant percentile cumulative failure in time and temperature for protected wires subjected to pulsed field stress during aging.

criterion was used for initial selection of wires. During step stress aging, all word solenoids and the test planes were connected in series and pulsed with 400 mA amplitude word current pulses at a 1 percent duty cycle. Thus, all bits in the test population were subjected to field stress during aging.

The 400 mA word current level was chosen for nondestructive readout during aging. This is a necessary condition since each bit must remain in an approximated single domain state during accelerated aging if anisotropy "recovery" during the interpulse interval is to take place. This procedure provides a not unreasonable simulation of the actual state of the memory sites in operation and avoids the complications that would be introduced, both in instrumentation and interpretation, if the memory were exercised in the destructive readout mode during aging.

In contrast to the situation for "no-field" aging, failures were observed to result primarily from increased skew as evidenced by an increase of the minimum digit write current and an asymmetry in bit failures for opposite polarities of digit write currents. In addition, the sense of skew correlated with the direction of the hard direction field pulses applied during aging.

The results of these experiments are given in Figs. 10 and 11. In Fig. 10 the 0.1 percent failure points represent the last stress temperature at which no failures were observed. An approximately logarithmic failure distribution is again found, in Fig. 10, although this relationship is not as well obeyed as the case for no-field aging, suggesting that the plated wires used were not homogeneous in field aging property. Once again, early failures tended to cluster on particular digit lines, but no obvious correlations to initial physical properties have as yet been established.

As already mentioned, no simple distribution could be obtained for a ± 20 percent range of digit current indicating the severity of the additional aging induced under field stress. In addition, Fig. 11 shows that the extrapolated lifetime for 0.1 percent failures and a ± 14 percent digit current range is substantially less than for "no-field" aging (Fig. 9), with a ± 20 percent margin. Furthermore, the step stress data points do not as satisfactorily fit a linear $1/T$ vs $\log t$ relationship, suggesting the possibility of even lower lifetimes as discussed in connection with Fig. 3.

On the other hand, the extrapolation shown in Fig. 11 is consistent with the results of a constant temperature aging experiment, which has been under way for 6500 hours at 140°C with no failures using the same ±14 percent digit margin criterion. However, a different batch of wires was used for the constant temperature aging experiment. Thus there is a residual uncertainty regarding the validity of the lifetime extrapolation, and more comprehensive measurements will be needed before lifetime predictions can be made with reasonable confidence. Assuming that the data of Fig. 11 is representative it can be concluded that the plated wire memory has an adequate lifetime for many applications even under pulsed magnetic field stress, provided that proper attention is paid to duty cycle and choice of operating range.

VII. DISCUSSION

As stated at the beginning, this paper's prime purpose is to describe the procedures that have been developed for accelerated aging of memory arrays using functional test criteria, and to illustrate the pitfalls that must be taken into account. It is not intended to provide definitive answers to the plated wire lifetime question. The limited data presented is encouraging and suggests that, given proper selection and use, reasonable lifetimes can be ensured. We caution, though, that a much more comprehensive study is needed before confident predictions can be made. Measurements using larger sample populations will reduce the statistical uncertainty in extrapolating failure distributions, and longer term measurements at lower temperatures will reduce the uncertainty in extrapolation to long periods.

Because a memory is a large integrated entity, and because in present day usage only small numbers of failures can be tolerated over years or decades of operation for economical reasons, the problem of determining reliability is difficult. It has not arisen in the case of ferrite core memories since no short term degradation in properties has been reported. The time scale of degradation in the properties of anisotropic magnetic alloy films, however, is such that the possibility of a lifetime limitation needs to be considered seriously. The physical mechanisms responsible for aging deserve as much attention as the origins of the induced anisotropy. The step stress aging technique used in this study followed those in common use for determining the reliability of semiconductor devices. With the increasingly large number of functional cells being integrated into semiconductor circuits, similar attention will need to be given to the limitations of the technique. This will be especially true should large semiconductor memories be realized.

It has been established that the aging mechanisms in magnetic films are thermally activated. Indeed, physical reasoning leads to that expectation. There is no evidence for a temperature threshold, which might only occur should a cooperative mechanism be responsible for aging. The activation energy is such that at normal temperatures, a 20°C temperature increment produces approximately one order of magnitude increment in predicted lifetime. Thus, if the long term reliability proves to be marginal for more extreme applications, improved heat sinking should be used. Magnetic film memory elements are unique in the small energy dissipated in the cell itself. Normally, the main cause of temperature rise above ambient is dissipation in peripheral circuits. It is also worth noticing that magnetic film elements are relatively unaffected by reduced temperatures. P. I. Bonyhard, in unpublished work, has shown that the plated wire can be operated to at least −70°C with no significant changes in operating margins.

Since we first drew attention to the potential severity of aging in plated wire memories, industry wide practice has followed the post-deposition stabilization anneal that we recommended. This practice has reduced aging from a first order to a less significant problem and, accordingly, has made reliable long term lifetime predictions more difficult. The measurement problem is also increased by the wide distribution of failure rates found. The step stress aging technique described in this paper reduces the measurement problem to experiments of reasonably short duration. Furthermore, the complementary longer term aging experiments at lower temperatures have provided reasonable confirmation of the extrapolations from the short term step stress measurements, although further corroborative studies are desirable.

The necessity for corrosion protection has been established by this study. In turn, it has been established that protected wires have adequate shelf life. Furthermore, this study also focusses attention on the importance of word pulse duty cycle in an operational memory. The desirability for adequate magnetic shielding against static environmental magnetic field follows implicitly.

The prime functional result of aging has been shown to be an erosion of both upper and lower limits of digit current. It is axiomatic, therefore, that for high reliability plated wire should be selected to have wider digit current margins than required operationally. Since an increase of the lower limit on digit current is likely more severe than the decrease of the upper limit, the center of the selection margin should be offset with respect to the nominal operational value. It also follows that correlations of aging with manufacturing process should best be performed, at least initially, with attention to the rate of change of the lower limit on digit current as determined by short term step-stress aging.

APPENDIX

Analysis Based on Magnetic Model

Let

$\mathbf{K}_1$ = "stable" component of anisotropy
$\mathbf{K}_2$ = "rotatable" component of anisotropy.

Assume that the rotation of $\mathbf{K}_2$ is reversible. Hard direction field pulses (applied normal to $\mathbf{K}_1$) rotate $\mathbf{K}_2$ through an angle β with respect to $\mathbf{K}_1$. Relaxation of $\mathbf{K}_2$ towards $\mathbf{K}_1$ takes place during the zero field interval between hard direction field pulses.

Of interest is the steady state situation under repetitive pulsing. Steady state is achieved when $\beta = \beta_1$ such that the incremental rotation $\Delta\beta$ produced by each successive field pulse of duration t_1 equals the relaxation $-\Delta\beta$ during each interpulse interval t_2.

We postulate that the rotation of $\mathbf{K}_1$ results from a torque exerted by the magnetization $\mathbf{M}$ upon $\mathbf{K}_1$. We further postulate that this torque has the same $\sin 2_\theta$ dependence as the torque exerted by $\mathbf{K}$ upon $\mathbf{M}$ in a uniaxial material, where θ is the angle between $\mathbf{K}$ and $\mathbf{M}$. These are physically reasonable assumptions, but are presented without experimental confirmation.

The dynamics of the rotation is assumed to be governed by some characteristic relaxation time constant τ. Its exact form is unimportant for the present discussion, but we do assume $\tau \gg t_1$ or t_2 in which case $\Delta\beta \ll \beta_1$. In that case for the steady state solution it is sufficient to consider the conditions required for a time averaged balance of the torques applicable during intervals t_1 and t_2. This condition can be expressed:

$$t_1 \sin 2(\theta_h - \beta_1) = -t_2 \sin 2(\theta_0 - \beta_1) \tag{1}$$

where θ_h is the angle between $\mathbf{M}$ and $\mathbf{K}_1$ during interval t_1 when the hard direction field pulse is applied, and θ_0 the angle between $\mathbf{M}$ and $\mathbf{K}_1$ during the interpulse interval t_2. θ_0 is related to K_1 and K_2 through minimization of the energy relation for zero applied field and negligible magnetostatic field. In this case:

$$0 = K_1 \sin 2\theta_0 + K_2 \sin 2(\theta_0 - \beta_1). \tag{2}$$

Thus, substituting for $(\theta_0 - \beta_1)$ from equation (2) in equation (1)

$$\sin 2\theta_0 \approx [K_2 t_1 \sin 2(\theta_h - \beta_1)]/K_1 t_2.$$

For cases of interest, (low duty cycle and stabilized material), we may assume small θ_0 and $\theta_h \gg \beta_1$. Under these circumstances the steady state skew produced by repetitive field pulsing is

$$\theta_0 \approx [K_2 t_1 \sin 2\theta_h]/2K_1 t_2.$$

VIII. ACKNOWLEDGMENTS

The authors gratefully acknowledge substantial contributions by A. H. Bobeck during the formative stages of this work. We also wish to thank F. B. Hagedorn and A. J. Perneski for helpful discussions throughout and for the benefit of unpublished complementary work on aging of vacuum deposited planar magnetic films. We thank W. H. Craft and R. R. Buckley for their cooperation in supplying plated wire for these measurements. Additional plated wire for complementary studies was kindly provided by J. Mathias, Univac, Bluebell, Pennsylvania.

REFERENCES

1. Mitchell, E. N., "Effects of Heat Treatment of Thin Ferromagnetic Films at Intermediate Temperatures," J. Appl. Phys., *29,* No. 8, part 2 (March 1958), pp. 286–287.
2. Chang, J. T., Gianola, U. F., and Sagal, M. W., "Aging and Stabilization of Electrodeposited Cylindrical Magnetic Thin Films," J. Appl. Phys., *35,* No. 3, part 2 (March 1964), pp. 830–831.
3. Chang, J. T., Von Neida, A. F., and Calbick, C. J., "Structural and Magnetic Characteristics of Annealed Electrodeposited Permalloy Films," J. Appl. Phys., *37,* No. 3, part 2 (March 1966), pp. 1472–1473.
4. Von Neida, A. R., and Hagedorn, F. B., "Cu Diffusion in Electrodeposited Permalloy Films," J. Appl. Phys., *38,* No. 3, part 2 (March 1967), pp. 1436–1438.
5. Rabinovici, B., and Renton, C. A., "Some Aging Properties of Cylindrical Electrodeposited Permalloy Memory Wires," Proc. Intermag. Conf., Stuttgart, Germany, (April 1966), pp. 2–5.
6. Dodson, G. A., and Howard, B. T., "High Stress Aging to Failure of Semiconductor Devices," Proc. 7th Nat. Symp. Reliability and Quality Control in Elec. (January 1961), pp. 262–272.
7. Danylchuk, I., Gianola, U. F., Perneski, A. J., and Sagal, M. W., "Plated Wire Magnetic Film Memories," Proc. Intermag. Conf., Washington, D. C., (April 1964), pp. 4–5.
8. Kubaschewski, O., and Hopkins, B. E., *Oxidation in Metals and Alloys,* London: Butterworth Scientific Publications, 1958, p. 163.
9. Chikazumi, S., *Physics of Magnetism,* New York: John Wiley and Sons, 1964, p. 359.