CREEP STRENGTH OF ALUMINUM ALLOY CONDUCTOR

by

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TABLE OF CONTENTS

Page

LIST OF FIGURES

Page

LIST OF TABLES

CREEP STRENGTH OF ALUMINUM
ALLOY CONDUCTOR

BACKGROUND

Introduction

The use of aluminum for conduction of electricity from the generating station to the user is now almost standard throughout the electrical power industry. The change from the use of copper, formerly used, has been brought about by the fortuitous combination of good electrical conductivity, good corrosion resistance, light weight, and relatively good strength possessed by aluminum. To decrease the cost of a trsnsmission line it is desirable to have as strong a conductor as possible, consistent with other factors, to enable the use of fewer towers. Recently, efforts have been made to increase the strength of aluminum by alloying and other treatments.

In addition to the electrical load, a conductor is required to withstand mechanically induced forces such as tension. These cause the conductor to sag. This sag has been found to increase over a period of time due to plastic flow. It is the purpose of this thesis to investigate the characteristics and extent of this plastic flow as a step toward evaluation of the new aluminum alloy conductor as a transmission line material.

The elastic deformation of a metal specimen subjected to a load within the proportional limit of the material may be predicted with a high degree of accuracy, since the modulus of elasticity remains essentially constant for the material. The limit of elastic strain and the plastic strain exhibited by metals undergoing relatively short time loads above the elastic limits is not as easy to determine, since each new alloy may exhibit a different plastic strain rate. However, these rates may be evaluated quickly by means of short time tests. This plastic strain is generally of but indirect importance to the designer who designs within the elastic limits; he uses plastic strain as an added factor of safety.

Of direct concern to the design engineer is the plastic deformation exhibited by metals subjected to constant stress at loads well below the elastic limit for long periods of time. Under ambient temperatures this plastic strain is almost negligible; indeed, under some conditions it might be undetectible without the aid of special equipment. However, in any part of great length this plastic deformation may become quite noticeable. Should the part be loaded for any long period of time, the plastic strain, which may continue indefinitely, may extend the part until it is too long, requiring maintenance or even replacement.

An example of an application in which this plastic deformation, commonly called creep, plays a major role is the high voltage electrical transmission line. In the field, the metal conductor is strung up on towers a considerable distance apart. The stress in this line is dependent upon both the weight of conductor between supports and upon the tension or sag with which it is hung. The creep rate of such a line is some function of the stress and temperature of operation, and thus varies with the span between the supports, the initial sag, the unit weight of the conductor, the electrical load, and the weather conditions. Unfortunately, not all of these factors are constants. The effect of span between supports varies with difference in elevation of the supports. The initial sag varies with the thermal expansion or contraction brought on by changes in temperature. The effect of the weight of the conductor may be greatly increased by wind or ice loads. Finally, the care by which the conductor is strung can introduce further deviations from ideal laboratory test conditions.

Since transmission lines are strung in cable form, one could expect a certain amount of strand settling upon initial application of the load. Experience in the field has shown that this settling results in an appreciable initial extension of the conductor. To alleviate this problem, the common practice today is to subject the lines to an initial tension considerably above the normal tension for a short period of time, then to decrease the tension to approximately 25 percent of the ultimate strength of the material. The purpose behind this practice is to eliminate much of the strand settling and also some of the initial creep from the conductor, resulting in less future sag.

The initial pretensioning of transmission lines is not excessively difficult or expensive upon initial construction of the line; however, any takeup required after the line has been put into service is not only expensive but requires interruption of service through that line for an appreciable period of time. It is, therefore, generally considered desirable to restretch transmission lines not oftener than every 50 years. A study of economics reveals that the most economical span length occurs when the cost of takeup per year equals the annual depreciation upon the line supports. The use of a conductor material with an excessive creep rate would necessitate both more frequent takeups and reduced spans, increasing the cost of the line and the cost of maintenance to the point of prohibiting the use of that material. If excessive sag is permitted, there is danger of gusty winds whipping adjacent lines together, resulting in a short circuit. In many cases, a minimum ground clearance for conductors is set by law. Good practice also requires a minimum clearance for safety's sake. Increased tensions require more substantial supports, increasing the unit cost. Therefore, the above factors must be analyzed and combined to determine a minimum acceptable creep rate; any prospective conductor material must possess a creep rate within these set limits to be acceptable for use in high voltage transmission of electrical energy.

Aluminum, although its electrical conductivity is somewhat less than that of copper, has long been used as an electrical conductor in view of its light weight and excellent corrision resistance. However, until recently, its use was limited to relatively short spans, since pure aluminum is weak and in alloyed form it loses much of its electrical conductivity. It is common, on long spans, to use a core of steel cable for strength, surrounded by strands of electrical conductor grade aluminum. A typical example of the above uses a 19 strand steel cable supporting 30 strands of aluminum.

However, this approach has not been completely satisfactory. In the first place, the combination of steel and aluminum in such close proximity invites galvanic corrosion, necessitating special treatment such as galvanizing, for the steel. Secondly, the cost of bimetallic conductors is higher than conductors of a single metal. Thirdly, bimetallic condicutors make splicing difficult, since both the steel and the aluminum must be joined separatly. And finally, such a bimetallic conductor loses much of the weight advantage inherent in an all aluminum conductor.

It comes as no surprise to learn that a great deal of research has been carried out in an effort to improve the mechanical properties of aluminum without seriously affecting its electrical conductivity. One of the aluminum producers has recently developed an alloy that apparently fulfills the above requirements; it has a tensile strength of nearly 50,000 psi, or nearly twice that of hand drawn aluminum, while still retaining 85 to 89% of the electrical conductivity of electrical conductor grade aluminum. However, to be economically feasible for use in the relatively long spans of high voltage electrical transmission lines, the new alloy must possess satisfactory creep rates. The determination of these rates is the subject of this thesis.

Objectives

The primary objective of this project was to determine the minimum creep rates of specimens of the new aluminum alloy conductor subjected to different preloads. Specimens were taken from two different manufacturing lots in which some difference in smelting, processing, and heat treating probably existed. Any effect upon creep rate brought on by variations in manufacturing is of great importance; part of the primary objective of this paper was to determine this effect.

There were three secondary objectives. Two single strands of conductor wire, each the center strand from a length of conductor, were tested. The first secondary objective was to determine the effect of stranding upon the creep rate of the conductor by analyzing its creep in comparison to that of a single strand. Next, an equation was to be determined which would predict the amount of plastic strain in a given conductor at any time in the future. Finally, recommendations were to be made to aid future investigators in testing and analyzing creep of aluminum alloy conductor cable.

Scope

The scope of this project includes the tests and test results that were performed by the writer on two manufacturing lots. This includes twelve test specimens, of which the first six were designated as Series III and the last six as Series IV. All analyses were based primarily upon the results of these tests; however, the results of prior tests using the same apparatus but covering a study of creep by means of slightly different testing procedure are referred to when in support of or in disagreement with data taken by the writer.

History

It is difficult to determine when creep was discovered. Lead sheeting which centuries ago was used for roofing was observed to droop under its own weight and to hang over the edge of roofs. This fact, although it may have been man's first observation of creep, was viewed as merely a curiosity; attempts made to explain this phenomena, if any, were not of any significance.

In spite of Andrade's extensive experiments beginning about 1910, the significance of creep was not fully realized until some years later. Metallurgical advances in steels had permitted the increasing of pressures and temperatures in steam boilers; designers, unaware of the extent of plastic flow, began to encounter failures in parts stressed well below the elastic limit. Further examination of the fractured parts revealed that, in some cases, well over five percent elongation had occurred. Alarmed, the American Society for Testing Materials and American Society of Mechanical Engineers organized a join committee to study creep. Meanwhile, creep became more important as modern machinery demanded lighter weight, higher temperatures, and increased speeds. A modern example of a part which must show an outstanding resistance to creep is the gas turbine blade, Clearance between the moving blade and the casing is so small that an extension of 0.2 percent over a 25 year period is the maximum permissible. On the other hand, a 5 percent elongation over a 5 year period is acceptable for some furnace parts.

Definition of Terms

Creep is defined as the relatively slow plastic deformation of a material held for long periods of time under constant or slowly changing loads. With regard to metals, creep is associated with the time rate of deformation present under stress intensities well below the yield point, the proportional limit, or the apparent elastic limit for the temperature in question. Creep rates, although they rise rapidly with increasing temperatures, may easily be of consequential magnititude at normal temperatures, depending upon the material in question and the degree to which freedom from plastic deformation is required.

The creep strength of a metal is that stress which will just produce a creep rate of some specified amount for a given prolonged period of time and at a given temperature. For some applications, the creep strength is listed as the stress which will produce a plastic deformation of 1 percent over a period of 10,000 hours at the operating temperature.

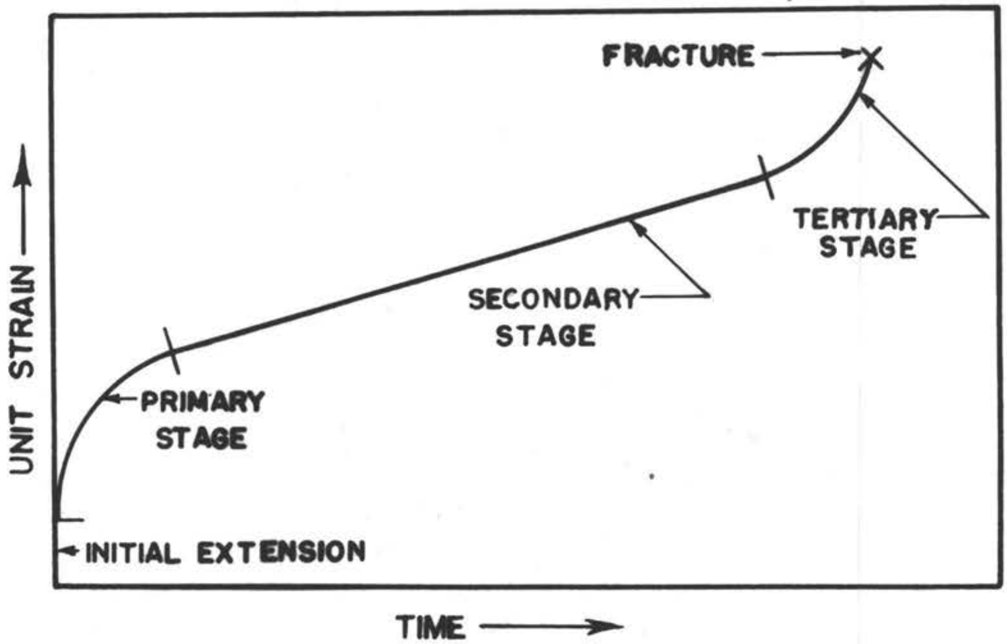

FIGURE 1. The Creep Curve

THEORY

Factors Affecting Creep

The curve shown in Figure 1 represents a very idealized form of creep of a specimen subjected to a constant tensile load and constant temperature. As is evident from the curve, it is composed of three stages, occurring after the initial extension. The first stage of creep, also called the initial, primary, or diminishing rate stage, is characterized by a relatively high rate of plastic deformation. However, at temperatures below which thermal recovery can take place, this plastic deformation is accompanied by strain hardening, by an almost negligible reduction in area, and sometimes by strain aging. The above combination of factors acting on the specimen combine to slow down the rate of deformation until it becomes essentially constant. The shape of the primary creep curve is approximately parabolic.

The second stage of creep, also called the secondary, constant rate, or steady state stage of creep, is characterized by a relatively constant creep rate. This has been explained by claims that the strain hardening is just balanced by the reduction in correctional area, that the rate of resoftening by recovery balances the rate of strain hardening, and that same unknown mechanism is operating. Most probably, the actual cause of the steady state stage of creep is a combination of the above. Some modern investigators deny that the second stage of creep is actually constant; they claim that it is but a transition from the first to the third stage.

The third stage of creep is characterized by a continually accelerating rate of creep culminating ultimately in fracture. Early explanations for this stage, also called the tertiary, increasing rate, or final stage, claimed that the increasing rate was due to the reduction in cross sectional area of the specimen. If this were the case, then, why was the creep rate relatively constant throughout the second stage? The cross sectional area was decreasing there, too. Later investigations revealed that the rate of creep throughout the third stage is much higher than that ascribable to reduction in cross sectional area alone. Evidently there is present, at least in the third stage, some unknown factor unexplainable by simple theory.

The complete creep curve as described appears only for tests made in simple tension, at moderate temperatures, and in response to constant loads that produce fracture within the time of the experiment. Either one or two of the stages may be absent from the creep curve. Whenever a specimen is loaded in such a manner that necking does not occur, the third stage of creep, if it exists at all, does not resemble that of the ideal. Under tension or bending, then, fracture would normally occur during the second stage or at the beginning of the third. It is believed that tensile tests made under constant stress do not exhibit a third stage; further tests are necessary to substantiate this. Under a compressive load, only the first stage is evident; any plastic strain is accompanied by an increase in cross sectional area which decreases the stress. Thus the creep rate in compression decreases until it is essentially zero. A series of tests performed over a wide range in temperatures reveals that the creep curve is not accurate at either very high or comparatively low temperatures.

It is relatively easy to formulate mathematical expressions for the above simple general explanations of creep phenomena. However, in light of the many exceptions to all previous simple explanations of plastic flow, it is necessary to consider the variables known to affect creep.

Creep is, of course, influenced greatly by changes in temperature and variations in stress. However, changes in heat treatment, grain size, chemical composition of the alloy in question, presence of impurities, differences in dispersions throughout a given alloy, and presence of residual stresses within the material also have a pronounced effect upon the creep rate of a material. These variables require further explanation.

One is not surprised to learn that the stress to which a specimen is subjected has a pronounced effect upon its creep rate. The extent of this effect varies among different alloys.

A factor that must be controlled most accurately in creep tests is the specimen temperature. It has been demonstrated that some materials under certain loads may exhibit a creep rate twice that of similar specimens under similar loads at a ten degree lower temperature. This fact explains why early investigations working with relatively high temperatures (obviously hard to maintain) reported much conflicting data on creep rates; indeed, some rates reported varied several hundred percent from other rates taken under supposedly similar conditions.

It has been found in connection with gas turbine work wherein extremely small creep rates are a necessity that sometimes a particular alloy is completely acceptable, whereas another alloy, only slightly different from the first, is useless; its creep rate is just too high. Chemical composition and presence of impurities thus have a profound effect upon creep rates.

Giedt, Shelby, and Dorn(18) have run extensive tests on aluminum-copper alloys, varying only the size of intermetallic compounds dispersed throughout the aluminum. They concluded that particle size has a substantial effect upon creep rates. Furthermore, they determined that, whereas in general the coarser dispersions exhibited more favorable creep rates, at low temperatures and high strain rates finer dispersions had more favorable creep rates. At high temperatures, too, creep rates were improved in specimens with finer dispersions. Thus one can see that the effect of size of the dispersed particles is not an independent variable, but changes with changing temperatures.

The effect of grain size upon creep rates may best be analyzed by comparing the strength of the grain boundary with that of the grain, shown schematically in figure 2. Thus at high temperatures failure occurs in the grain boundaries, whereas at low temperatures failure occurs across the grains. The boundaries are more important in determining creep characteristics of of a fine grained material than those of the coarse grained material because of the greater grain boundary

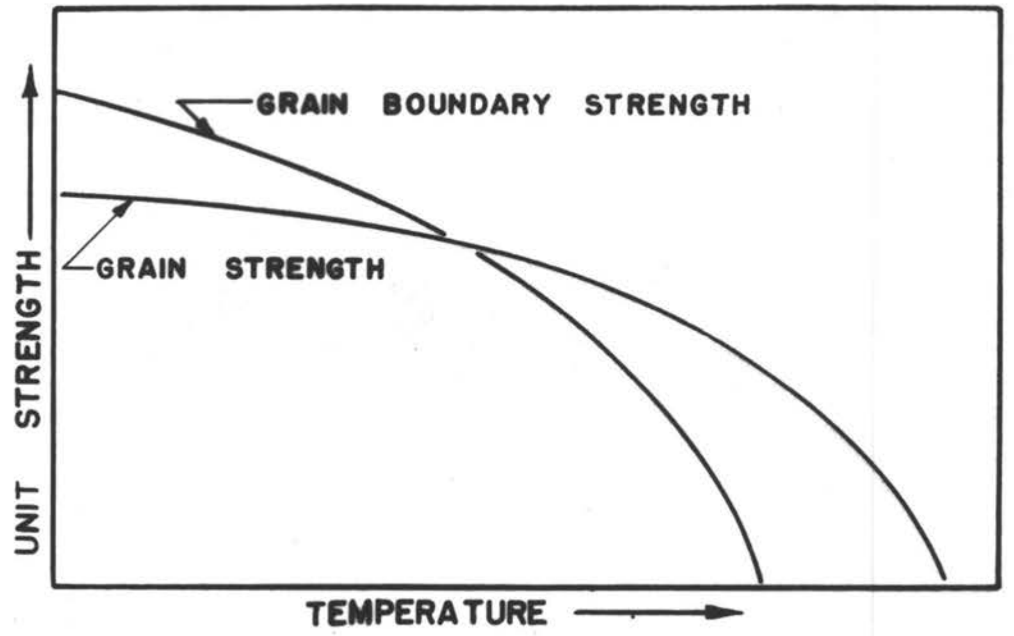

FIGURE 2. Effect of Temperature on the Strength of Grains and Grain Boundaries

area, precentage-wise, in the former case. One could expect, then, that low temperature creep properties are superior in fine grained materials, whereas for high temperatures the reverse is true. Experimental evidence also supports this argument(35). Linked in with the grain size of a material is the heat treatment it receives. Heat treatment is also a prime factor in determining age hardening and the amount and size of dispersions in a given alloy. It becomes very difficult to determine the precise effect each variable has on the creep rate of a material because the variables are so interlocked that separate analysis for each becomes almost impossible.

Metallurgical Explanations

A reasonable understanding of methods of analysis of plastic flow is not complete without an understanding of the mechanism of the permanent deformation during creep; therefore, some further explanation is in order.

When the deformation of a metal is rapid and extensive, it occurs principally by slip. A single crystal of metal generally contains one plane that is weaker than the others; fairly high stresses force these weaker planes to slip slightly. Thus a polished specimen, strained above its yield point, exhibits concentric parallel bands readily visible through a microscope. This slipping is the primary mechanism present in the first and third stages of creep; its rate varies with the amount of strain hardening induced by the slip. As long as slip is the primary cause of creep, the effect of temperature can be explained on the basis of its effect in eliminating strain hardening. Thus at increased temperatures, the strain hardening taking place is eliminated as it takes place by increased recovery rates. This has the same effects upon strength as overaging. With all strengthening effects nullified by increased temperatures, a specimen subjected to any load of enough magnitude to induce slip will gradually extend until it fails. This rapid stage of deformation is now commonly called transient creep.

The second stage of creep, characterized by a slow, relatively constant creep rate, is now known as viscous or quasi-viscous creep. It is primary importance because most of the service life of a part subjected to plastic deformation occurs at a time when quasi-viscous creep is the primary mechanism. This form of creep is called viscous because it resembles the plastic flow of a true amorphous material such as pitch; it is termed quasi-viscous because the materials in which it is present are not truly amorphous. Thus the flow rate is not directly proportional to the stress.

Quasi-viscous creep has been further subdivided into two mechanisms, quasi-viscous flow and slipless flow. The rate of deformation of these two phenomena is so low that it is of no importance except in a study of creep.

Viscous flow is a thermal flow occurring in the grain boundaries. The grains themselves thus are left undeformed, much as a gravel in an asphalt road remains undeformed in spite of amorphous flow occurring around it. As viscous flow produces no appreciable change in individual grains, it produces no slip bands within the grains; however, it does change the relative positions of different grains, much as asphalt flow within the surface of a highway may disturb the relative locations and positions of gravel within the roadbed. It is possible to see the effect of the viscous flow with a microscope; free surfaces under stress become covered with elevations and depressions which are grains that have changed their relative locations.

The concept of viscous flow is comparable to that of recovery in that their modes of operation are similar. Both are accomplished in regions where, because of unfavorable crystal location, eccentric loading, or higher temperature, the internal energy within the metal is exceptionally high; both act in an effect to reduce the distortion within the metal by diffusion of atoms under the highest stress. Both processes increase with temperature, both are very slow. The two differ in that recovery occurs principally within the grains themselves, reducing stresses developed by previous mechanical deformation, whereas viscous flow occurs only within grain boundaries, reducing stresses developed locally by external loading.

It must be understood that the various mechanisms of creep do not occur alone; rather, especially in the primary and tertiary stages, they may occur simultaneously. Thus, especially at higher temperatures and high stresses, although deformation by slip greatly exceeds that by viscous flow, they are both present. This fact becomes especially important when a specimen is subjected to a load of insufficient magnitude to produce slip and to a relatively high temperature. Even under light loads, when the temperature is high, the internal energy of the specimen is also high. It has been demonstrated (35)that when the internal energy of a metal reaches the energy of self diffusion, rapid diffusion of atoms can occur. To understand the effect such dispersion may have upon creep, one must analyze the structure of a metal on an atomic level.

The ideal metallic crystal would be many times stronger than any metallic substance we have today. An ideal specimen would be but one crystal, formed of even rows of atoms. No impurity would mar this perfect crystal; not one atom would be out of place. To subject this specimen to a stress sufficient to culminate in failure would require a proportionally enormous load, for failure is preceeded by slip. But for slip to occur within the ideal crystal would require simultaneous movement of atoms over an area at least equal to the cross sectional area of the specimen. It has been determined mathamatically that the shear strength of the perfect metal specimen would lie between 10^3 and 10^4 times that of a normal metal specimen.

It is not surprising to learn, therefore, that the actual crystal is filled with dislocations and vacancies. A dislocation is a defect in the periodicity of an atomic lattice; for example, a plane of atoms either at an oblique angle with respect to the majority or overhanging an edge of a crystal. A vacancy is an absence of one atom from its regular position within the crystal lattice. Thus a load imposed upon an imperfect specimen need not shear a plane of atoms equal to at least the cross sectional area of the specimen, but need only shear the small sections of a crystal at the dislocation, causing the dislocation to move. Thus plastic strain involves not only flow of grain boundaries, but proceeds through the grains as well. Since individual grains are irregular in shape, these surfaces provide ideal points from which dislocations can form. These newly formed dislocations, together with those already present in the crystal, in turn move through the grains, absorbing vacancies in some places and creating new ones in others. The grains thus elongate plastically under load. When two or more dislocations moving in different directions come together, they create a barrier to further movement. A higher level of energy is then necessary to force one of the interacting dislocations to climb into another plane of atoms, that movement may proceed. This movement of dislocations is called slip. Some authors term the slip predominant in the primary and tertiary stages of creep as normal slip and the slip predominant in the secondary stage as slipless flow. Slip, by its interaction of dislocations imparing further movement, is generally considered to be the cause of strain hardening.

It would seem conceivable that the movement of dislocations could tend to absorb more crystal imperfections than they create. However, this theory obviously could not be extended to mean that creep would eventually produce a perfect metal crystal. The grain boundary, which generally flows at a different rate than the rate of crystal extension, continually provides new areas of high energy concentrations in regions where a group of dislocations or a precipitated particle interrupts either grain elongation or grain boundary flow. If the areas have insufficient energy to formulate new dislocations immediately, if the stress is high enough, the internal energy will increase until it approaches the activation energy, at which time diffusion takes place.

The diffused atoms may then result in the formation of new vacancies, so that the progress of plastic flow continues. Thus, although the movement of vacancies and dislocations may result in improved mechanical properties of individual grains, it can be no means result in a specimen of extreme strength.

In a specimen subjected to high temperatures but to relatively low stresses below that necessary to produce much normal slip, creep occurs primarily by viscous flow. As has been said before, viscous flow is an extremely slow process, requiring years to accumulate a total strain producible in minutes in a short time tensile test. However, since the specimen temperature is high, only a small amount of additional energy is necessary for diffusion. Therefore, a considerable number of atoms are continually loosed from their positions within the grains and the grain boundaries and are dispersed throughout the specimen. In the grain boundaries especially, where a relatively great number of dislocations are present, this movement affords easy condensation of dislocations which enlarge to the extent of forming a small pore. Were the creep rate faster, this pore would probably be closed immediately by crystal deformation, but normal slip, requisite to rapid flow, is not present. The presence of the pore creates areas of stress concentration around it, increasing the energy level in its vicinity, diffusing more atoms. Thus the pore extends into a small crack. If this theory is correct, failure would occur soon, and at surprisingly low stresses and total strain. It has been found by actual tests that failure in specimens subjected to high temperatures and low stresses does occur in the above manner and fracture is intercrystalline, as this theory would predict. This one circumstance is the cnly case wherein creep failure may be attributed primarily to quasi-viscous creep.

Between the stress regions of rapid plastic extension due to normal slip and the extremely slow creep rates attributable to viscous flow lie the areas of primary industrial importance. These are regions where the stresses high enough to be of value produce acceptable creep rates. Creep in these regions occur primarily through a phenomena called slipless flow.

Early observers of slipless flow found that, unlike normal slip, it produced no visible slip bands on prepared specimens; hence its name. Later, however, it was found that slipless flow produced changes in the general shape of individual crystals that greatly resembled the shape changes induced by normal slip. Furthermore, slipless flow produced a strain hardening effect equal to that of normal slip. now, although other mechanisms may induce strain hardening, only slip is known to produce it; hence most observers now feel that, in spite of its name, slipless flow does involve some slip. Evidently this slip occurs on a smaller scale than normal slip, producing many more disturbances but much smaller in size, affecting planes individually rather than in groups; else it would be visible. This type of behavior is probably aided somewhat by recovery which is in turn linked with diffusion. However, the major cause of slipless flow is believed to be the viscous flow of grain boundaries. It has been found that when polished specimens having mixed grain size are deformed slowly under moderate temperatures, all crystals exhibit similar changes in shape, but only the larger crystals develop slip bands. This is another indication of the great influence that grain boundaries play in influencing the creep mechanism. Since the major part of resistance to slip of a given specimen is thought due to the existence of a grain boundary which, although filled with dislocations, offers few planes favorable to slip, it is not inconceivable that only the larger grains be subject to normal slip. The smaller grains, having a much greater surface and area per unit volume, are more affected by dislocations and diffusion induced by grain boundary movement. Evidently these mechanisms combine to provide extension of small grains without as severe a slip as that induced in large crystals. Obviously, dislocation and diffusion caused by grain boundary disturbances affect larger crystals too; their effect is proportionally much less on larger crystals.

Another theory given to cxplain the lack of slip on small crystals is based on findings that the grain boundary is extremely thin; calculations have shown it to be of the order of thirty atoms thick. In view of the slow rate of viscous flow, yielding of the grain boundaries would permit only a very limited displacement along each slip plane as it became exposed. This displacement would be far too small to be seen in the form of slip bands. Thus the so-called slipless flow would occur at a rate proportional to that of viscous flow; in other words, it would proceed at a very slow rate, even though deformation occurred by slip. This interaction between the viscous flow of grain boundaries and the so-called slipless flow provides a very satisfactory explanation for quasi-viscous creep. The reader should understand that the foregoing pages contain primarily theories which attempt to explain the seemingly simple phenomena of creep on a rather complex basis. No present theory satisfactorily explains all the mechanisms known to affect creep. The mere presence of so many theories indicates that the nature of creep is yet largely unknown and poorly understood.

In review of this theoretical material, some discussion of these theories and their correlation with experimental facts is in order. The creep curve showed that a specimen under just sufficient load to culminate eventually in fracture will generally undergo a period of high but rapidly decreasing strain rate followed by a time wherein the strain rate is approximately constant followed by a period of rapidly increasing strain rate ending in fracture. This may be explained in theory as follows. Upon initial application of the load, strain is sufficient to produce a considerable amount of intercrystalline slip. This slip produces a strain hardening effect that rapidly decreases the creep rate, until the specimen has sufficient strength to withstand the imposed load without further normal slip. At this point quasi-viscous creep, which is really a combination of quasi-viscous flow and slipless flow, and which has been acting at a slow but constant rate since application of the load, now becomes the important factor in determining the creep rate. Since viscous flow is constant at a given temperature, and since slipless flow is a function of viscous flow, the creep rate remains essentially constant for a considerable period of time. The strain rate, although constant, gradually increases the internal energy of the metal, until it becomes almost equal to the energy of self diffusion. At this point, diffusion, which formerly had occurred primarily in a few areas of high energy concentration only, now plays a major role in the behavior of the specimen by releasing critical atoms from their bonds, promoting recovery. Then slip begins again, and since recovery now occurs simultaneously with strain hardening, the creep rate increases rapidly, reducing the cross sectional area of the specimen which increases the creep rate further. Failure of the specimen is imminent within a short time. It is important that the reader realize that the theory of creep mentioned above is not limited to specimens which follow the ideal creep curve. Rather, the behavior of any specimen known to the writer may be analyzed reasonably well on the basis of that theory, no matter where or how failure occurs, and even if failure does not occur at all. As it stands, this theory is but a hypothesis which seems to explain experimental data; it must not be interpreted as proven fact.

Creep Correlations

Perhaps the first investigator of real importance in the field of creep was Andrade(1) whose work was first published in 1910. His work was primarily acedemic. In 1922 the first creep studies of true industrial importance was published by Dickenson(2); his work was done in behalf of the boiler industry and was concerned primarily with various steels subjected to high temperatures within furnaces. Perhaps his most significant discovery was that commercial metallic materials, when used at elevated temperatures, underwent an alarming rate of plastic flow well within the stresses allowed by good design practice and safety factors at that time.

A great deal of experimentation was wasted during the six years after Dickenson's work was published, in an effort to prove the existence of "creep limits", then defined as that practical stress at which, for elevated temperatures, creep either no longer would take place or at least was of inconsequential magnititude. Creep observations were made from this point of view, and both French in 1926 and Lea(2) in 1927 attempted to show that proportional limits determined with sufficient delicacy might be regarded as creep limits. Refinements were later made on the creep testing apparatus, producing more accurate data, and Kanter and Spring(2) published a treatise in 1928, revealing that creep strain was exhibited by metals at stresses well below the lowest proportional limits obtainable.

A considerable expenditure of money and effort was used in an effort to derive long time creep rates on the basis of very short time tests. Gillett(32), among others, has demonstrated, however, that materials require in general from 50 to 500 hours to settle down to a relatively constant rate of creep. Since short time data reveals only the primary stage of creep, such data are generally worthless for long time predictions. Thus investigators who arrived at empirical formulas which attempted to extrapolate years into the future from the results of tests of but a few hours duration either were in error for many alloys, or were compelled to use an abnormally high factor of safety.

Andrade, who, as was mentioned earlier, first published articles on creep in 1910, later arrived at the concept of primary or transient creep as the principal mechanism of plastic flow throughout the first stage of creep and of quasi-viscous flow as the mechanism of plastic flow during the extended second stage of creep. He, on the basis of experimental data arrived at the following equation for creep, commonly called the $t^{\frac{1}{3}}$ law:

$$l = l_o \quad (1 + Bt^{1/3}) \exp KT$$

Where: l_o = initial length
l = final length
l = time
B = a constant
K = a flow of constant rate per unit length

In the light of metallurgical background given earlier, it can be seen that B represents transient creep which decreases rapidly with the cube root of time. K, on the other hand, expresses the concept of quasi-viscous flow. Reasonably good results may be found by using this equation for specimens under moderate temperatures. Under ambient temperatures, Wyatt(1) found that another equation becomes necessary; under high temperatures, still another. Thus pure emperical equations leave something to be desired in analysis of creep data; generally, at least, the useful temperature range of the equation is quite limited.

The ideal equation for creep would, of course, include all the variable present in creep. It has been recognized for some time that creep is a rate process. A complex, either molecular or atomic, requires an energy level above some minimum value to cross a potential energy barrier. Now, assuming that thermo-dynamic equilibrium must always exist during movement within the metal, an equation may be written indicating the number of activated complexes crossing a barrier each second per unit concentration:

$$\text{rate} = \frac{RT}{h} e^{-\left[\frac{\Delta H}{RT}\right]}$$

In this equation, R is the gas constant; T, the absolute temperature; h, Planck's constant; and ΔH, the activation energy of the material in question. Machlin and Nowick(35), assuming that the generation and movement of each dislocation is accompanied by a strain of d/L where d is the spacing between atoms and L is the dimension of the grain within which the slip occurs, developed the following equation for creep rate:

$$\dot{\varepsilon} = \frac{KT}{h} e^{\left[\frac{VGx^2f^2+PT}{kT}\right]} \sinh\left[\frac{2Vxf(\sigma-2bT)}{kT}\right]$$

This equation takes work hardening into account. In using a purely analytical approach, it is a notable accomplishment in the theory of creep. However, it cannot take into account all the effects upon creep induced by alloying. Therefore, good correlation was found primarily in pure metals. Its complexity, however valid from a scholastic approach, necessitates much experimentation to determine the many constants; therefore it is extremely doubtful that this equation will find much application in industry.

One might suspect that an empirical equation, utilizing the hypotheses behind the rate process theory but simplifying the terms into constants and variables both more easily obtainable and easier to use, would prove accurate over a wider range of temperature than a straight empirical equation. This type of equation would not only be more accurate in determining creep rates of alloys than the purely theoretical equation of Macklin and Nowick, but would be far easier to manipulate.

Larson and Miller(23) started with the general rate expression,

$$r = A \exp -\left[\frac{\Delta H}{RT}\right],$$

where A is a constant, ΔH is the activation energy, R is the gas constant, and T is the absolute temperature. Their approach was to combine all the creep variables, stress excepted, into a simple equation which was based upon the above rate process theory. Their solution was the development of the following parameter:

$$\frac{\Delta H}{2.3\ R} = T\,(C + \mathrm{Log}\, t) = \mathrm{Const.}$$

This equation relates time to rupture to temperature for a given stress. It also may be used in the determination of minimum creep rates. Larson and Miller have approximated the constant C at 20 for all materials. Other investigators, using this equation, have found that the value of 20 was accurate for approximately one half the alloys tested; the remainder required constants ranging from 16 to 40.

In practice, the parameter is evaluated for many different temperatures and times to rupture. These values are plotted against the log of the stress producing failure. The resulting points approximate a master curve such that, once it has been plotted, the time to rupture at any stress or temperature may be determined by evaluating the parameter with the aid of the master curve. This method produces excellent correlation at temperatures as low as 200° F.

In the derivation of this parameter, Larson and Miller, in their efforts to produce an equation which would agree with experimental results, have sacrificed some of the theory behind the dislocation-rate hypothesis. Among other questionable approaches, they have assumed that the activation energy is a single valued function of the stress. At moderate to high temperatures wherein this parameter has its most successful applications, it has rather been shown that the activation energy during creep is independent of temperature, time, strain, stress, grain size, and substructures developed under creep, and is found to agree with the activation energy for self diffusion.

Manson and Haferd(17), upon examination of physical data, proposed the following parameter: $\left[\frac{T - T_a}{\text{Log}\, t - \text{Log}\, t_a}\right]$, where T represents the temperature in degrees Fahrenheit, t the rupture time in hours, and T_a and t_a are material constants. As is the case in the Larson-Miller parameter, that of Manson and Haferd is plotted against log stress; however the latter parameter approximates a straight line regardless of specimen temperature. This parameter may be used for evaluating minimum creep rates by replacing the denominator by the quantity ($\log r + \log r_a$) where r is the minimum creep rate and r_a is a constant of the material in question. The accuracy of this parameter in predicting times to rupture has proved good for many steels, high temperature alloys, and aluminum alloys.

Many others, notably Shelby, Orr, McGreger, Fisher, Giedt, and others have added greatly to our knowledge of creep and to our means of predicting it. However, the theories presented here are perhaps as accurate as any. They also illustrate typical approaches to the problem.

Summary

Judging from the accuracy and range of the parameters and equations proposed for the prediction of future creep data, it is apparent that the most successful equations deviate somewhat from the complexity of true creep theory, but utilize the basic rate equation as a starting point. The basic rate equation presents one unavoidable complication in its attempts to handle creep of metals analogous to flow of gases. It lies in the fact that, whereas the mechanical properties of gases deal with the relation between pressure, volume and temperature, those of metals deal not only with the corresponding variables stress, strain, and temperature, but in addition, with time. Even assuming that creep rate were dependent solely upon the above four variables and did not change with specimens subject to age hardening and to other such creep variables, the presence of four primary variables would demand not only extensive experiments, but a systematic method of sorting out their relationships. Furthermore, the work of Los (35) demonstrated that the four unknowns could not in general be related by any form of equation in which one quantity is uniquely determined when the values of the remaining three are given. The basis for most modern creep correlations is the rate equation $r = A \exp\left(\frac{-\Delta H}{RT}\right)$; this is an equation of state analogous to the gas law $PV = NRT$. Modern

parameters and equations are developed generally by beginning with a promising form of the rate equation and by modifying it to meet the specific objections raised by the experimental results. This approach will be utilized in formulating equations for creep rates of the aluminum alloy conductors tested in this experiment. However the parameters listed previously are unacceptable for evaluation of creep data from aluminum alloys at ambient temperatures, because the activation energy, which has been assumed to be a constant approximately equal to the energy for self diffusion, varies with stress and temperature at low temperatures. Thus good correlation with the previous equations is possible only at temperatures at least approaching these of high temperature creep. The lower limit of high temperature creep is considered to be 0.45 of the absolute melting point. This is well above the temperature employed throughout the tests reported here.

CREEP TESTING

ASTM Specifications

The American Society for Testing Materials has established recommended standards for long time tension tests. Whereas these standards are primarily for high temperature testing, they were followed as closely as possible.

However, the manufacturer for whom this study is being conducted has specified both the material and the loading conditions for this test; his specifications must be followed.

ASTM designation E 22 - 41 specifications call for a test period dependent upon the life of the material; a test period of less than one per cent of the expected life of the product is deemed inadequate to give significant results. Rather, a test period of ten per cent of the expected life of the material is preferable if at all feasible. Short time tests may be used to determine whether an alloy is either very good or very poor, recalling at all times that short and long term tests may indicate different relative merits of the alloy.

The above specifications also call for measurements to be taken of temperature, cross-sectional area, extension, length, and load. Of these measurements, temperature is the most critical, since under some circumstances a ten degree temperature increase has been known to double the creep rate. Consequently, in testing creep under ambient conditions, the temperature must be held to within plus or minus three degrees of the design temperature.

Specimens should have a minimum diameter of 0.252 inches and a gage length of at least two inches; however a 0.505 inch diameter and longer gage lengths are preferred. The specimen diameter should have a maximum tolerance of

0.5 percent of the nominal diameter throughout the gage length. The specimen should be free from scratches or tool marks.

Loading should be applied by means of a dead weight or by means of a lever system; the load should be accurate to within one per cent. Especially with short specimens, care should be taken to avoid eccentricity.

The extension measuring equipment should be at least as accurate in terms of percentage as the method of applying load. Extension readings should be taken at sufficiently frequent intervals to define the extension-time curve.

The ASTM specifications suggest that in interpreting results, curves be plotted on rectangular coordinate paper using an amply large scale, and expressing time in hours. They recommend log-log plots of stress as the ordinate against creep rate as the abscissa. They also recommend a similar plot of (log) strength versus temperature, but caution against extrapolation from the latter curves. They suggest that special ASTM forms be used in reporting the data.

<u>Creep Testing of Aluminum Alloy Conductors</u>.

In many respects, aluminum is an ideal metal on which to test creep rates. It need not be handled with the care necessary in testing lead, yet its creep rate is much more rapid than that of steel, thereby permitting somewhat less sensitive extensometers. Consequently, little difficulty was expected in determination of the experimental results. However, because creep becomes important only at high temperatures in most applications, very little data have been obtained for creep in aluminum at low temperatures. As recovery is extremely slow at low temperature, correlation of low temperature data by means of high temperature methods is generally impossible, necessitating the determination of a new, more valid approach in evaluating the experimental data. Furthermore, the testing of cables requires an analysis of the effect of stranding upon both tensile strength and creep rate. Consequently, the evaluation of the experimental results derived from these tests may be expected to prove the major difficulty in testing aluminum alloy conductors.

Test Material.

The material to be tested was aluminum alloy conductor, stranded into cable form. Two coils were supplied from different manufacturing lots in which there were possible differences in processing. These were designated as Lot 1 and Lot 2; Lot 1 was shipped in a coil of relatively large diameter, whereas Lot 2 was shipped in a much tighter coil. The diameter of a single strand of conductor wire was 0.188 inch. When stranded into cable form, a pitch of seven inches per revolution of each of the six outside stranded was employed; the center strand remained relatively straight, being deformed only slightly by the stranding operation.

The nominal composition of the alloy is as follows:

TABLE I

Nominal Composition of the Test Material

Alloying Element	Per Cent by Weight
Magnesium	0.70%
Silicon	0.60%
Iron	0.25%
Copper	0.02%
Aluminum	balance

The principal alloying elements are the silicon and the magnesium. As a small variation in alloy can cause a phenomenal difference in creep rate, it is unfortunate that the exact alloying elements of both Lot 1 and Lot 2 are not known. However, a small deviation from the above constituents also can cause a serious decline not only in the electrical conductivity, but also possibly in the mechanical properties of the conductor; consequently, the manufacturer doubtless maintains careful quality control on the alloying constituents of the conductor to avoid paying a serious price penalty on a product that is not up to standards.

The processing of the conductor wire consists of rolling the billet into a 0.375 diameter rod; this is followed by a drawing process in which the diameter is reduced to 0.334 inch. At this point the alloy receives a solution heat treatment; this is followed by a cold drawing process in which the wire is reduced in size to its final diameter of 0.188 inch. This is followed by an artificial aging at 350 F. for 5½ hours. Fabrication is completed by coiling or stranding followed by coiling, depending upon the customers' requisitions.

In the light of the previous discussion of creep phenomena, some discussion of the age hardening process to which the test material is subjected is in order. The quantity of alloying elements in an alloy that may be present in solid solution is dependent upon the temperature; at high temperatures a much higher percentage of alloying elements will dissolve into solution. Consequently, there is no difficulty in forming a solid solution of the alloying elements in the parent metal.

When an age hardenable alloy has undergone its final hot working operation, it is ready for heat treatment. It is heated to a temperature just above that required for a saturated solid solution. It is held at this temperature for some time, giving the alloying elements time to go into solution. It is then quenched, freezing the foreign atoms in their places and preventing them from gradually precipitating out of the now supersaturated solid solution because the rigidity of the solidified grain at low temperatures is too great.

When such an alloy is subjected to stress, it behaves much like a pure metal; the foreign atoms have merely replaced atoms of the present metal within the crystal lattice. If the foreign atoms are allowed to precipitate gradually from the supersaturated solid solution, they tend to gather in clusters. These clusters restrict dislocations from moving through the lattice or grain boundary, since a higher level of energy is necessary to force the dislocation around the cluster. This is called aging. If the precipitation process is carried too far, the clusters of foreign atoms become large, reducing the total number of clusters. Since the number of dislocations whose movement is restricted by the presense of clusters is more dependent upon the number of clusters rather than upon their size, excessive cluster growth results in reduced strength. This is called overaging.

As the metal would not age harden appreciably under ambient conditions, it must be heated to a temperature more favorable to precipitation of the alloying elements. Since the rate of precipitation is proportional to the temperature, the aging process may be accelerated immeasurably by subjecting the metal to moderate temperatures for a period of time. Exact control over the aging process can also be maintained, that the desired properties may be duplicated in different lots of the same alloy. The time required for aging is dependent upon the temperature of the alloy and its constituents; it is determined experimentally. The conductor wire is aged 5½ hours at 350 F. Since both the mechanical and electrical properties of the conductor are drastically affected by this treatment, it is imperative that it be executed properly.

The only mechanical property furnished by the manufacturer was the ultimate tensile strength of a single strand conductor wire. Seven strands of wire drawn from seven different spools of Lot 1 conductor wire tested; the average tensile strength developed was 49,329 pounds per square inch. This value was checked; the tensile strength of the conductor was also tested. The results of these tests will be mentioned later.

<u>Creep Testing Machines</u>.

The essence of a creep testing machine includes a means of applying load, maintaining constant temperature and measuring elongation. Rigidity is important; poor experimental data invariably results from equipment subject to distortion under load. Good axial alighment is necessary, especially in machines used for testing short specimens. Friction must be avoided as much as possible, as it causes a variable load on the specimen. Grips which hold the specimen without inducing excessive stress concentration or permitting slippage are a necessity. Some means of controlling the maximum temperature fluctuation to within plus or minus three degrees Fahrenheit must be provided. An accurate means of determining the elongation of the gage length of the specimen is required. Finally, some means of adjustment must be provided to allow for extension of the specimen.

Test Equipment

Company requirements dictated the testing of conductors, using a gage length of 200 inches. The extreme length of the specimens demanded that unique machines be constructed to accommodate the specimens. Because added lengths would be required to accommodate the grips and some means of specimen adjustment, and yet allow some distance between the grips and the gage length to minimize the possible effects of end connections, an overall column length of thirty feet was decided upon. Since the conductor in coiled form was extremely unmanageable, and since some means of reading the extensometer had to be provided anyway,

Figure 3. Interior View of the Enclosure

an open lattice column was constructed, greatly facilitating installation of specimens. To provide sufficient rigidity, the column was designed for a capacity of 20,000 pounds; four lengths of 2 x 2x3/16 inch angle iron were employed to form the corners, with reinforcing provided by welding cross braces of 1/8 by 1/4 inch steel bar stock to the angles. To permit multiple testing of specimens at different stresses, six separate columns were constructed, numbered from 1 to 6 from left to right as seen in Figure 3. This arrangement also permitted one specimen to be changed without disturbing the remainder. Each column was bolted down rigidly at both ends and at two places in the middle so that deflection and distortion were minimized.

Since a load of up to 8,000 pounds would have to be applied, the use of a dead weight was out of the question; consequently, a lever system with a multiplying ratio of approximately twenty to one was devised. The lever was cut from one inch plate. To minimize friction and thus provide a more constant load, needle bearings were employed both at the pivot of the lever and at the place where the connecting linkage was attached to the lever. The lever was not mounted to the lattace column, but was attached to a vertical column independent of the horizontal or loading one. To insure that the force induced by the lever be applied axially to the loading column, the vertical column rested

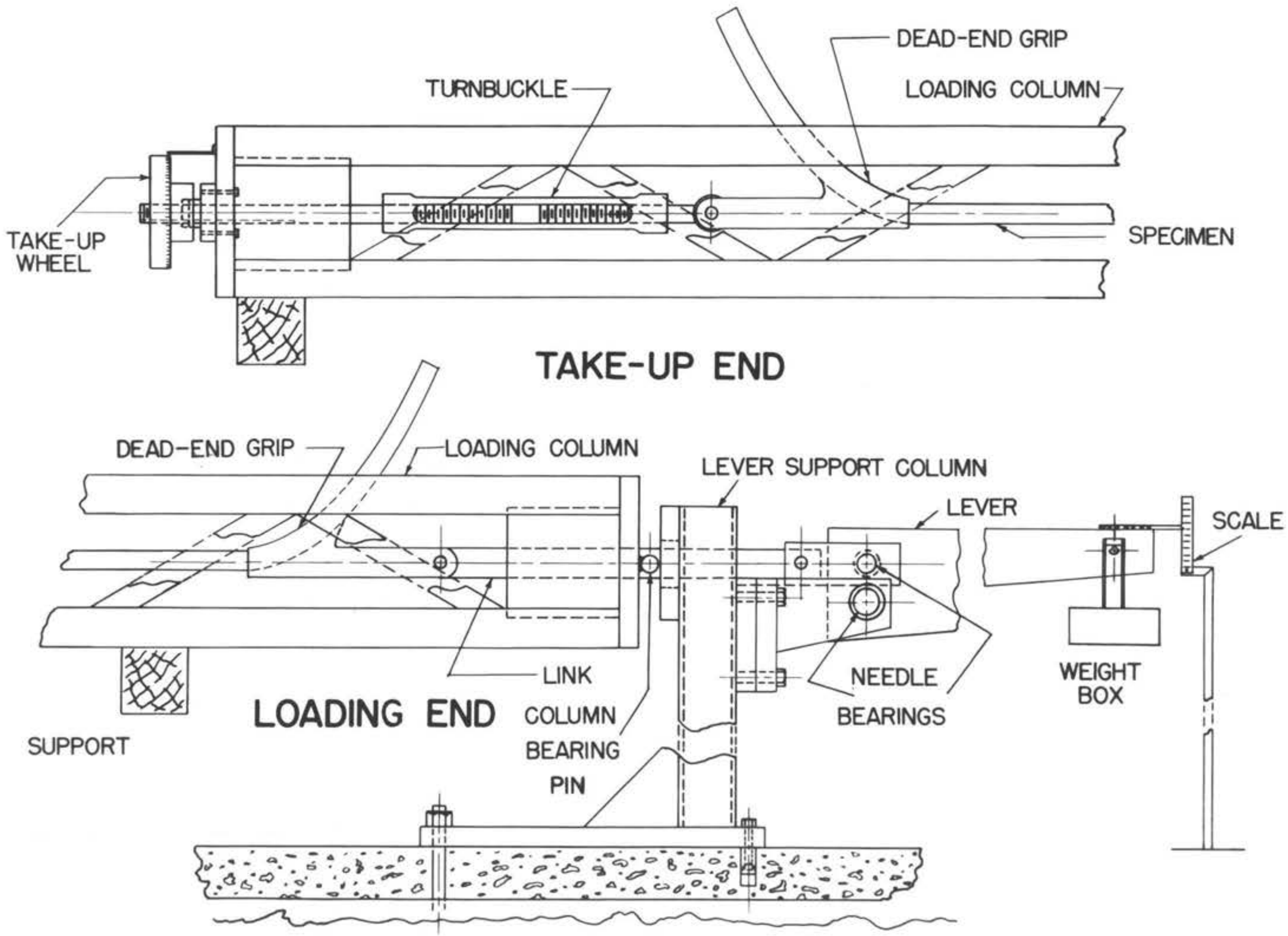

Figure 4. Loading and Takeup Ends of the Creep Testing Machine

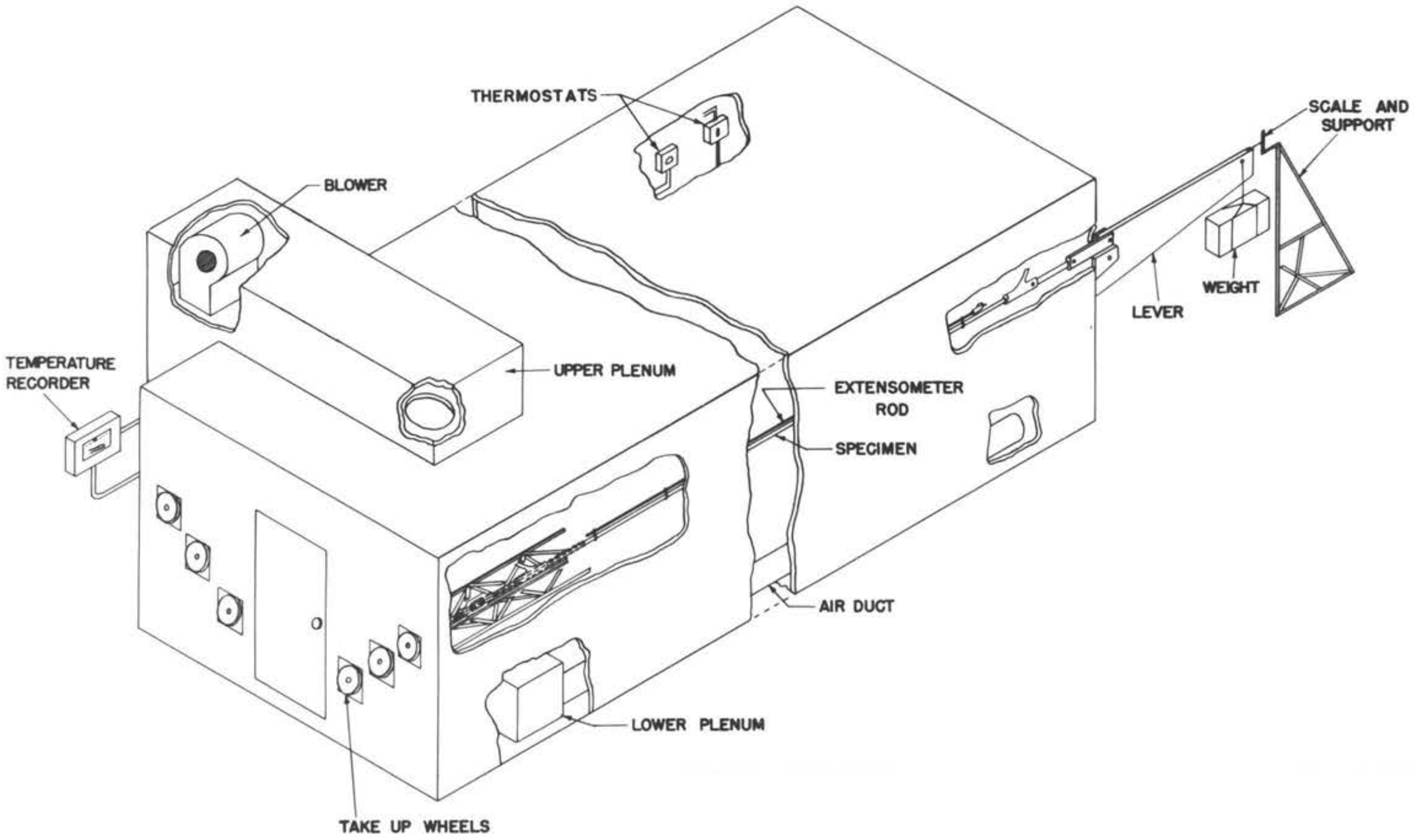

Figure 5. Cutaway Sketch of the Enclosure

against a pin welded to the end plate of the horizontal column. Specimens were loaded by means of a box of lead shot attached to knife edge supports near the outer end of the lever. The knife edges were machined from high carbon steel and hardened to minimize wear. The completed lever assembly is visible in Figure 4.

Two means of takeup were provided. The grips were coupled to a 12-inch turnbuckle which adjusted for variation in overall conductor length and was used for facility in installation of specimens. The second takeup device consisted of a large nut, visible on the extreme left end of the enclosure in Figure 5. The nut was turned by a spanner wrench; friction was minimized by the use of a ball thrust bearing located between the adjusting nut and the column end. The one inch diameter takeup screw was prevented from turning by means of a loose fitting key located in the end of the column. The takeup nut was graduated to indicate the amount of the takeup for a given fraction of a revolution.

The grips chosen were Cooline clamps; they bent the specimen on a gentle radius to make an approximate 60° angle with the loading column. The back of the clamps afforded connection to the takeup screw on one end of the specimen and to the lever connecting linkage on the other end in such a way that the centerline of the cable remained on the centerline of the loading column. The clamps are shown schematically in Figure 4.

Column 6, which is the upper right hand column in Figure 3, is the lone exception to the previous description of grips and lever system. It was designed to test creep rates of single strand aluminum alloy conductor wire; consequently it was to be subject to far less load than the other columns. The horizontal loading column and the vertical column were identical with the other columns. However the entire lever linkage was not employed; instead a four inch diameter steel pulley was substituted and a dead weight used to apply load. A steel cable was used to link the dead weight to the grip; a swivel was provided to minimize twisting of the specimen. The grips for the single strand conductor test consisted of a tapered chucks with matching tapered jaws tightened by means of a nut. The surfaces of the jaws which gripped the specimen were threaded to insure freedom from slippage.

Extension of the six columns was measured identically. Dial indicators manufactured by the Tubular Micrometer Company were employed; they had a three inch face, a two inch travel and were graduated in 0.001 inch. The indicators were clamped to the specimen at one end of the gage length. An aluminum tube, threaded at one end to accommodate the dial indicator and clamped opposite it at the other end of the gage length, completed the construction of the extensometer. Clips, spaced on approximately 15 inch centers, supported the aluminum tube in position directly above the specimen.

Some comments are in order concerning selection of an aluminum tube to measure extension. Dividing the 0.0001 minimum extension measurement possible by the 200 inch gage length, one finds that unit strains were determined with an accuracy of $\pm$ 5 x 10^{-7} in./in. The coefficient of linear expansion of aluminum is 133 x 10^{-7} in./in./ F; that of steel is 58 x 10^{-7} in./in./ F. Thus each degree of temperature change in the specimen would result in a thermal change in length of fifteen times the minimum extension measurement possible, if a steel extensometer rod were used. As the temperature of the enclosure may vary a maximum of $\pm$ 3 degrees, a thermal change of length of several times a week's plastic extension could occur. Therefore, in spite of the fact that the aluminum tube was rather fragile, it was necessary to use it to minimize differential changes in length between the specimen and the extensometer tube. A second advantage of the aluminum tube was its light weight. This had a negligible effect on the conductors but was important on the single strand test when a slight load in the middle of the space was sufficient to produce sagging.

Figure 6. External View of the Enclosure

In order to learn the effect of the clamps upon the creep rate as well as to determine if the clamps should slip slightly, it was necessary to provide a means of measuring overall extension. This was accomplished by attaching a pointer to the outboard end of each loading lever. A six inch steel scales were attached to a frame placed behind the pointers; the graduation on the scales permitted readings of lever deflections accurate to the nearest 0.01 inch. The levers then amplified the overall extension by a factor equal to the lever ratio. Thus the unit extension of the specimen could be determined by the following formula:

$$E = \frac{\text{deflection on scale}}{\text{lever ratio x overall length of specimen}}$$

Unit extension measurements accurate to within 3×10^{-6} inches per inch were possible. The overall unit extension could then be compared with the unit extension present within the gage length, revealing the effect of the gripping devices upon the creep rate.

Temperature control is perhaps the most important single factor in creep testing. To maintain the test temperature of 75 F. within the maximum variation of 3 F. permitted, it was decided to construct an enclosure around the group of loading columns. A framework of 2 x 4's was erected; this was covered by Firtex, a good thermal insulator.

The entire enclosure, complete with the temperature control system, can be seen in Figure 6. A circulating air system was used for air conditioning. Air was drawn out of the chamber through a duct near the ceiling; it then passed through the fan over either an electrically heated coil or a water cooled coil, and through a duct outside one wall of the enclosure. The wall duct carried the conditioned air into a distributing chamber in the floor. From this point the air passed into two ten inch diameter distribution pipes which carried the air the length of the enclosure and exhausted it. The conditioned air then passed back over the specimens to the intake and was then recirculated. Precise temperature control was provided by a two way bulb type thermostat placed near the exhaust end of one of the distribution pipes. It was wired through a relay system which activated the heating element upon contact of the low temperature sensor or the cooling water valve upon contact of the high temperature sensor. The controller was set to maintain the test temperature of 75 F. with a maximum deviation of less than 1 F. The air conditioning system is shown schematically in Figure 7.

During the summer months when the ambient temperatures were above 80F, it was found that the water cooling system was inadequate to maintain the test temperature accurately. Consequently a refrigeration system was installed to

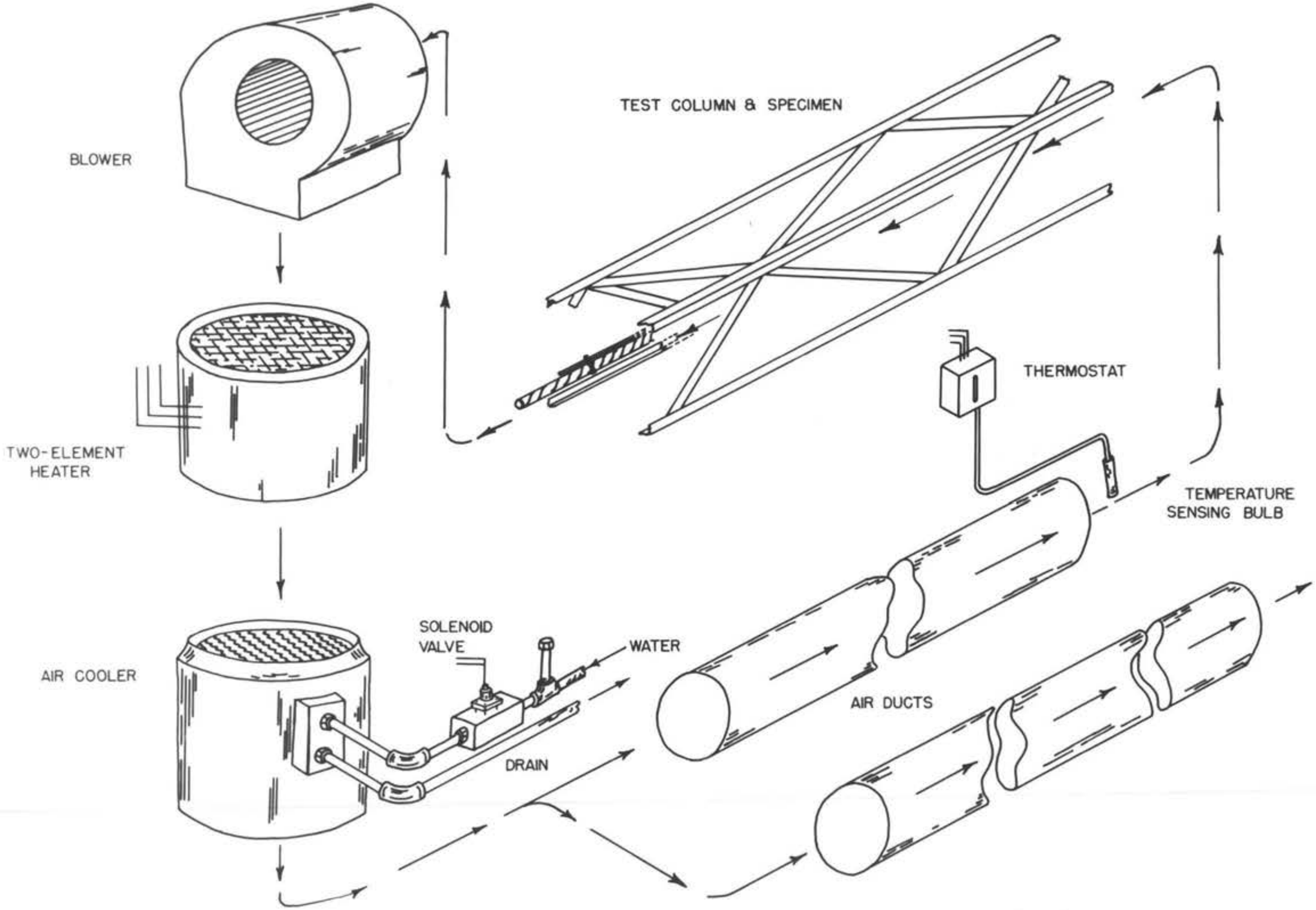

Figure 7. Schematic of the Air Conditioning System

subcool the cooling water. For the greater part of the year, the conditioning system operated on the heating cycle only.

Since variation in temperature within different sections of a specimen was to be avoided, it was necessary to know whether these variations existed. Therefore a complex network of thermocouples was installed, one at each of fifteen different locations within the enclosure. A Brown sixteen point electronic temperature recorder maintained a permanent record of the temperature at each of the fifteen thermocouple locations within the enclosure; it recorded the ambient temperature on the sixteenth point.

The enclosure was wired and sockets were installed for three electric lights. A safety device was employed in the enclosure; the air conditioning fan deflected a hinged flap which supported a mercury switch. Should the fan stop, the flap would descend, turning off the mercury switch. This shut off the heating system. Fire thus could not have resulted from locally overheated walls if the fan should have failed.

Calibration

There were two items to be calibrated; load and temperature.

Load Calibration.

Several means were available for calibrating the weight of the dead load required for a given tension in the specimen. The lever ratio could have been measured with a steel scale; this means, although simpler, would not have been sufficiently accurate. A hydraulic jack equipped with a pressure gage could have been used, but the gage on such a mechanism would not have fine enough graduations. Standard weights could have been employed; however, as it was desirable to test the lever under its full working load, four tons of standard weights would have been required, making this approach very impractical. The ring dynamometer method of calibration was decided upon and a ring seven inches in diameter of 11/16 by 2 inch steel plate was formed. Four strain gages were placed on the sides of the ring, two inside, the other two outside, 90° from the points of load application. The completed ring was tested on a universal testing machine, using the latter as a standard, by taking numerous strain gage readings throughout both loading and the unloading cycles. The above procedure was repeated several times to insure accuracy. The dynamometer proved to be sensitive to a load variation of five pounds.

Using the ring dynamometer as a standard and a steel cable substituted for a specimen, each of the six columns was calibrated, both on loading and unloading cycles. Friction in the lever mechanism proved negligible, as a change in load upon a dummy specimen of ten pounds was apparent on the strain gage meter. Since the minimum load employed on the conductors was 2275 pounds, this was well within the one percent accuracy specified by the ASTM.

The temperature of the different locations within the enclosure as well as that of the exterior location were measured by means of copper - constantan thermocouples. Each thermocouple was checked for accuracy against a precision mercury thermometer.

All sixteen thermocouples checked within one degree Fahrenheit of the standard temperature.

TEST CONDITIONS

The test conditions were specified primarily by the manufacturer. They will be discussed in detail below. Since all six specimens from a given run were replaced at approximately the same time, it was possible to assign a different series number to each new run to differentiate the various runs. This paper, then, is concerned with the results obtained from data taken on Series 3 and Series 4 specimens.

To provide a method of referring to a particular specimen of a given manufacturing lot number subjected to a certain preload and test load without writing a brief descriptive paragraph for each specimen, it was necessary to devise a code. Accordingly, symbols were assigned to indicate whether the specimen was a conductor or single strand; whether it was from Lot 1 or Lot 2; the amount of its preload expressed as a per cent of its ultimate tensile strength; the duration of the preload; and the amount of its test load, expressed as a per cent of its ultimate tensile strength. The symbols were arranged in the above order. Thus C-2-50, 1-25 may be interpreted as a conductor from Lot 2, subjected to a preload of 50 per cent of its ultimate tensile strength for one hour, followed by a test load of 25 per cent of its ultimate tensile strength. Likewise S-1-0-25 represents a single strand of conductor wire from Lot 1, subjected to a test load of 25 per cent of its ultimate tensile strength, no preload being employed. This designation system was used on the graphs in this report.

Specimens.

The specimens tested in Series 3 and Series 4 included ten lengths of 4/0 seven strand all aluminum alloy conductor and two lengths of conductor wire. The specimens were all approximately 26 feet long. Of the ten conductor specimens tested, nine were from Lot 2; the tenth was from

Lot 1. One single strand specimen was taken from each manufacturing lot. Each of the Lot 1 specimens tested duplicated a test made on a Lot 2 specimen, that the effect of processing differencesupon creep rates might become evident. Each specimen was assumed to be a representative sample of its particular manufacturing lot.

Loads.

Since in service conductors are generally prestressed for short periods before they are permanently strung, the manufacturer wished to determine the effect of this prestressing upon creep rates. Accordingly, he specified that most of the specimens be preloaded at varying percentages of their ultimate strength. Therefore Series 3 and Series 4 tests were arranged as shown in Table 2.

The table indicates that all the specimens were subjected to a test load of 25 per cent of the specimen ultimate tensile strength. Actually, however, the two single strand specimens tested in column 6 were subjected to test loads of 1/28 of the conductor strength. Since the conductor was composed of seven strands, it would seem that this would correspond to a test load of 25 per cent of the ultimate tensile strength of a single strand. However, such was not quite the case. Stranding induced additional stresses which reduced the overall conductor strength by

TABLE 2. Test Conditions of Series 3 and Series 4 Specimens

Column Number	Code Number	Prestress Conditions: Percent U.T.S.	Load lb	True Stress psi	Duration Hours	Test Conditions: Percent UTS	Load lb	True Stress psi
			Series 3 Tests					
1	C-2-80,1-25	80	7280	38,900	1	25	2275	12,310
2	C-2-90,1-25	90	8190	44,300	1	25	2275	12.310
3	C-2-70,1-25	70	6370	34,500	1	25	2275	12,310
4	C-2-60,1-25	60	5460	29,550	1	25	2275	12,310
5	C-2-75,3000-25	75	6825	36,700	3000	25	2275	12,310
6	S-2-0-25		None			25	325	12,310
			Series 4 Test					
1	C-2-50,1-25	50	4550	24,600	1	25	2275	12,310
2	C-2-0-25		None			25	2275	12,310
3	C-2-40,1-25	40	3640	19,700	1	25	2275	12,310
4	C-2-30,1-25	30	2730	14,770	1	25	2275	12,310
5	C-1-30,1-25	30	2730	14,770	1	25	2275	12,310
6	S-1-0-25		None			25	325	12,310

about five per cent. Therefore the single strand specimens were actually tested at approximately 24 per cent of their ultimate tensile strength.

Duration of Test.

Since the effect of prestressing upon creep rates was unknown at the beginning of the Series 3 tests, no definite time was set for completion of the tests. For the tests to have a practical value, however, it was necessary that they continue until the individual specimens had indicated definite strain-time curves. Once a pattern in the curves had been established, test periods of extreme length (e.g., 5000 to 10,000 hours) would probably be no longer necessary.

Observations.

The frequency of extension readings required at the start of the tests was another unknown quantity; therefore on early tests more readings were taken than necessary. The procedure followed later was as follows: Readings were taken each hour for the first twelve hours. After this period, readings were taken every day for a week; readings were then taken twice a week for the duration of the test.

On specimens subjected to preloads, extension readings were taken at ten minute intervals for one hour. The excess load was removed quickly; the above procedure was then followed for the duration of the test.

RESULTS

General

The data determined as a result of these tests may be found in the appendix. However, the graphs which follow form a far better means of comparison of specimens and of determination of results. The rectangular coordinate graphs reveal that, in general, the total extension of the specimens during the first 500 hours of the test was considerably greater than that of the next 4000 hours. This initial rapid decrease in creep rates indicated that perhaps more than one mechanism was operating, at least in the early hours of the tests. These indications were confirmed upon examination of the log-log plots, wherein two curves were required to define the extent of plastic flow of each specimen. A complete interpretation of these curves is discussed later in this paper. The curves show slight variations in the plotted points, part of which was evidently due to strand settling and part to variations in the creep testing apparatus. As these variations had an effect on the accuracy of the tests, they were important. They are discussed in detail below.

Performance of Equipment

Generally speaking, the performance of the equipment left little to be desired. However, two tests were interrupted; one by an equipment breakdown and the other by a freak accident. The specimen subjected to a 90 per cent preload had been under test for over 2000 hours when the pointer at the end of the loading lever hung up on the steel scale used to measure overall elongation. This went unnoticed until strain-time curves were plotted on the results from this test. These curves showed a suddenly reduced creep rate. The source of the trouble was then located and the test was continued; however, the data taken from this test after 2000 hours were of very doubtful value. Consequently, all curves drawn of data taken from this test do not include data for the full 4000 hour duration of this test.

The Lot 1 single strand test was interrupted after about 1800 hours by an equipment failure. A soldered joint, joining the steel loading cable to a connection which supported the dead weight, pulled out, releasing the specimen from the load. The connection was not subjected to any known sudden overload. It was not stressed above its elastic limit, else it would have doubtless have failed much earlier. Ironically, then, one may logically conclude that the creep testing machine failed in creep.

Whereas the curves seemed to follow regular patterns, some deviation of points from the curve was evident. For example, it was not too unusual for a specimen which had been elongating at the rate of 0.001 inch over its gage length per week occasionally to indicate a 0.003 inch extension over a three day period. Indeed, extensions as great as 0.006 inch or over have been indicated over a three or four day period. There was no known explanation for this. However, it was very doubtful if this sudden apparent extension can be attributed to creep. Creep is a rate process; its rate of flow produces a smooth curve. A far more likely explanation would attribute these irregular indications to friction in the testing machine, either within the extensometer or within the loading system. The extensometer tube was very light; friction in the supporting clips could induce a slight tensile stress in the tube. This stress would increase until it was sufficient to overcome the friction in the clips. It would then jump suddenly, producing an occasional abnormally high strain reading. The loading system, too, probably caused an occasional high strain reading. Friction in the bearings could permit the loading lever to descend in jerks with the gradual extension of the specimen. Friction in the dial indicators was also of some consequence, but these were tapped before each reading was taken to minimize internal friction.

A close examination of the test data revealed that a large indicated extension in overall length was not always accompanied by a large extension over the gage length. However the entire loading systems were located outside the enclosure and were thus subject to thermal expansions and contractions above those within the enclosure. Furthermore, any slipping within the gripping devices obviously would not be registered within the gage length, whereas any such slip was definitely included in the measurement of overall extension. The only extension common to both the gage length and overall extension was creep; one could not, therefore, expect any direct correlation between individual extension readings when each measuring system was affected by different variables.

The temperature control of the enclosure was considered to be excellent. During the entire period the writer was affiliated with the creep testing apparatus, at no time did the Brown electronic recorder indicate a temperature deviation anywhere within the enclosure of more than three degrees from the test temperature of 75 F. A mercury thermometer located at specimen height at about the mid-point of the enclosure was read every time strain gage readings were taken. Never was it observed more than one degree from the required 75 F. It was quite unlikely that the temperature of the gage length of any of the test specimens varied more than two degrees from the desired 75 F.

INTERPRETATION OF RESULTS

General Correlations.

As has been mentioned earlier, the creep curve shown in Figure 1 generally does not hold for specimens tested at ambient temperatures. Therefore, it came as no surprise upon analysis of the results presented in this paper to learn that no constant rate of creep was evident at any time during the test. This phenomenon may be explained as follows: Quasi-viscous creep, the combination of quasi-viscous flow and slipless flow which comprises the entire known plastic flow mechanism throughout the secondary stage of creep, does produce some strain hardening due to the action of slipless flow. However, the interaction of dislocations causing this strengthening effect is balanced at moderate temperatures by thermal recovery which is in turn caused by diffusion. At ambient temperatures, then, one might expect a continually decreasing rate of creep, because recovery effects then are extremely slight in comparison with the work hardening effects. Therefore, at ambient temperatures, creep of the specimens tested could be expressed as a diminishing rate process.

The formulas and parameters explained earlier were devised as a means of correlating creep rates of specimens subjected to either different stresses or different temperatures. Consequently, in their present forms they were of little value in analyzing data taken in the foregoing tests, all of which were subjected to identical test load stresses and temperatures. However the basic rate equation $\dot{\varepsilon} = Ae^{-\left[\frac{\Delta H}{RT}\right]}$ used in the derivation of these parameters and equations was of value in explaining the results of these tests. Since the gas constant R and the absolute temperature T were obviously constant throughout the test, the only exponential variable remaining was the activation energy ΔH. But the activation energy, although variable with both temperature and stress under ambient test conditions, remains constant for a given load and a given temperature. Therefore, under the test conditions the exponent $-\left(\frac{\Delta H}{RT}\right)$ could be replaced with the exponent "n", constant for any particular test.

The low temperature creep evident in the foregoing tests has been defined as a diminishing rate process. Was it not possible, then, in view of the above facts, that the creep rate would diminish according to some exponential function of time? As a test, strain versus time curves were plotted on log-log coordinate paper. Without exception, it was possible to describe the plotted points by means of straight lines. This would indicate that the equation for total strain at any time may be expressed as follows:

$$\varepsilon = At^n,$$

where ε is total strain;

A is a constant; it is the strain intercept at one hour;

t is the time in hours;

n is a constant for given loading and preloading conditions.

The strain rate at any time may be evaluated by differentiating the expression for total strain with respect to time:

$$\dot{\varepsilon} = n\,At^{n-1}$$

where $\dot{\varepsilon}$ is a strain rate.

This expression implies that the creep rate would never become constant; it therefore agrees with the experimental results. However, it does indicate that plots of this creep data on rectangular coordinates are of little value in extrapolating to future strains. Although the coordinate plots, especially the one shown in Figure 12 which ran for 10,000 hours, show that the creep rates have seemingly approached a constant value, a larger scale showed a continuing decline in creep rate. Obviously, then, the strain at some future time could not be extrapolated directly from the rectangular coordinate plots, but could be determined only from the log-log plots or from the use of the equation of the curve; i.e., from the exponential equation given above.

The above approach, although it differed from most of the previously proposed parameters, is not new. Wyatt(1) proposed a logarithmic law for low temperature creep; Schoeck(1) indicated that the creep rate as a function of time may often be expressed as an exponential relationship not unlike the one chosen above.

Having determined an equation which suitably described the creep curves, the constants A and n had to be evaluated. This was accomplished as follows. The logarithm was determined for both sides of the strain equation, resulting in the following expression:

$$\log \varepsilon = \log A + n \log t$$

Specific values for both ε and t were substituted into the equation from two points on the curve. The resulting equations were then solved simultaneously thus evaluating the constants. These constants are found in Table 3.

Preload

The specimens subjected to one hour preloads showed marked reductions in total strain for the times they were under test loads. In order to correlate this reduction in

TABLE 3

Table of Constants for the Creep Equation

Code Number	Initial Stage A	Initial Stage n	Secondary Stage A	Secondary Stage n
C-2-90,1-25	0.0708	0.915	0.716	0.559
C-2-80,1-25	0.0100	1.097	0.235	0.652
C-2-70,1-25	0.0537	0.984	1.192	0.527
C-2-60,1-25	0.6713	0.715	4.60	0.417
C-2-50,1-25	1.332	0.665	5.78	0.423
C-2-40,1-25	8.104	0.540	19.32	0.316
C-2-30,1-25	6.891	0.585	39.65	0.262
C-2-0-25	61.35	0.276	106.10	0.181
C-1-30,1-25	9.01	0.408	18.91	0.278
C-2-75,3000-25	13.51	0.338	25.36	0.140
S-2-0-25	35.90	0.326	95.96	0.198
S-1-0-25	23.03	0.300	37.27	0.221

later strain with the stress induced during preloading, an equation had to be derived relating stress and strain at one hour.

Stress was plotted, rather than load, in order that specimens of varying sizes in other tests might be compared on the same basis. However, this presented a problem, since stranding weakens a cable slightly; the reduction in strength is dependent upon the pitch and uniformity of the weave. In order, then, to use true stress as an ordinate, it was necessary to determine, quantitatively, the ratio between the ultimate strength of a single strand compared to that of the conductor. This ratio was found to be 1.052. Accordingly, graphs were plotted on both logarithmic and arithmetic coordinates of strain at one hour versus true stress, found by multiplying the apparent stress induced by the various preloads by the ratio 1.052. They may be seen as Figures 8 and 9, respectively. Analysis of the log-log plot showed that, although the points were somewhat scattered, the strain at one hour could be expressed as an exponential function of the stress. The equation, with constants fitted, is expressed below.

$$\varepsilon = \left(\frac{G}{2207}\right)^{2.195}$$

Where: G equals the prestress;
ε equals strain at one hour;
2.195 equals 1/n, where n is the slope of the curve;
2207 equals the stress intercept.

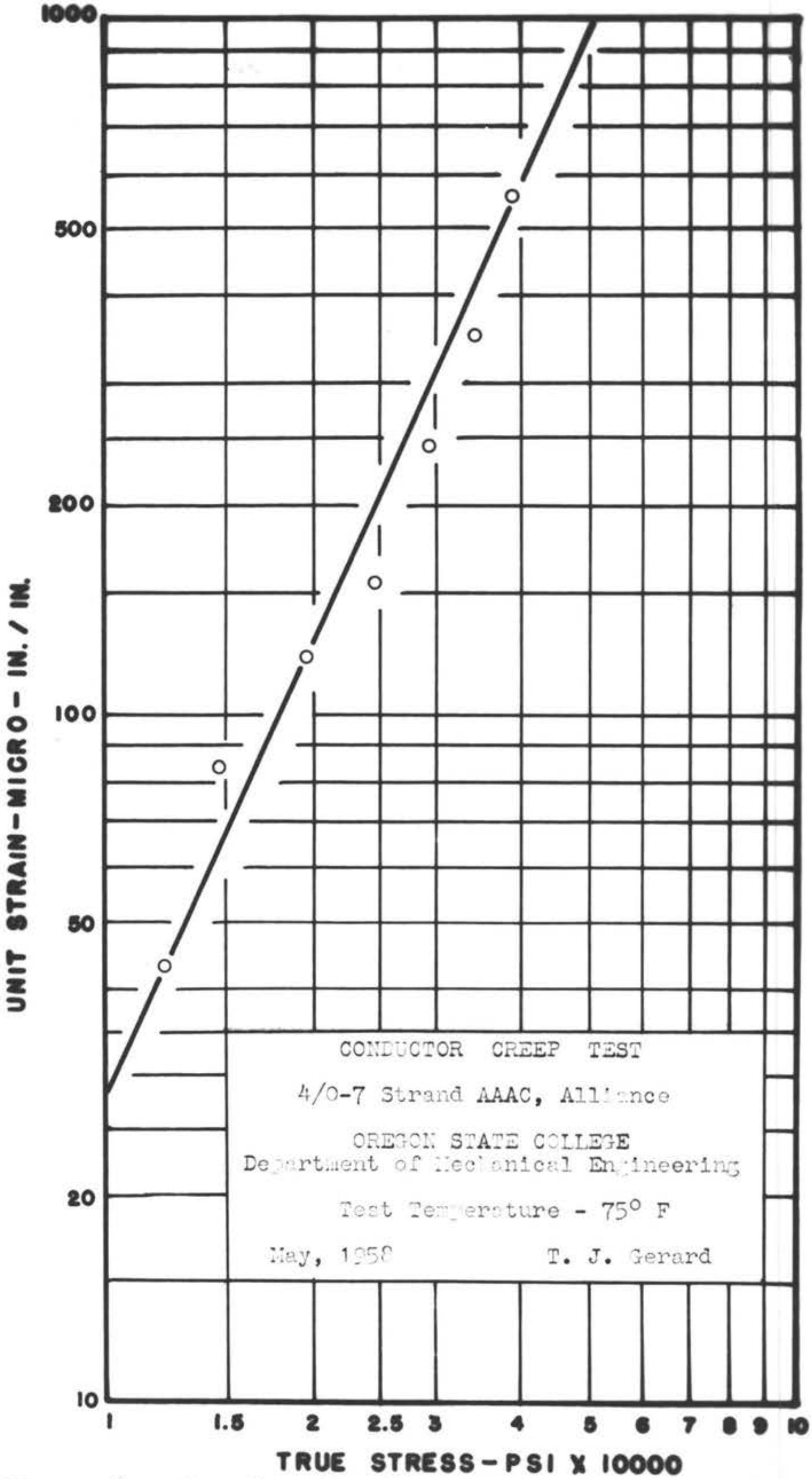

Figure 8. Log-Log One Hour Preload Correlation Curve

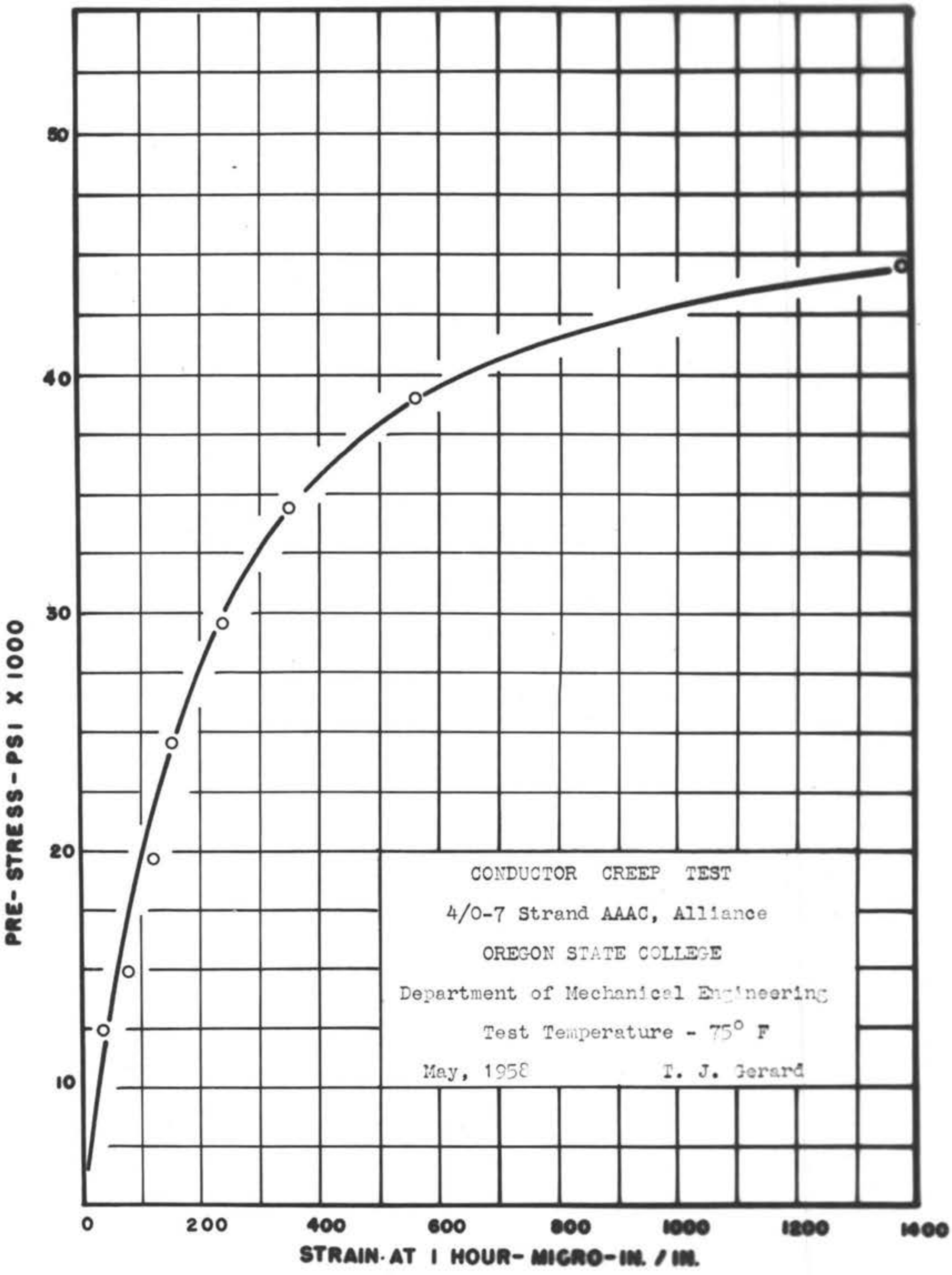

Figure 9. Stress-Strain Curve for one Hour Preloads

Attempts to correlate prestress in terms of strain measured over the test period that followed were unsuccessful. The work of former investigators was then examined, in hopes that a workable solution to the problem might be found. Although no similar testing procedure was uncovered, it was found that attempts have been made to correlate prior strain with creep. Dorn, Goldberg, and Tietz (13) attempted to correlate creep rates of specimens which had been subjected to varying amounts of prior strain. The strains employed in their tests were well above those encountered in the conductor creep tests. Furthermore, they were not successful in deriving even an approximation for future creep in terms of prior strain. It is, therefore, not possible to present a solution to this problem here.

Correlation of Prestressed Specimens.

A substantial reduction in total creep was effected over the duration of the test period by means of preloading, with the greatest reductions in total creep strain following the greatest prestresses. Evidence of this fact is immediately noticeable upon examination of Figure 10. One exception was found; the specimen subjected to a preload 90 per cent of its ultimate tensile strength suffered more creep than the one subjected to an 80 per cent preload. Although the exact cause of this difference was not

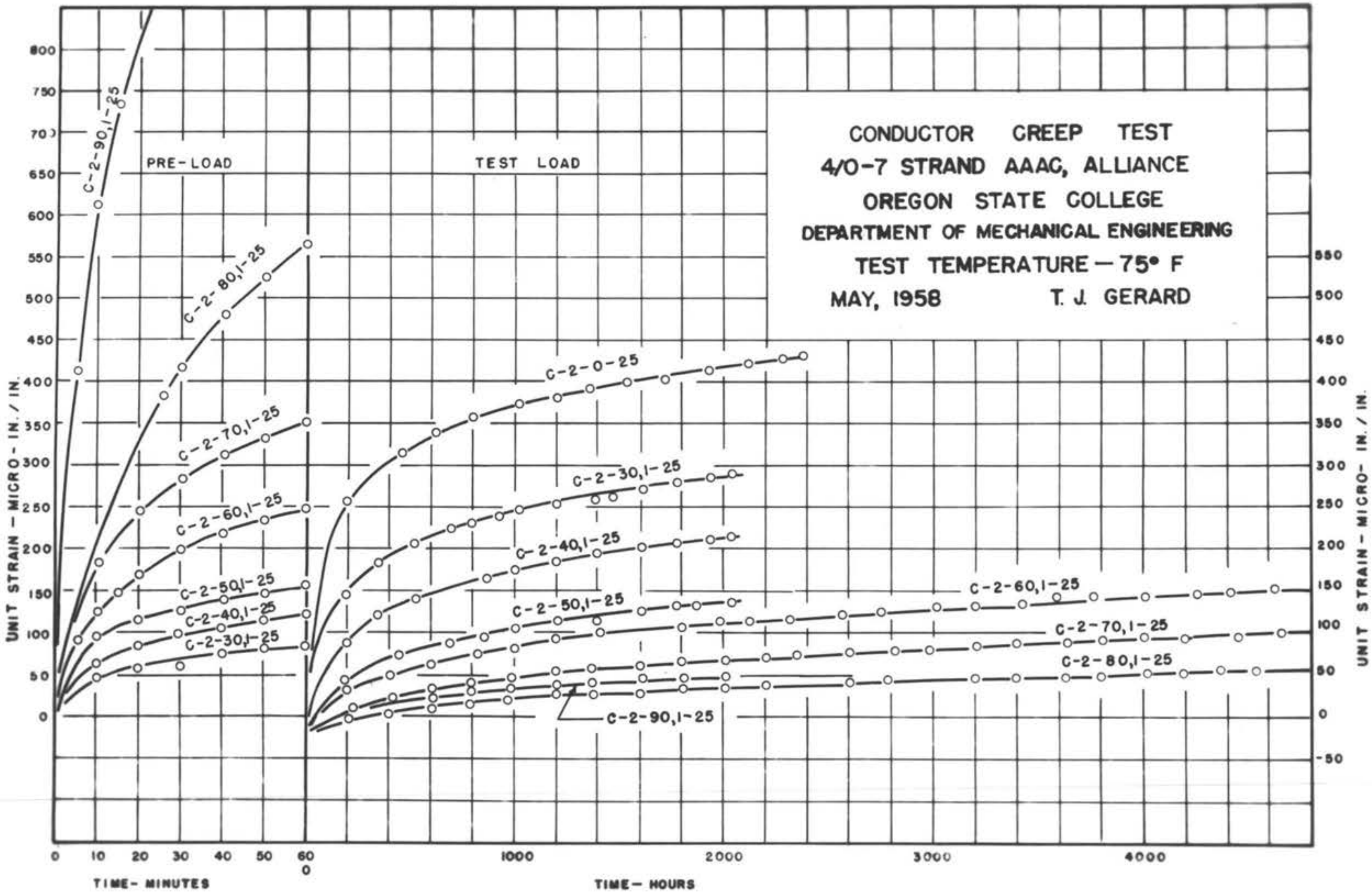

Figure 10. Strain-Time Comparison Curves of Prestressed Specimens

definitely known, one might surmise that the specimen subjected to the 90 per cent preload was overstressed. Analysis of a stress-strain curve for this alloy revealed that the latter specimen was prestressed above its proportional limit. Since recovery is fairly rapid at such stresses, one might surmise that the effect of the increased recovery rates present under the 90 per cent prestress was greater than the work hardening effects induced by increasing the stress from 80 per cent to 90 per cent of the ultimate strength of the conductor. Thus the unconformity of this specimen with the remainder was probably not due to an unrepresentative samples or to faulty equipment, but was to be expected.

Theoretically, the various curves mentioned above should have been spaced at regular intervals on the graphs. Such, however, was not the case, especially between the specimens prestressed to 50 per cent and 60 per cent of their ultimate tensile strengths. This was not regarded as significant, however, because the many uncontrollable factors present were fully sufficient to produce such a deviation. In the first place, conductor is generally manufactured with a weight (and therefore strength) tolerance of two per cent. Then stranding, handling, and even heat treating could have varied slightly within the same manufacturing lot. Finally, some experimental error was

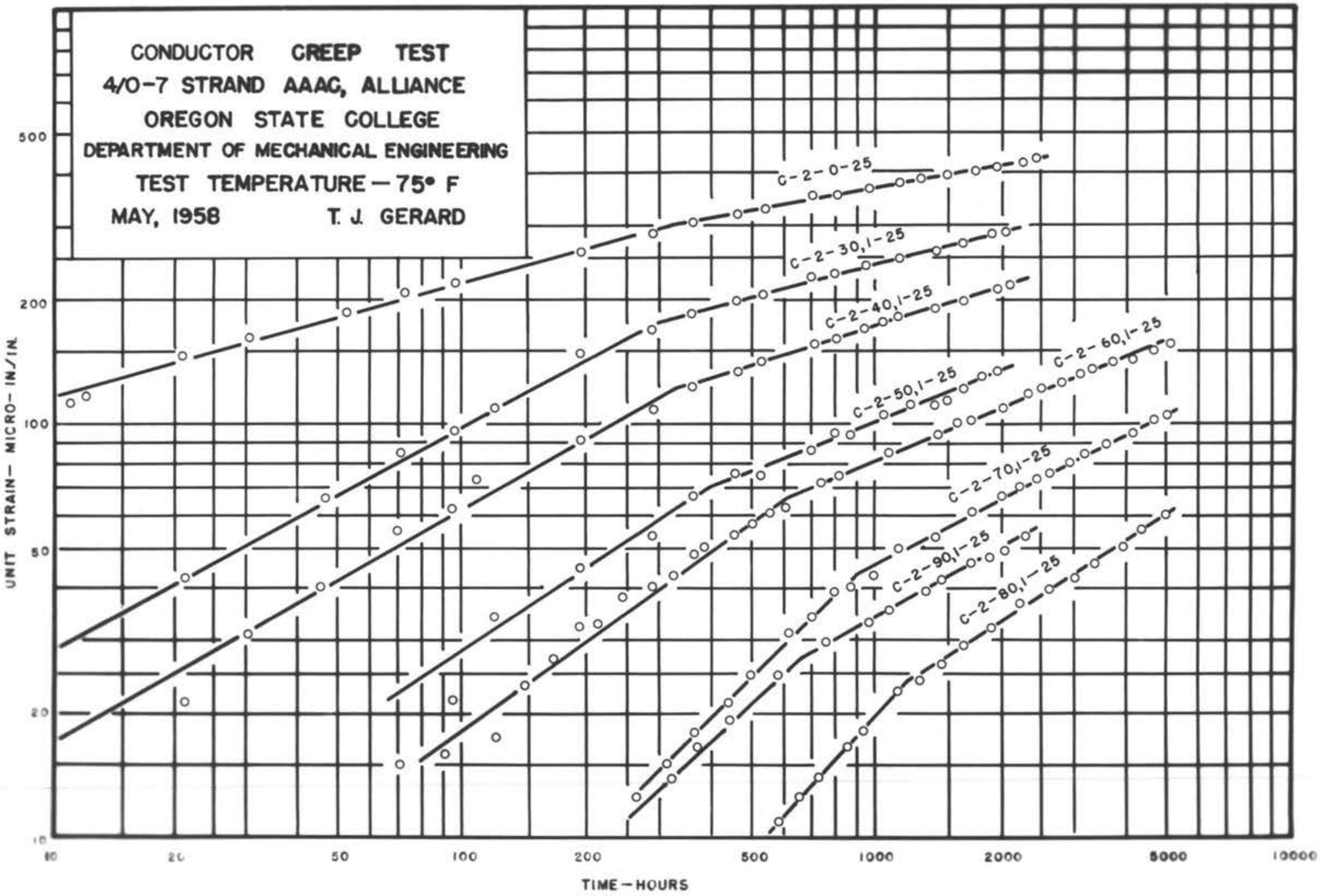

Figure 11. Log-Log Correlation Curves of Prestressed Specimens

doubtless present. These factors in combination could easily have caused the apparent discrepancy in curve spacing.

Figure 10 shows that the highly prestressed specimens showed some negative strain immediately after application of the test load. The large scale necessary for this graph does not present the true picture of what happened. The test load was applied by merely removing some of the preload from the specimens. Initial readings were taken immediately. All the anelastic strain present in the specimen as a result of the high initial load did not have time to come out of the specimen during the brief period between the reducing of loads and the initial readings. Consequently, as the rate of return of the anelastic strain was greater than the initial creep rate, an apparent negative creep rate was produced. Although the amount of this apparent negative creep varied considerably, generally it increased with increased preloads, as would be expected.

Difficulty was expected in determining an equation to fit the conductor strain-time curves. A certain amount of mechanical strand settling was expected, and since cables exhibit lower strength, no elastic limit and a reduced modulus of elasticity, further difficulty was expected on these bases. However, although slight variations did exist, it was always possible to approximate the log-log curves of the conductors by means of straight lines, although more point spread was present than on single strand plots. The equation $\mathcal{E} = At^n$ was then evaluated for each specimen tested; the respective constants and exponents are listed in Table 3.

A study of the log-log plot shown in Figure 11 revealed some interesting phenomena. The fact that two straight lines defined the creep curve on the log-log plots would not only seem to indicate that at least two distinct mechanisms were operating, but that the intersection of these lines apparently would define the changeover from the primary stage of creep to the secondary stage. However, as the plastic flow present was accompanied by the effects of strand settling and coiling, the latter was not necessarily the case. For purposes of identification, though, the times bounded by the first and second curves will be termed the initial and secondary stages, respectively.

In general, a higher preload resulted in less total initial creep strain, as was expected. However, the time at which the secondary stage began was found to be also dependent upon the preload, with the higher prestressed specimens displaying greatly lengthened periods of initial creep. The initial creep rate as well as the secondary creep rate was also substantially increased in specimens subjected to higher preloads.

Perhaps the most interesting observation that can be made on this log-log plot lay within the regularity with which the specimens varied in their secondary creep rates. A glance revealed that the secondary creep curves were convergent; extrapolation revealed that every curve intersected a constant strain line at approximately the same point, located at a time of approximately 480,000 hours. Although an extrapolation this far into the future must be regarded with uncertainty, this fact was of notable importance. It would indicate that prestressing to reduce future strain is of no value if restringing is not to be done oftener than 55 years. Indeed, it would indicate that a specimen prestressed for one hour would sag more over a 60 year period than one strung up without prestressing.

Although it was amazing that all the different strain time curves should intersect at a point, the fact that they converged had been determined in other tests. The work of Dorn, Goldberg, and Tietz (13) best bore this out.

Since efforts to correlate prestress with the strain under a test load were unsuccessful, the next step was to derive a method of predicting total test load strain for any preload from the experimental data. Accordingly, the constant A and exponent n for each specimen were plotted against prestress. It was found that the n of secondary creep was a linear function of the prestress, suggesting that prestressing left a definite effect upon the activation energy.

However, when the constant A had been plotted it became evident that no simple equation, if indeed, any equation at all, could produce the resulting curve. The points were just too scattered to evaluate at all, indicating that a considerable variation in coiling and stranding effects was present. Consequently, it was not possible to predict accurately total future strain at any time from any given prestress data, even in conjunction with known test results. The most accurate way of approximating future strain for any preloaded specimen subjected to a test load of 25 per cent of its ultimate strength would be to sketch in a curve at a likely location on the log-log plot shown in Figure 11.

As any metallurgical explanation of the above phenomena would be mere speculation, none will be given here. These tests, together with those of Dorn, Goldberg, and Tietz (13), indicate that the mechanisms which cause the phenomena listed above are extremely uncertain. Perhaps further research will better reveal the nature of these mechanisms.

10,000 Hour Test.

Whereas all specimens prestressed for one hour exhibited lengthened initial creep periods, the 10,000 hour test specimen, prestressed for 3000 hours, displayed a comparatively brief period of initial creep. One explanation for this fact was that the length of the prestressing period exceeded the length of the initial creep stage. Theoretically, then, the only primary stage evident should have been due to recovery during the brief period of removal of the load and the readjustment period immediately following. Other preloaded specimens indicated an increase in creep rate following prestressing. This specimen apparently did not follow that pattern. However, it should be considered that all creep rates measured during these tests were decreasing. The reapplication of load after 3000 hours of preloading was similar to starting a new series of creep measurements after the creep rate has been allowed to decrease for 3000 hours. This accounted for the low creep rates of this test.

The 10,000 hour test demonstrated several facts; first, the logarithmic creep law was verified for times up to 10,000 hours, indicating a probably indefinite continuation of gradually declining creep rates. Second, the decline in creep rate after long periods of time was almost negligible, as is shown on the rectangular coordinate plot of Figure 12;

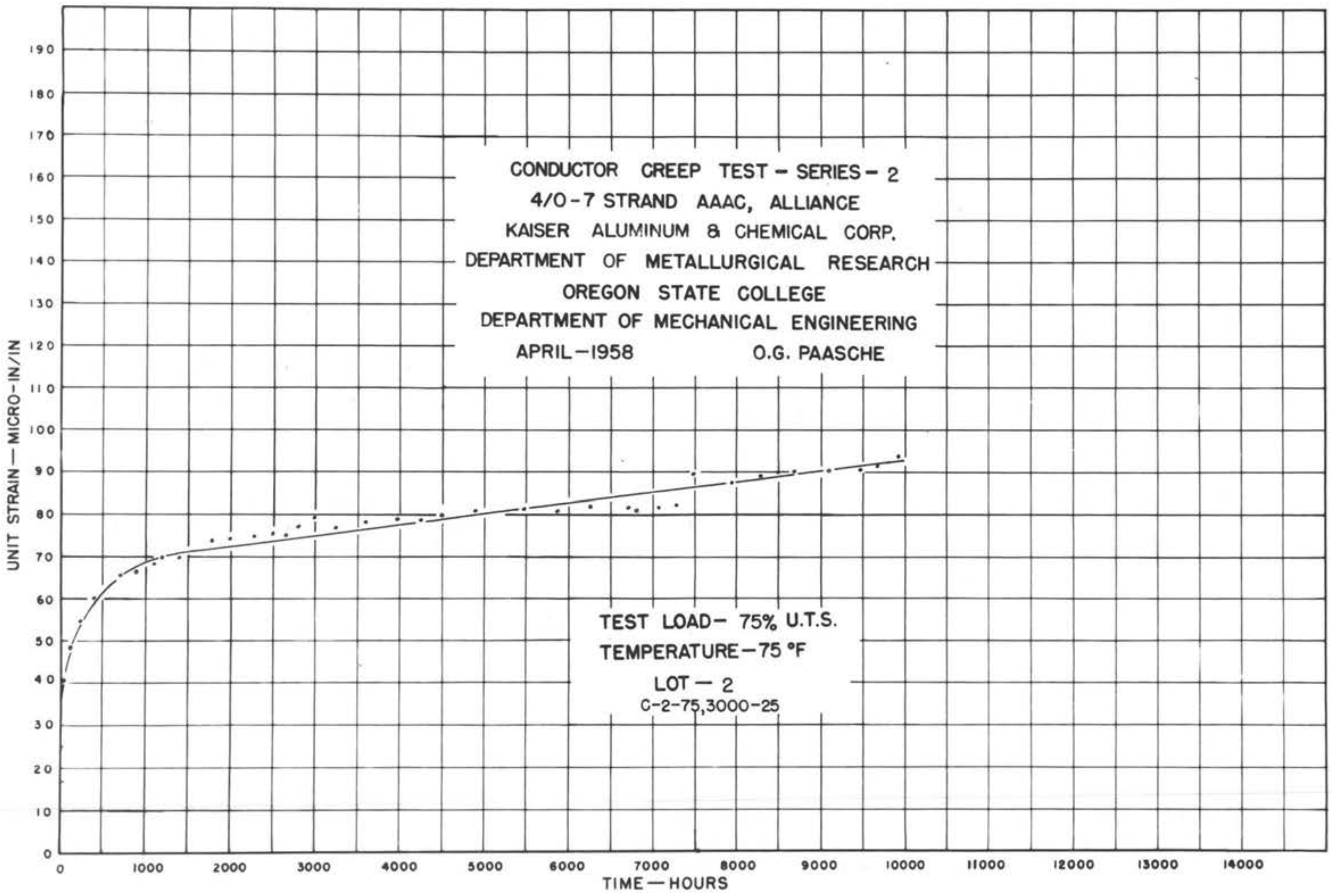

Figure 12. Strain-Time Curve for the 10,000 Hour Test Specimen

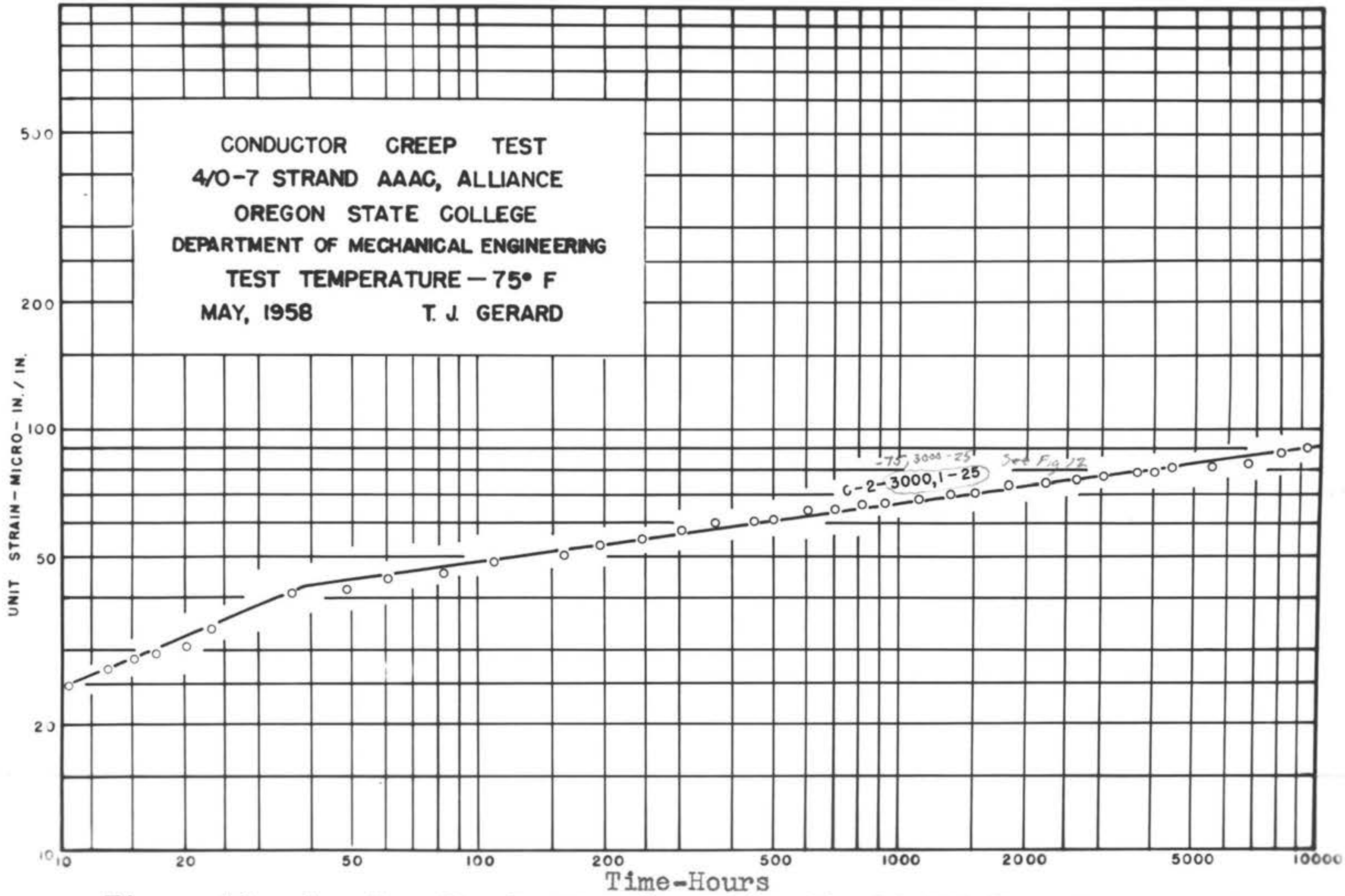

Figure 13. Log-Log Strain-Time Curve for the 10,000 Hour Test Specimen

the curve is very nearly a straight line. Third, extensive prestressing not only reduced the amount of primary creep and its duration, but also the amount of secondary creep to the extent that after 10,000 hours of testing, this specimen showed less total strain than any other specimen tested, including the single strands which were tested for periods of only 2,000 hours. Finally, the creep rate of this specimen at a given time, best indicated by the slope of the curve on Figure 13, was the lowest of all specimens tested.

Conductor and Wire Correlations.

As was expected, the conductor specimen exhibited a higher initial creep strain than a single strand of the same manufacturing lot. This is evident in Figure 14. This was partially due to the added stresses in the cable induced by stranding and to unequal strand loading caused by uneven gripping of the clamps, but primarily to the mechanical strand settling present initially. As can be seen on the log-log plot of these specimens, shown in Figure 15, the initial effects of stranding disappeared at approximately 300 hours; from then to the duration of the test, both conductor and single strand exhibited quite similar rates of plastic flow.

Since the only significant difference between the secondary creep rates between the single strand specimen

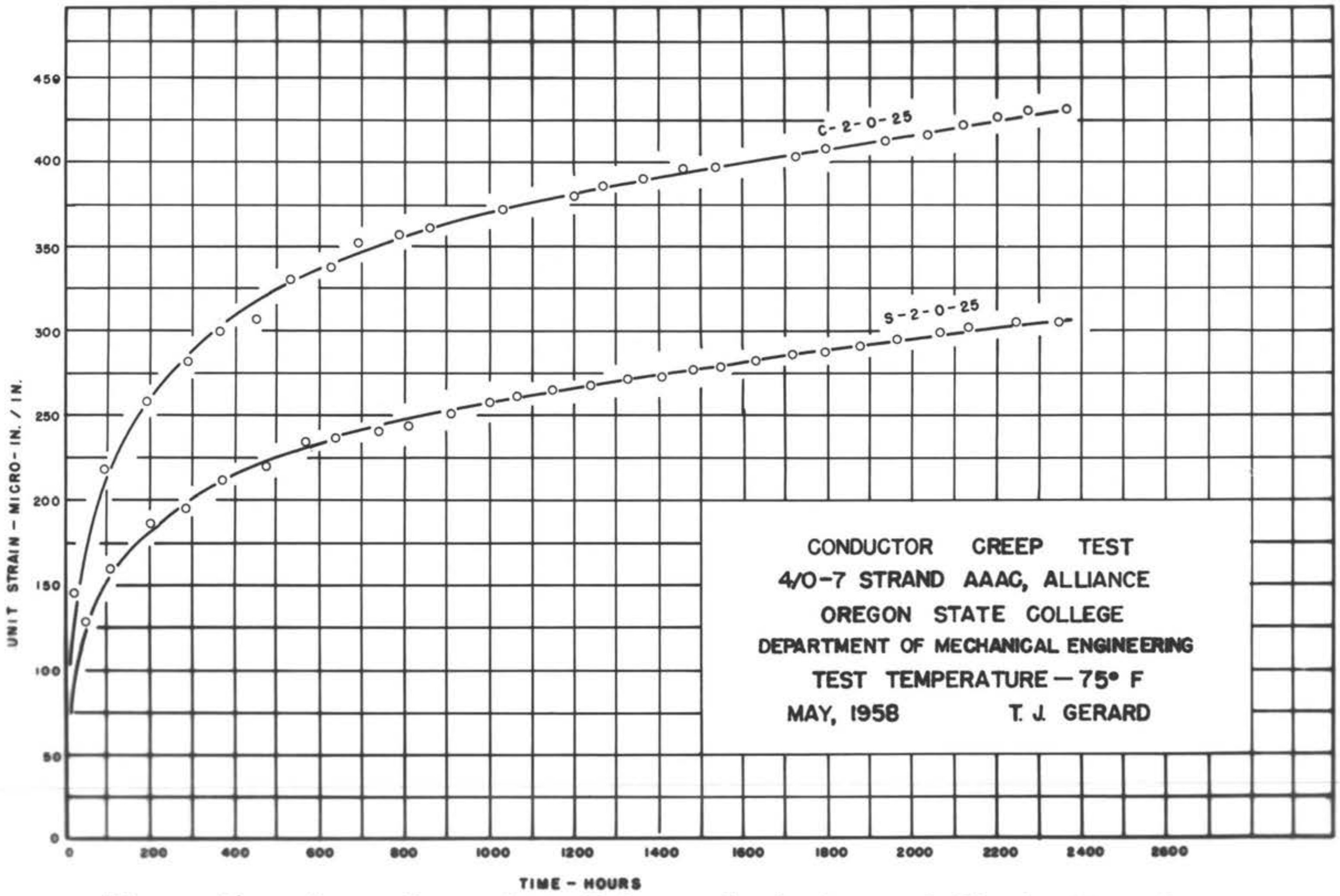

Figure 14, Creep Comparison Between Conductor and Single Strand

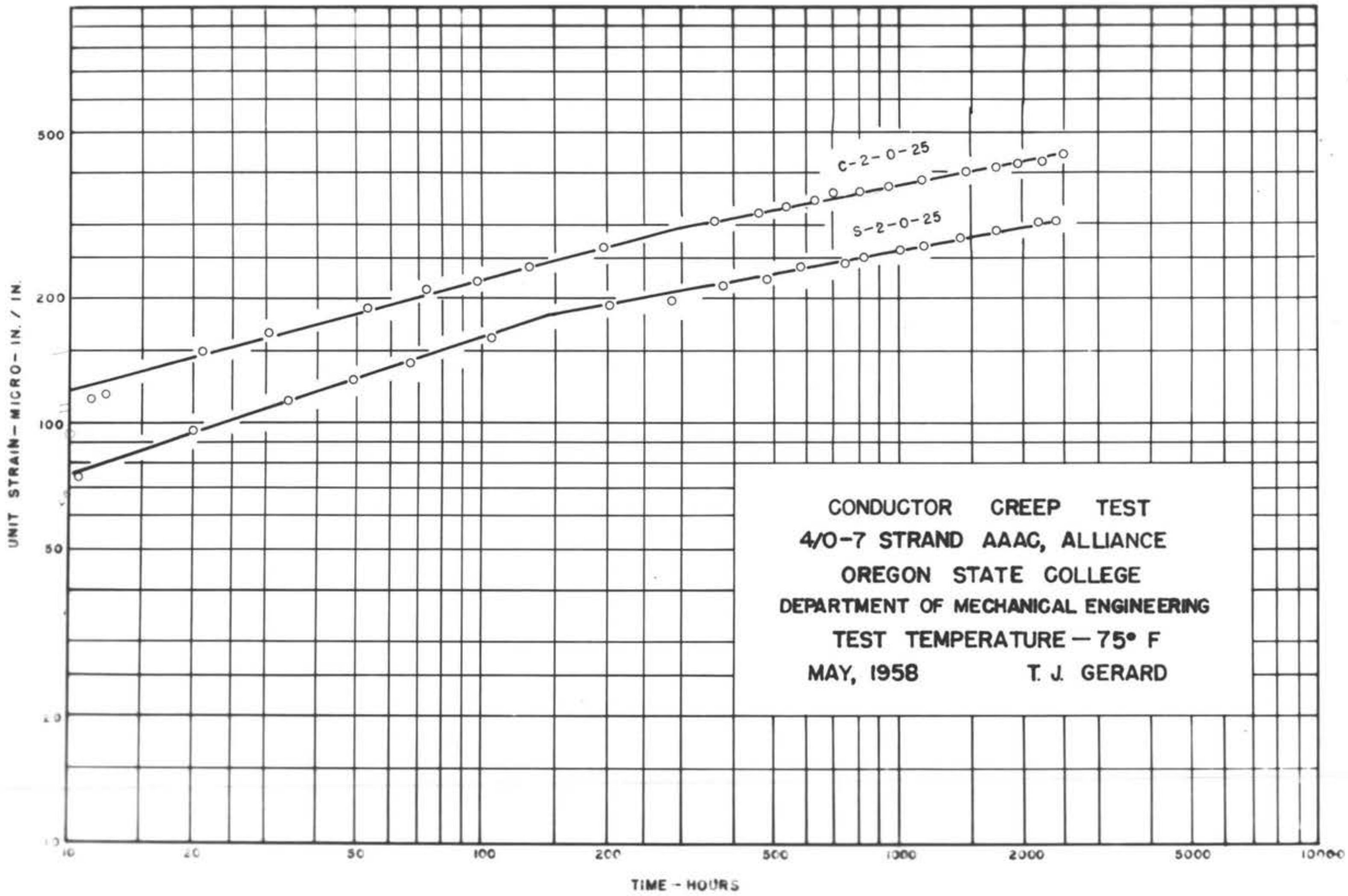

Figure 15. Log-Log Correlation of Creep of Conductor and Single Strand

and the identically loaded conductor was the intercept A, it was easy to equate the conductor creep in terms of the single strand. For the specimen tested, then, the conductor creep strain could be approximated at any time by

$$\varepsilon = 1.6At^{m},$$

where A equals a constant - the strain intercept of the single strand;
t equals the time in question,
n equals the slope of the log-log plot of the single strand;
1.6 equals the ratio between intercepts of of the conductor and the single strand.

As stated, this equation was known to hold true only for unprestressed specimens subjected to a test load of 25 per cent of their ultimate tensile strength. However, as stranding effects in a given specimen probably are not too variable with load, one might expect that this relationship might hold true for any test load. Further tests would be necessary to substantiate this, however.

Manufacturing Lot Correlations.

A surprising difference was found in creep rates of specimens taken from the different manufacturing lots as can be seen on Figures 16 through 19. The two single strand tests indicated a marked difference in the values of the intercepts "A", with only a slight difference in the creep rates at any time, evidenced by the relatively slight variation in their exponents "n". Table 3 lists these

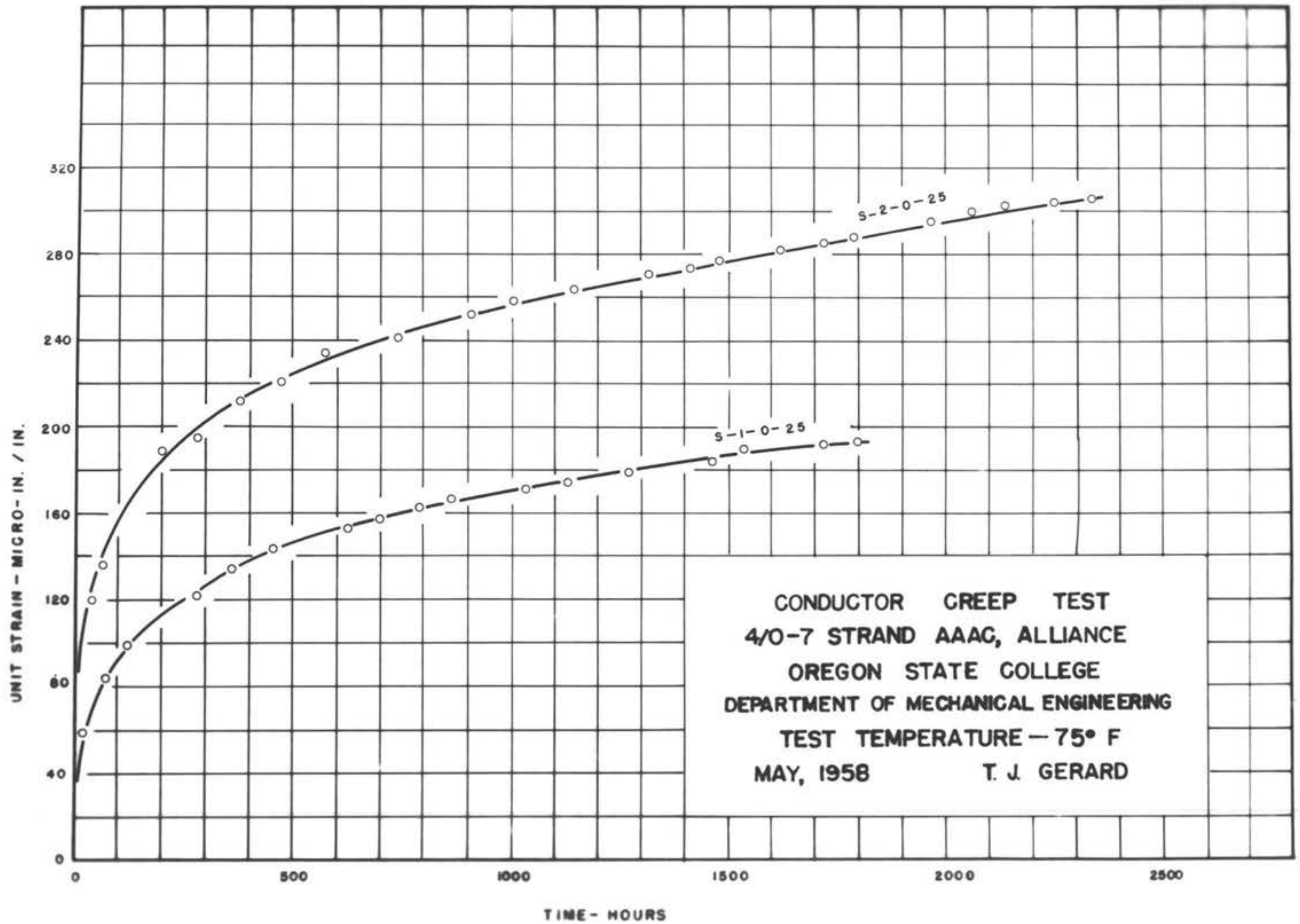

Figure 16. Manufacturing Lot Variations in Creep of Single Strands

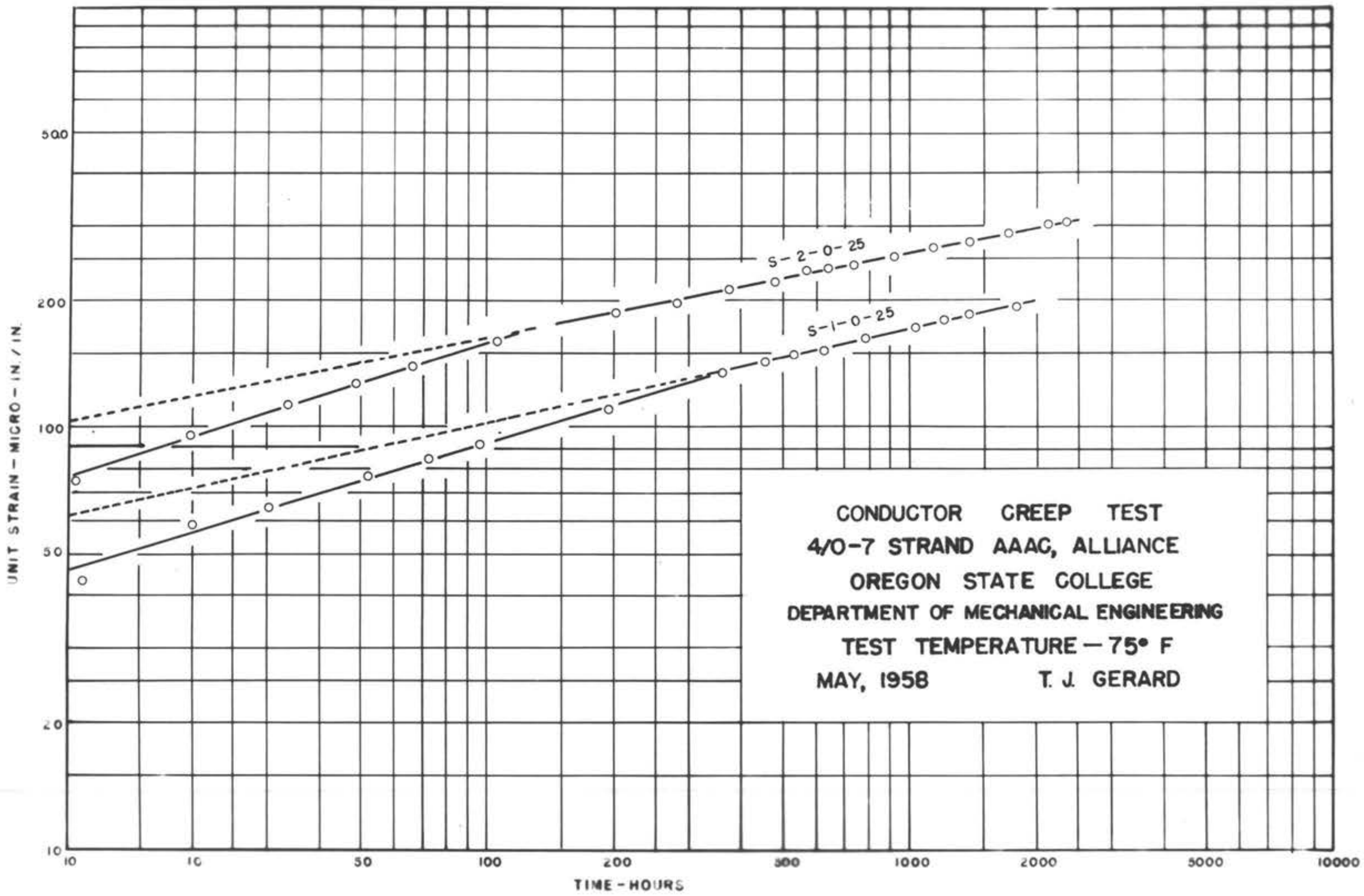

Figure 17. Log-Log Creep Correlation of Manufacturing Lot Variations in Single Strands

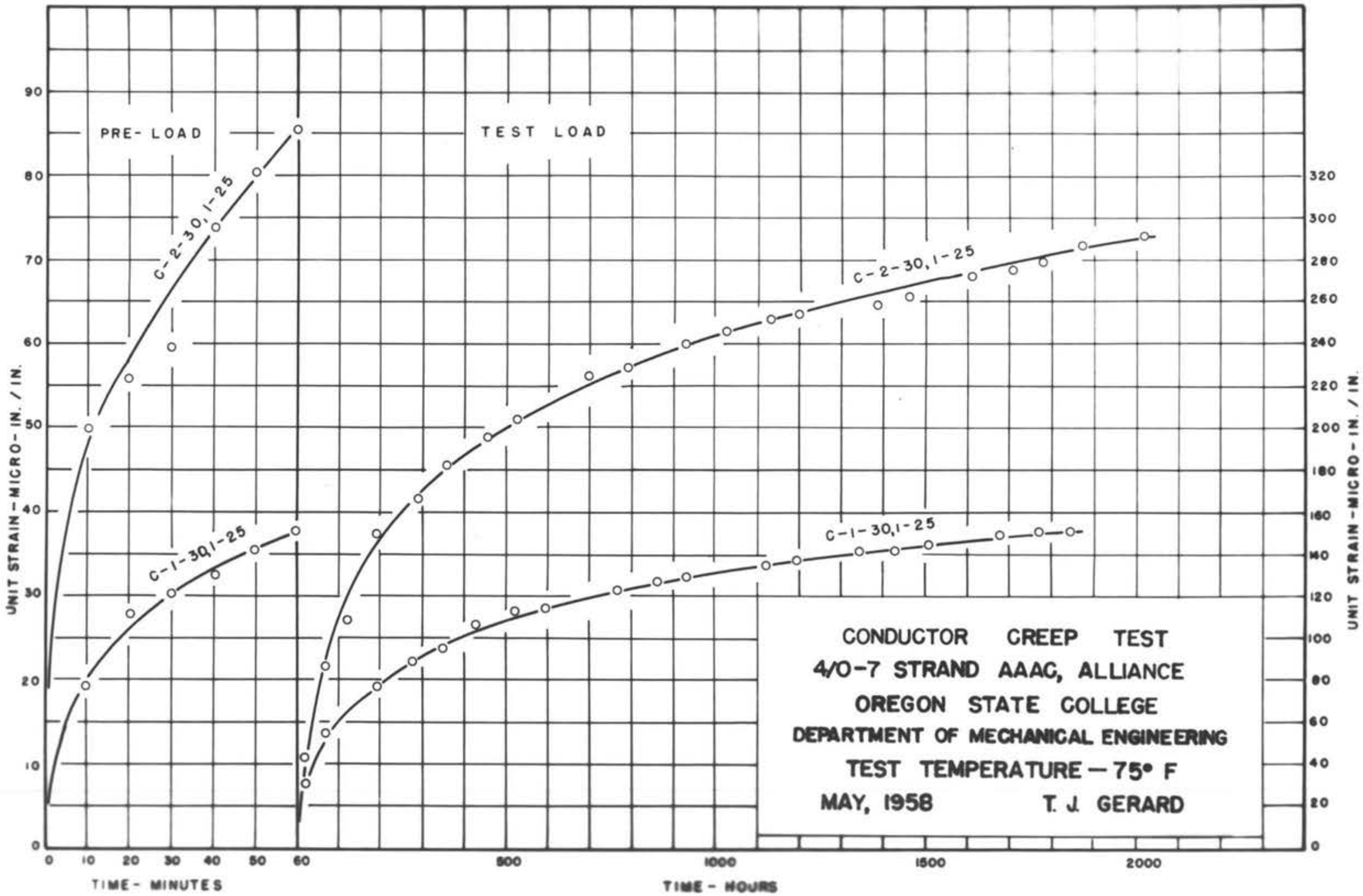

Figure 18. Manufacturing Lot Variations in Creep of Conductors

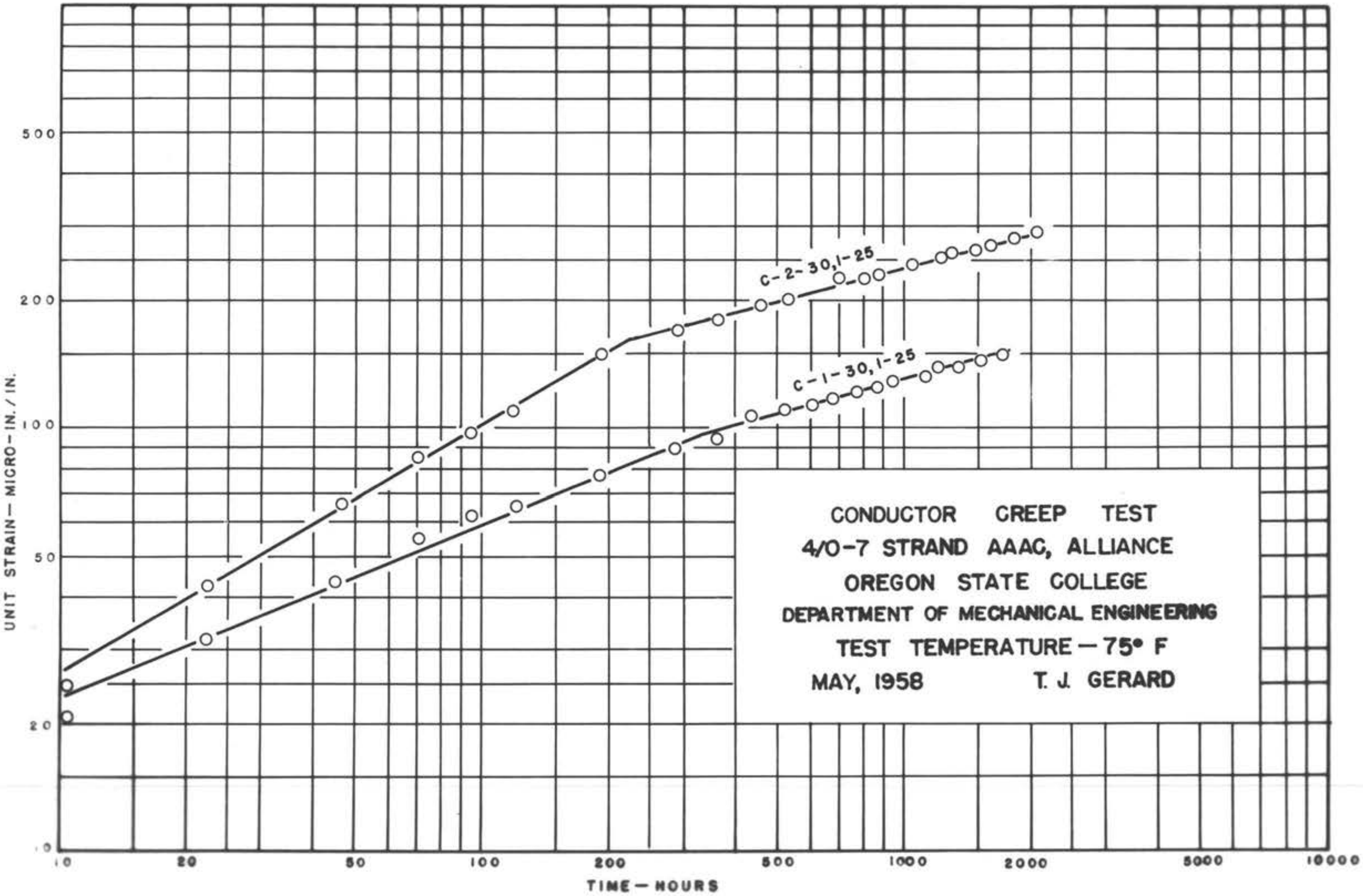

Figure 19. Log-Log Creep Correlation of Manufacturing Lot Variations in Conductors

values. This fact would indicate that Lot 1 was cold worked more than Lot 2, since the former demonstrated all the effects of prestressing: a longer period of initial creep, a much lower intercept, but somewhat more rapid initial and secondary creep rates.

Somewhat similar results were found in the results of the two tests of different lots subjected to 30 per cent preloads. Again the Lot 1 specimen exhibited a lower intercept and a somewhat more rapid rate of secondary creep. However, in the latter case, the initial creep rate was greater in the Lot 2 specimen. This was not considered to be of great importance, however, for the initial stage of creep is but a temporary and often widely variable mechanism. The probable cause of this difference between manufacturing lots probably lay within the cold working each received; however, variations in aging could have produced similar effects.

Residual Stresses.

Figure 20 is a photograph of the Series 3 specimens after they had been removed from the loading columns. They are in the following order from left to right - 80, 90, 70, and 60 per cent prestressed specimens and last, the 10,000 hour test specimen. It was evident that the length of loading and amount of preload had a pronounced effect upon

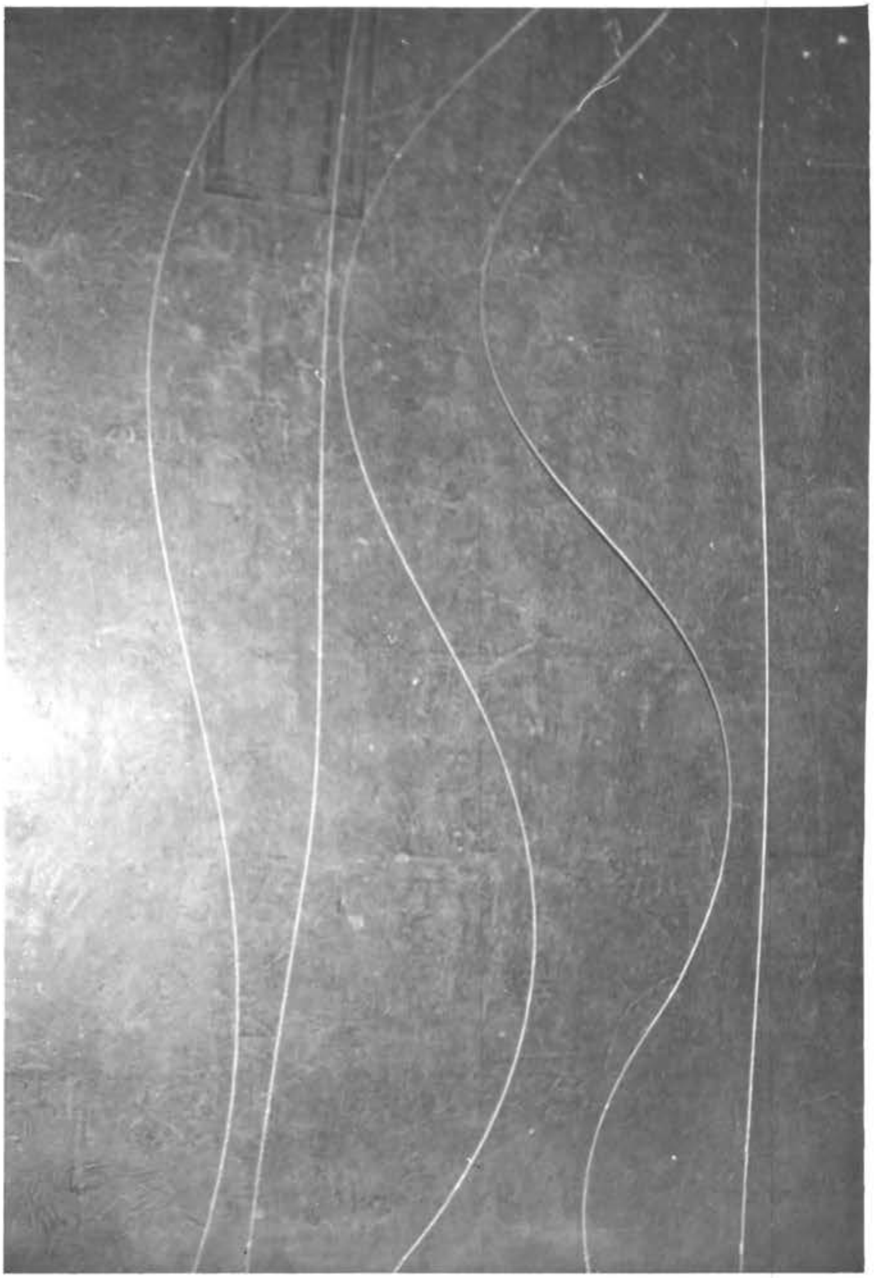

Figure 20. Effect of Creep Strain upon Residual Stresses in Conductors

the residual stresses. Although the specimens were extremely unmanageable as a result of the coiling operation, the ones subjected to the greatest loads were almost perfectly straight, indicating that all residual stresses had become equalized. While not of direct value in formulating explanations for creep, this photograph illustrates the effect of creep upon unbalanced residual stresses.

Effect of Clamps.

Although some Series 4 specimens indicated a considerable increase in overall unit extension as compared with the unit extension measured over the gage length, this was not attributed to creep induced by stress concentrations near the clamps. Since one conductor (C-2-30,1-25) showed no significant difference between unit overall extension and unit extension over the gage length, it was probable that such differences found in other specimens were due to slipping of the cable as it settled within the clamps. Further evidence that this was the case was found when the Series 3 specimens were replaced with those in Series 4. Many of the clamps were quite loose although each bolt had been tightened to 60 foot pounds upon installation of Series 3 specimens. The amount of the theoretical differences between overall and gage length unit strains may be found in the Series 4 data in the appendix.

CONCLUSIONS

Theory

The mechanism of creep apparent in these tests seemed to be due primarily to normal slip throughout the primary stage and to quasi-viscous creep throughout the secondary stage. Coiling and stranding effects made it impossible to determine exactly when secondary creep set in, even though the log-log curves apparently indicated a marked difference between the two stages, with two straight lines necessary to describe both stages accurately.

Attempts to correlate various parameters and equations previously proposed were impractical, since these parameters were subject to great error below 0.45 of the absolute melting temperature of the specimen. However, the basic rate equation used in the development of these parameters was found to be of value in evaluating the test results.

Equipment

The test equipment, with minor exceptions, operated satisfactorily. No modifications or alterations of the basic equipment design were necessary, although one test was interrupted by failure of the apparatus. The extensometers seemed to operate well, although an occasional reading was out of line. The temperature control left little to be desired; it maintained the test temperature well within ASTM standards.

Procedure

The testing procedure was considered to be entirely satisfactory. Perhaps more readings than necessary were taken on early tests; this was necessary, however, to determine the proper intervals at which the readings should be taken. Both temperature and load calibration were well within ASTM standards. The specimens were chosen to indicate differences between variations in preloading and manufacturing lot, and to evaluate the effect of stranding upon the creep rate.

Test Results

The total strain ε at any time t for any of the specimens tested may be evaluated by means of the following empirical equation:

$$\varepsilon = At^n,$$

where A is a constant for a given specimen and n is the slope of the log-log plot. The constants A and n were evaluated for all the specimens tested. Although n was found to be a linear function of stress, no correlation could be found between specimens subjected to different prestresses, as no equation could be found which would describe A. The results of other tests indicated that no satisfactory relationship between prestressing and creep rates had been discovered.

It was possible to equate creep strain of single strand specimens in terms of that of conductor specimens by multiplying the constant A for the single strand by 1.6 and substituting into the above equation the appropriate values for n and t from the single strand test.

A surprising difference between manufacturing lots was discovered. Lot 1 appeared to have subjected to more cold working than Lot 2; it had a lower intercept A and a slightly higher exponent n, much the same effect as was produced by prestressing.

Prestressing conductors for one hour, although it greatly decreased total creep strain over the times of these tests, resulted in an increased creep rate. Extrapolation from a log-log plot revealed that the differently prestressed specimens all intersected a constant strain line at a time of 480,000 hours. This indicated that such prestressing was of no value for specimens subjected to similar loads for upwards of 55 years. The tests revealed that the existence of "creep limits" was out of the question for the test alloy, as a considerable amount of creep was still present under a stress of 25 per cent of the ultimate tensile strength of the specimens.

Although the reliability of the test equipment had been demonstrated by duplicate testing before the Series 3 and 4 tests were run, the many variables present in these tests could cause serious deviations from the values for the constants given in Table 3 . Further tests are needed to establish the reliability of the present data and to substantiate the results found here.

RECOMMENDATIONS

Although the creep testing apparatus performed satisfactorily, it is believed that some modifications would be helpful in producing more consistent results. The electrical circuit supplying power for lighting, air conditioning, temperature recording and timing should be put on a special circuit. Fuses blown in other sections of the building should not have an effect upon this experiment.

The vertical columns which support the loading levers are bolted to the floor and thus are subject to building vibrations. While it is felt that these vibrations produce no more than a very slight effect upon the loading, any unnecessary variables are to be avoided.

The loading system would be better if it were included within the enclosure. At present, it is not only subject to changes in ambient temperature, but it is also more susceptible to disturbance from curious passersby.

With regard to the test material, a complete knowledge of the processing history of the conductor would be of great value in evaluating data. Specimens shipped in uncoiled form or at least in coils of equal diameter would help to minimize variations in results. And, while on the subject of the test material, the writer would like to pose a question: "Why should the manufacturer choose a pitch as fast as seven inches per strand revolution and thus suffer over a five per cent reduction in strength coupled with probably higher amounts of strand settling and thus initial creep strain when a slower pitch would theoretically prove more favorable in all these respects?"

Finally, although it is believed that these tests are of value, they must be substantiated by further testing before their results may be considered reliable. Every specimen tested in Series 3 and 4 was tested uniquely; there were no duplicate tests. Several substantiating tests of each sample must be made before the results presented here may be used with confidence.

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APPENDIX

TABLE 1. CREEP TEST DATA

Subject Creep Test: Aluminum Alloy Conductor Cable

By: T. Gerard Date: June 27, 1957

Column Number: 2 Lot Number: 2

Series Number: 3 Lever Multiplication: 20.6

Gage Length: 200 in. Overall Length: 24 ft approx

Preload: 90% of the Ultimate tensile strength (8190 lb)
1 hr

Test Load: 25% of the ultiment tensile strength (2275 lb)

OBSERVATIONS

ELAPSED TIME hours	STRAIN GAGE READING 0.001 in.	UNIT ELONGATION micro-inches/in.	SCALE READING inches	OVERALL ELONGATION Thousands in.
		(Preload)		
0 min	0.0	0.0	0.0	0.0
5 min	82.4	412.0	2.25	109.1
10 min	123.7	618.5	3.60	174.7
15 min	147.7	738.5	4.28	208.0
20 min	173.7	868.5	4.50	218.1
30 min	206.4	1032.0	5.50	267.0
40 min	234.0	1170.0	6.38	310.0
50 min	255.8	1279.0	7.05	342.0
60 min	275.4	1377.0	7.61	370.0
(Reduced load to 2275 lb. Specimen now under test load.)				
0.0	0.0	0.0	0.0	0.0
1.1	-0.2	-1.0	0.0	0.0
2.3	-1.3	-6.5	0.03	1.46
3.6	-1.3	-6.5		
5.2	-1.4	-7.0		

TABLE 1. (cont.)

OBSERVATIONS				
ELAPSED TIME hours	STRAIN GAGE READING 0.001 in.	UNIT ELONGATION micro-inches/in.	SCALE READING inches	OVERALL ELONGATION thousands in.
11.0	-1.4	-7.0		
20.0	-1.3	-6.5	-0.03	-1.46
28.3	-0.5	-2.5		
53.3	-0.3	-1.5		
82.3	-0.1	-0.5	0.01	0.486
101.3	0.5	2.5		
121.7	0.7	3.5		
147.5	1.0	5.0		
176.8	1.5	7.5		
191.9	1.6	8.0	0.09	4.37
244.3	2.1	10.5		
266.2	2.1	10.5	0.09	4.37
288.1	2.6	13.0		
314.1	2.8	14.0		
341.2	2.9	14.5		
364.7	3.3	16.5	0.13	6.32
408.5	3.8	19.0		
442.1	3.8	19.0		
482.0	4.1	20.5	0.15	7.30
504.1	4.2	21.0		
527.1	4.5	22.5		
575.7	4.9	24.5		
605.6	5.1	25.5		
622.7	5.1	25.5	0.19	9.23
653.4	5.2	26.0		
670.7	5.5	27.5		
697.6	5.5	27.5	0.19	9.23
725.0	5.5	27.5		
766.6	5.9	29.5		

TABLE 1. (cont.)

OBSERVATIONS				
ELAPSED TIME hours	STRAIN GAGE READING 0.001 in.	UNIT ELONGATION micro-inches/in.	SCALE READING inches	OVERALL ELONGATION thousands in.
793.3	6.0	30.0	0.21	10.40
842.3	6.2	31.0		
860.8	6.2	31.0	0.22	10.69
932.7	6.5	32.5		
983.3	6.6	33.0	0.19	9.23
1061.5	7.1	35.5		
1132.4	7.6	38.0	0.26	12.60
1196.0	7.7	39.5		
1269.4	7.9	39.5	0.27	13.1
1324.9	7.9	39.5		
1372.4	8.0	40.0	0.30	14.56
1438.2	8.4	42.0		
1516.8	8.6	43.0	0.31	15.05
1607.0	8.8	44.0		
1676.3	9.2	46.0	0.32	15.55
1727.3	9.7	48.5		
1804.7	9.6	48.0	0.36	17.5
1873.0	9.5	47.5		
1948.9	9.3	49.0	0.35	17.0
2021.3	9.9	49.5		
2114.2	10.2	51.0	0.36	17.5
2204.9	10.5	52.5		
2288.3	10.8	54.0		
2301.3	10.7	53.5		
2353.0	10.7	53.5		
2441.1	10.9	54.5		
2506.3	10.8	54.0		
2603.0	10.8	54.0		
2684.0	10.7	53.5		

TABLE 1. (cont.)

	OBSERVATIONS			
ELAPSED TIME	STRAIN GAGE READING 0.001 in.	UNIT ELONGATION micro-inches/in.	SCALE READING inches	OVERALL ELONGATION thousands in.
2780.0	10.6	53.0		
2833.5	10.6	53.0		
2877.4	10.8	54.0		
2901.4			0.40	19.4
2933.9	11.0	55.0	0.40	19.4
3045.9	11.0	55.0	0.41	19.9
3141.9	11.1	55.5	0.33	17.0
3213.9	11.1	55.5	0.39	18.9
3309.9	11.7	58.5	0.42	20.4
3405.9	11.8	59.0	0.42	20.4
3477.9	11.8	59.0	0.43	20.9
3549.9	11.8	59.0		
3645.9	12.3	61.5	0.45	21.9
3717.9	12.9	64.5		
3813.9	12.7	63.5	0.46	22.4
3885.9	13.0	65.0		
3957.9	12.4	64.5	0.47	22.8
4029.9	13.0	65.0		

The test was interrupted by a lever malfunction after about 2200 hours. Data taken after that time is of questionable value. Test discontinued December 12,1957.

TABLE 2. CREEP TEST DATA

Subject Creep Test: Aluminum Alloy Conductor Cable

By: T. Gerard Date: June 27, 1957

Column Number: 1 Lot Number: 2

Series Number: 3 Lever Multiplication: 20.8 to 1

Gage Length: 200 in. Overall Length: 24 ft approx

Preload: 80% of the ultimate tensile strength (7280 lb)

1 hr

Test Load: 25% of the ultimate tensile strength (2275 lb)

OBSERVATIONS

ELAPSED TIME hours	STRAIN GAGE READING 0.001.in.	UNIT ELONGATION micro-inches/in.	SCALE READING inches	OVERALL ELONGATION thousands in.
		(Preload)		
0 min	0.0	0.0	0.00	0.00
5 min	24.4	122.0	0.90	43.2
10 min	25.3	126.5	0.91	43.7
20 min	26.3	131.5	0.92	44.2
Discovered lever resting on block - pulled block out.				
25 min	73.3	381.5	2.70	130.0
30 min	83.7	418.5	2.90	139.5
35 min	90.9	454.5	3.13	152.0
40 min	96.7	483.5	3.32	159.2
45 min	101.5	507.5	3.47	166.8
50 min	105.8	529.0	3.60	173.0
55 min	109.3	546.5	3.70	177.8
60 min	112.5	567.5	3.80	182.7

TABLE 2. (cont.)

OBSERVATIONS				
ELAPSED TIME hours	STRAIN GAGE READING 0.001 in.	UNIT ELONGATION micro-inches/in.	SCALE READING inches	OVERALL ELONGATION thousands in.
Reduced load to 2275 lb. Specimen now under test load.				
0.0	0.0	0.0	0.0	0.0
0.6	-0.9	-4.5		
1.5	-2.6	-13.0		
2.6	-4.4	-22.0	-0.09	-4.33
3.8	-4.6	-23.0	-0.11	-5.28
5.1	-4.6	-23.0		
6.7	-4.6	-23.0		
12.5	-4.6	-23.0		
21.5	-4.6	-23.0	-0.20	-9.62
29.8	-4.4	-22.0		
54.8	-4.3	-21.5		
83.8	-3.7	-18.5	-0.16	-7.7
102.8	-3.3	-16.4		
123.2	-2.4	-12.0		
149.0	-1.8	-9.0		
178.3	-1.1	-5.5		
193.4	-0.9	-4.5	-0.10	-4.81
213.5	-0.2	-1.0		
245.8	-0.2	-1.0		
267.7	-0.1	-0.5	-0.08	-3.84
289.6	-0.1	-0.5		
315.6	0.0	0.0		
342.7	0.0	0.0		
366.2	0.1	0.5	-0.08	-3.84
410.0	0.7	3.5		
443.6	0.7	3.5		
483.5	1.1	5.5	-0.08	-3.84
505.6	1.4	7.0		

TABLE 2. (cont.)

OBSERVATIONS				
ELAPSED TIME hours	STRAIN GAGE READING 0.001 in.	UNIT ELONGATION micro-inches/in.	SCALE READING inches	OVERALL ELONGATION thousands in.
528.1	1.4	7.0		
577.2	2.2	11.0		
607.1	2.4	12.0		
624.2	2.4	12.0	-0.01	-0.481
654.9	2.5	12.5		
672.2	2.5	12.5		
699.1	2.5	12.5	-0.01	-0.481
726.5	2.8	14.0		
768.1	2.8	14.0		
795.0	2.9	14.5	0.06	2.88
843.8	3.3	16.5		
862.3	3.3	16.5	0.06	2.88
934.2	3.6	18.0		
984.8	3.7	18.5	-0.01	-0.481
1063.0	4.1	20.5		
1133.9	4.5	22.5	0.06	2.88
1197.5	4.8	24.0		
1270.0	4.8	24.0	0.09	4.32
1326.4	4.8	24.0		
1373.9	4.8	24.0	0.15	7.21
1439.7	5.2	26.0		
1518.3	5.7	28.5	0.13	6.25
1608.5	5.8	29.0		
1677.8	6.4	32.0	0.13	6.25
1728.8	6.7	33.5		
1806.2	6.7	33.5	0.18	8.65
1874.5	6.4	32.0		
1950.4	6.6	33.0	0.17	8.16
2022.8	6.8	34.0		
2115.7	6.8	34.0		
2206.4	7.4	37.0		
2289.8	7.6	38.0		
2302.8	7.6	38.0		

TABLE 2. (cont.)

OBSERVATIONS				
ELAPSED TIME hours	STRAIN GAGE READING 0.001 in.	UNIT ELONGATION micro-inches/in	SCALE READING inches	OVERALL ELONGATION thousands in.
2354.5	7.6	38.0		
2445.6	7.6	38.0		
2507.8	7.6	38.0		
2604.5	8.1	40.5		
2685.5	8.1	40.5		
2781.5	8.1	40.5		
2834.0	8.2	41.0		
2877.9	8.3	41.5		
2901.9			0.23	11.06
2973.9	8.5	42.5	0.23	11.06
3095.3	8.5	42.5	0.24	11.53
3141.9	8.6	43	0.24	11.53
3213.9	8.7	43.5	0.25	12.01
3309.9	9.1	45.5	0.25	12.01
3405.9	9.1	45.5	0.25	12.01
3472.9	9.2	46.0	0.25	12.01
3549.9	9.4	47.0		
3645.9	9.5	47.5	0.29	13.9
3717.9	9.6	48.0		
3873.9	9.7	48.5	0.30	14.4
3885.9	10.1	50.5		
3957.9	10.2	51.0	0.30	14.4
4029.9	10.3	51.5		
4125.9	10.4	52.0	0.29	13.9
4197.9	10.6	52.0		
4372.1	11.0	55.0	0.32	15.4
4469.1	10.9	59.0		
4591.1	11.0	55.0		
4636.9	11.1	55.5		
4750.3	11.1	55.5	0.32	15.9
4849.1	12.0	60.0		
4919.1	12.3	61.3	0.32	15.4

Test Completed - January 18, 1958.

TABLE 3. CREEP TEST DATA

Subject Creep Test: Aluminum Alloy Conductor Cable

By: T. Gerard Date: June 27, 1957

Column Number: 3 Lot Number: 2

Series Number: 3 Lever Multiplication: 22 to 1

Gage Length: 200 in. Overall Length: 24 ft approx

Preload: 70% of the ultimate tensile strength (6370 lb)

Test Load: 25% of Ultimate tensile strength (2275 lb)

OBSERVATIONS

ELAPSED TIME hours	STRAIN GAGE READING 0.001 in.	UNIT ELONGATION micro-inches/in.	SCALE READING inches	OVERALL ELONGATION thousand in.
		(Preload)		
0 min	0.0	0.0	0.0	0.0
5 min	29.0	146.5	0.99	45.0
12 min	37.9	189.5	1.29	58.7
20 min	49.0	245.0	1.70	77.3
30 min	56.8	284.0	1.98	90.1
40 min	62.1	310.5	2.17	98.8
50 min	66.8	334.0	2.34	106.2
60 min	70.3	351.5	2.47	112.2
Reduced load to 2275 lb. Specimen now under test load.				
0.0	0.0	0.0	0.0	0.0
1.0	-4.8	-24.0		
2.6	-5.3	-26.5		
8.4	-5.3	-26.5		
17.4	-4.6	-23.0	-0.20	-9.10

TABLE 3 (cont.)

OBSERVATIONS				
ELAPSED TIME hours	STRAIN GAGE READING	UNIT ELONGATION micro-inches/in.	SCALE READING inches	OVERALL ELONGATION thousand in.
25.7	-3.5	-17.5		
50.7	-2.9	-14.5		
79.7	-1.8	- 9.0	-0.10	-4.55
98.7	-0.9	- 4.5		
119.1	-0.5	- 2.5		
144.9	0.4	2.0		
175.2	1.0	5.0		
189.3	1.1	5.5	0.0	0.0
209.4	1.7	8.5		
241.7	1.9	9.5		
263.6	2.5	12.5	0.03	1.36
285.5	2.6	13.0		
311.5	3.0	15.0		
338.6	3.2	16.0		
362.1	3.7	18.5	0.03	3.64
405.9	4.1	20.5		
439.5	4.5	22.5		
479.4	4.9	24.5	0.11	5.00
501.5	5.1	25.5		
524.5	5.3	26.5		
573.1	5.9	29.5		
603.0	6.2	31.0		
620.1	6.3	31.5	0.15	6.83
650.8	6.5	32.5		
668.1	6.7	33.5		
695.0	6.8	34.0	0.17	7.74
722.4	6.8	34.0		
764.0	7.2	36.0		
790.9	7.6	38.0	0.20	9.10
839.7	7.9	39.5		
858.2	8.0	40.0	0.21	9.55
930.1	8.4	42.0		

TABLE 3. (cont.)

OBSERVATIONS				
ELAPSED TIME hours	STRAIN GAGE READING 0.001 in.	UNIT ELONGATION micro-inches/in.	SCALE READING inches	OVERALL ELONGATION thousand in.
980.7	8.6	43.0	0.20	9.10
1058.9	9.5	47.5		
1129.8	10.5	50.0	0.28	12.72
1193.5	10.0	50.0		
1266.9	10.1	50.5	0.28	12.72
1322.4	10.6	53.0		
1369.9	10.7	53.5	0.32	14.52
1435.6	11.0	55.0		
1514.2	11.4	57.0	0.34	15.42
1604.4	11.8	59.0		
1673.7	12.3	61.5	0.34	15.42
1724.7	12.8	64.0		
1802.1	12.8	64.0	0.41	18.6
1870.4	12.8	64.0		
1946.3	13.3	66.5	0.40	18.2
2018.7	13.3	66.5		
2111.6	14.4	72.0	0.42	19.1
2202.3	14.0	70.0		
2285.7	14.4	72.0		
2298.7	14.2	71.0		
2350.4	14.5	72.5		
2441.5	14.7	73.5		
2503.7	14.9	74.5		
2600.4	15.1	75.5		
2681.4	15.3	76.5		
2777.4	15.9	79.5		
2830.7	15.7	78.5		
2898.6			0.47	21.9
2970.6	16.6	83.0	0.47	21.9
3042.6	16.8	84.0	0.47	21.4
3138.6	16.8	84.0	0.41	18.6

TABLE 3. (cont.)

OBSERVATIONS				
ELAPSED TIME hours	STRAIN GAGE READING 0.001 in.	UNIT ELONGATION micro-inches/in.	SCALE READING inches	OVERALL ELONGATION thousand in.
3210.6	16.9	84.5	0.52	23.6
3306.6	17.0	85.0	0.51	23.2
3402.6	17.4	87.0	0.52	23.6
3479.6	17.3	86.5	0.52	23.6
3546.6	17.8	89.0		
3642.6	17.9	89.5	0.55	25.0
3714.6	18.2	91.0		
3810.6	18.2	91.0	0.56	25.5
3882.6	18.6	93.0		
3954.6	18.5	92.5	0.56	25.5
4026.6	18.8	94.0		
4122.6	18.8	94.0	0.58	26.4
4194.6	19.1	95.5		
4368.8	19.8	99.0	0.59	26.8
4465.8	19.8	99.0		
4537.8	19.8	99.5		
4653.6	20.1	100.5		
4747.0	20.2	101.0	0.61	27.7
4845.8	20.9	104.5		
4915.8	21.1	105.5	0.64	29.1

Test concluded January 18, 1958

TABLE 4. CREEP TEST DATA

Subject Creep Test: Aluminum Alloy Conductor Cable

By: T. Gerard Date: July 2, 1957

Column Number: 4 Lot Number: 2

Series Number: 3 Lever Multiplication: 22 to 1

Gage Length: 200 in. Overall Length: 24 ft approx

Preload: 60% of ultimate tensile strength (5460 lb)

Test Load: 25% of ultimate tensile strength (2275 lb)

OBSERVATIONS

ELAPSED TIME hours	STRAIN GAGE READING 0.001 in.	UNIT ELONGATION micro-inches/in.	SCALE READING inches	OVERALL ELONGATION thousands in.
(Preload)				
0 min	0.0	0.0	0.0	0.0
5 min	19.0	95.0	0.63	28.6
15 min	30.2	151.0	1.01	45.9
20 min	33.9	169.5	1.17	53.2
30 min	39.3	196.5	1.32	60.0
40 min	42.9	214.5	1.45	65.9
50 min	46.8	234.5	1.55	70.5
60 min	49.0	245.0	1.65	75.0
(Reduced load to 2275 lb. Specimen now under test load.)				
0.0	0.0	0.0	0.0	0.0
24.3	-0.1	-5.0		
53.6	1.5	7.5		
68.7	2.1	10.5	0.08	3.63
88.8	3.2	16.0		
121.1	3.5	17.5		
143.0	4.7	23.5	0.18	8.18

TABLE 4. (cont.)

OBSERVATIONS				
ELAPSED TIME hours	STRAIN GAGE 0.001 in.	UNIT ELONGATION micro-inches/in.	SCALE READING inches	OVERALL ELONGATION thousands in.
164.9	5.4	27.0		
190.9	6.5	32.5		
218.0	6.6	33.0		
241.5	7.6	38.0	0.28	12.72
285.3	8.1	40.5		
318.9	8.6	43.0		
358.8	9.6	48.0	0.32	14.53
380.9	10.0	50.0		
403.9	10.1	50.5		
452.5	10.8	54.0		
482.3	11.1	55.5		
499.5	11.4	57.0	0.38	17.25
530.2	12.0	60.0		
547.5	12.1	60.5		
574.4	12.1	60.5	0.42	19.08
599.8	12.4	62.0		
643.4	12.8	64.0		
670.3	13.8	69.0	0.46	20.9
719.1	14.2	71.0		
732.6	14.4	72.0	0.48	21.8
809.5	15.1	75.5		
860.0	15.5	77.5	0.48	21.8
938.3	16.2	81.0		
1009.2	16.5	82.5	0.54	24.5
1073.1	17.0	85.0		
1146.5	17.5	87.5	0.58	26.35
1202.0	17.7	88.5		
1249.2	17.9	89.5	0.62	28.15
1314.0	19.8	99.0		
1396.3	18.8	94.0	0.63	28.6
1483.8	19.6	98.0		
1553.1	19.9	99.5	0.65	29.5
1604.1	20.4	102.0		

TABLE 4. (cont.)

OBSERVATIONS				
ELAPSED TIME hours	STRAIN GAGE READING 0.001 in.	UNIT ELONGATION micro-inches/in.	SCALE READING inches	OVERALL ELONGATION thousands in.
1681.5	20.1	100.5	0.69	30.4
1749.8	20.8	104.0		
1825.7	20.8	104.0	0.69	31.4
1898.1	21.6	108.0		
1991.0	21.4	107.0	0.69	31.4
2081.7	22.2	114.0		
2165.1	22.2	111.0		
2178.1	22.8	114.0		
2229.8	23.6	118.0		
2320.9	23.8	119.0		
2479.8	24.1	120.5		
2860.8	24.1	120.5		
2656.8	24.6	123		
2710.3	24.9	124.5		
2754.2	25.0	125.0		
2778.2			0.79	35.9
2850.2	25.8	129.0	0.79	35.9
2922.2	26.0	130.0	0.79	35.9
3018.2	26.0	120.0	0.79	35.9
3090.2	26.0	130.0	0.82	37.3
3186.2	26.1	135.0	0.84	38.2
3882.2	27.0	135.0	0.86	39.0
3354.2	27.1	135.5	0.88	40.0
3526.2	27.0	135.0		
3522.2	27.6	138.0	0.89	40.5
3594.2	28.6	143.0		
3690.2	28.6	143.0	0.92	41.8
3762.2	28.6	143.0		
3834.2	28.6	143.0	0.93	42.3
3906.2	28.7	143.5		
4012.2	28.8	149.0	0.94	42.7
4084.2	28.9	149.5		

TABLE 4. (cont.)

OBSERVATIONS				
ELAPSED TIME hours	STRAIN GAGE READING 0.001 in.	UNIT ELONGATION micro-inches/in.	SCALE READING inches	OVERALL ELONGATION thousands in.
4258.2	29.1	155.5	0.94	42.7
4352.5	29.3	146.5		
4425.2	29.7	148.5		
4541.2	29.9	149.5		
4635.2	30.0	150.0	0.96	42.6
4733.2	31.5	157.5		
4803.2	31.9	159.5	1.04	47.3

Test concluded January 18, 1958

TABLE 5. CREEP TEST DATA

Subject Creep Test: Aluminum Alloy Conductor Cable

By: T. Gerard Date: January 26, 1958

Column Number: 1 Lot Number: 2

Series Number: 4 Lever Multiplication: 20.8 to 1

Gage Length: 200 in. Overall Length: 23 ft 10 in.

Preload: 50% of ultimate tensile strength (4550 lb) 1 hr

Test Load: 25% of ultimate tensile strength (2275 lb)

OBSERVATIONS

ELAPSED TIME hours	STRAIN GAGE READING 0.001 in.	UNIT ELONGATION micro-inches/in.	OVERALL ELONGATION thousands in.	OVERALL UNIT ELONGATION micro-inches/in.
(Preload)				
0 min	0.0	0.0	0.0	0.0
10 min	19.7	98.5	31.2	109
20 min	22.3	111.5	34.4	120.
30 min	24.2	121.0	39.0	136
40 min	27.4	137.0	45.7	160
50 min	29.0	145.0	50.0	176
60 min	30.7	158.5	53.4	187
(Reduced load to 2275 lb. Specimen now under test load.)				
0	0.0	0.0	0.0	0.0
1	-2.2	-11.0	-4.33	-15
2	-2.7	-13.5	-4.33	-15
3	-2.7	-13.5	-4.33	-15
4	-2.9	-14.5	-4.33	-15
5	-2.9	-14.5		
6	-2.9	-14.5		

TABLE 5. (cont.)

OBSERVATIONS				
ELAPSED TIME hours	STRAIN GAGE READING 0.001 in.	UNIT ELONGATION micro-inches/in.	OVERALL ELONGATION thousands in.	OVERALL UNIT ELONGATION Micro-inches/in.
7	-2.9	-14.5		
8	-2.9	-14.5		
9	-2.8	-14.0		
10	-2.7	-13.5		
11	-2.6	-13.0		
22	-0.9	- 4.5		
46	1.0	5.0	3.85	13
70	3.0	15.0		
94	4.3	21.5	9.14	32
118	6.9	34.5		
190	9.9	44.5		
286	10.7	53.5	18.7	65
357	13.3	66.5		
454	14.0	75.0	24.0	84
526	15.1	75.5		
694	17.3	86.5	28.3	98
790	19.0	95.0		
862	19.0	95.0	33.2	116
933	19.5	97.5		
1030	21.0	105.0	34.6	121
1126	21.9	109.5		
1198	22.3	111.5	35.1	123
1388	22.2	111.0	38.5	136
1460	22.7	113.5		
1606	24.2	121.0	39.4	138
1702	24.9	124.5		
1774	26.1	130.5	42.3	148
1870	26.1	130.5		
1942	27.1	135.5	42.3	148
2038	27.1	135.5		

Test still in progress. (April 21, 1958)

TABLE 6. CREEP TEST DATA

Subject Creep Test: Aluminum Alloy Conductor Cable

By: T. Gerard Date: January 26, 1958

Column Number: 3 Lot Number: 2

Series Number: 4 Lever Multiplication: 22.0

Gage Length: 200 in. Overall Length: 23 ft 10 in.

Preload: 40% of ultimate tensile strength 1 hr (3640 lb)

Test Load: 25% of ultimate tensile strength (2275 lb)

OBSERVATIONS

ELAPSED TIME hours	STRAIN GAGE READING 0.001 in.	UNIT ELONGATION micro-inches/in.	OVERALL ELONGATION thousands in.	OVERALL UNIT ELONGATION micro-inches/in.
0 min	0.0	0.0	0.0	0.0
10 min	12.2	61.0	20.4	71
20 min	16.7	83.5	28.2	99
30 min	20.1	100.5	32.7	115
40 min	21.0	105.0	35.8	126
50 min	22.3	111.0	40.9	144
60 min	24.5	122.5	44.1	155
(Reduced load to 2275 lb. Specimen now under test load.)				
0.0	0.0	0.0	0.0	0.0
0.33	-1.4	-7.0	-1.8	6
1.33	-1.1	-5.5	1.4	5
2.33	-0.8	-4.0	0.5	2
3.33	-0.6	-3.0	0.0	0
4.33	0.2	1.0		
5.33	0.4	2.0		
6.33	0.4	2.0		

TABLE 6. (cont.)

OBSERVATIONS				
ELAPSED TIME hours	STRAIN GAGE READING 0.001 in.	UNIT ELONGATION micro-inches/in.	OVERALL ELONGATION thousands in.	OVERALL UNIT ELONGATION micro-inches/in.
6.33	0.4	2.0		
7.33	0.9	4.5		
8.33	1.3	6.5		
9.33	1.5	7.5		
10.33	1.9	9.5		
21.3	4.5	22.5		
45.3	8.1	40.5	15.6	55
69.3	11.0	55.0		
93.3	12.5	62.5	22.7	80
117.3	14.8	74.0		
189.3	18.3	91.5		
285.3	21.6	108.0	38.3	131
356.3	24.7	123.5		
453.3	26.6	133.0	45.0	158
525.3	28.1	140.4		
693.3	31.2	156.0	50.9	179
789.3	32.2	161.0		
861	33.0	165.0	56.3	198
932	34.1	170.5		
1029	3502	176.0	58.6	206
1125	36.1	180.5		
1197	36.7	183.5	60.5	213
1387	38.1	190.5	63.6	224
1459	38.9	194.5		
1605	39.8	199.0	64.5	227
1701	40.4	202.0		
1773	41.1	205.5	68.2	240
1869	41.9	209.9		
1941	42.5	212.5	69.5	245
2037	43.1	215.5		

Test still in progress (April 21, 1958)

TABLE 7. CREEP TEST DATA

Subject Creep Test: Alluminum Alloy Conductor Cable

By: T. Gerard Date: January 26, 1958

Column Number: 4 Lot Number: 2

Series Number: 4 Lever Multiplication: 22.0

Gage Length: 200 in. Overall Length: 23 ft 9 3/4 in.

Preload: 30% of ultimate tensile strength (2730 lb) 1 hr

Test Load: 25% of ultimate tensile strength (2275 lb)

OBSERVATIONS

ELAPSED TIME Hours	STRAIN GAGE READING 0.001 in.	UNIT ELONGATION micro-inches/in.	OVERALL ELONGATION thousands in.	OVERALL UNIT ELONGATION micro-inches/in.
0 min	0.0	0.0	0.0	0.0
10 min	10.0	50.0	13.6	48
20 min	11.1	55.5	18.2	64
30 min	11.9	59.5	22.3	78
40 min	14.8	74.0	25.4	89
50 min	16.1	80.5	27.7	97
60 min	17.1	85.5	29.5	103

(Reduced load to 2275 lb. Specimen now under test load.)

0.0	0.0	0.0	0.0	0.0
1.1	0.4	2.0	0.5	2
2.1	1.3	6.5	1.8	6
3.1	1.5	7.5	3.2	11
4.1	2.6	13.0	3.2	
5.1	2.7	13.5		
6.1	3.3	16.5		
7.1	3.6	18.0		
8.1	4.4	22.0		

TABLE 7. (cont.)

OBSERVATIONS

ELAPSED TIME hours	STRAIN GAGE READING 0.001 in.	UNIT ELONGATION micro-inches/in.	OVERALL ELONGATION thousands in.	OVERALL UNIT ELONGATION micro-inches/in.
8.1	4.4	22.0		
9.1	4.5	22.5		
10.1	4.9	24.5		
22.1	8.6	43.0		
46.1	13.3	66.5	21.6	76
70.1	17.2	86.0		
94.1	19.4	97.0	30.5	105
118.1	21.4	109.0		
190.1	29.6	148.0		
286.1	33.5	167.5	47.7	167
357.1	36.7	183.5		
454.1	39.3	196.6	57.8	202
526.1	40.8	204.0		
694.1	44.3	226.5	13.6	225
790.	45.6	228.0		
862	96.5	232.5	70.0	245
933	48.1	240.5		
1030	49.1	295.5	71.8	251
1126	50.3	251.5		
1198	50.7	253.5	73.6	258
1388	51.9	259.5	77.3	270
1460	52.5	262.5		
1606	54.3	271.5	78.6	275
1702	55.0	275.0		
1774	55.9	279.5	82.6	289
1870	57.5	287.5		
1942	58.0	290.0	83.6	293
2038	58.3	241.5		

Test still in progress (April 21, 1958)

TABLE 8. CREEP TEST DATA

Subject Creep Test: Aluminum Alloy Conductor Cable

By: T. Gerard Date: January 12, 1958

Column Number: 2 Lot Number: 2

Series Number: 4 Lever Multiplication: 20.6

Gage Length: 200 in. Overall Length: 23 ft 113/8 in.

Preload: None

Test Load: 25% of ultimate tensile strength

OBSERVATIONS

ELAPSED TIME hours	STRAIN GAGE READING 0.001 in.	UNIT ELONGATION micro-inches/in.	OVERALL ELONGATION thousands in.	OVERALL UNIT ELONGATION micro-inches/in.
0	0.0	0.0	0.0	
1	8.7	43.5	17.9	62
2	11.7	58.5	23.3	81
3	14.0	70.0	27.2	95
4	15.5	77.5	29.6	103
5	16.9	84.5	32.0	111
6	18.5	92.5		
7	19.4	97.0		
8	20.2	101.0		
9	20.9	104.0		
10	22.3	111.5		
11	22.7	113.5		
12	23.5	117.5		
20.5	29.3	146.5		
30	32.6	161.5		
52	37.3	186.5		
72	41.1	205.5		
95	43.6	218.0		
192	51.6	258.0	87.8	305

TABLE 8. (cont.)

OBSERVATIONS				
ELAPSED TIME hours	STRAIN GAGE READING 0.001 in.	UNIT ELONGATION micro-inches/in.	OVERALL ELONGATION thousands in.	OVERALL EL UNIT ELONGATION micro-inches/in.
288	56.5	282.5	95.3	334
360	60.3	301.5		
456	63.6	318.0		
528	66.3	331.5		
624	67.8	339.0	115.5	402
695	70.8	354.0		
792	71.5	357.5	125	435
864	72.1	360.5		
1032	74.6	373.0	127	442
1128	75.6	378.0		
1200	76.0	380.0	132	460
1271	77.3	386.5		
1368	78.1	390.5	133	462
1464	79.3	396.5		
1536	79.7	398.5	136	472
1726	80.6	403.0	138	480
1798	81.4	407.0		
1944	82.6	413.0	141	490
2040	83.3	416.5		
2112	84.4	422.0	145	505
2208	85.5	427.5		
2280	86.2	431.0	146	508
2376	86.4	432.0		

Test still in progress.(April 21, 1958)

TABLE 9. CREEP TEST DATA

Subject Creep Test: Aluminum Alloy Conductor Cable

By: T. Gerard Date: February 2, 1958

Column Number: 5 Lot Number: 1

Series Number: 4 Lever Multiplication: 22.0 6

Gage Length: 200 in. Overall Length: 24 ft 10 1/8 in.

Preload: 30% of ultimate tensile strength (2730 lb) 1 hr

Test Load: 25% of ultimate tensile strength (2275 lb)

OBSERVATIONS

ELAPSED TIME hours	STRAIN GAGE READING 0.001 in.	UNIT ELONGATION micro-inches/in.	OVERALL ELONGATION thousands in.	OVERALL UNIT ELONGATION micro-inches/in.
0 min	0.0	0.0	0.0	0.0
10 min	3.9	19.5	8.7	29
20 min	5.2	26.0	10.9	37
30 min	6.1	30.5	13.6	46
40 min	6.5	32.5	15.0	50
50 min	7.1	35.5	16.3	55
60 min	7.6	38.0	17.7	59

(Reduced load to 2275 lb. Specimen now under test load.)

0.0	0.0	0.0	0.0	0.0
1	0.8	4.0	0.9	3
2	1.4	7.0	1.8	6
3	1.7	8.5	2.3	8
4	2.2	11.0	2.7	9
5	2.6	13.0	3.6	12
6	2.9	14.5		
7	3.3	16.5		
8	3.6	18.0		

TABLE 9. (cont.)

OBSERVATIONS				
ELAPSED TIME hours	STRAIN GAGE READING 0.001 in.	UNIT ELONGATION micro-inches/in.	OVERALL ELONGATION thousands in.	OVERALL UNIT ELONGATION micro-inches/in.
9	3.8	19.0		
10	4.1	20.5		
22	6.2	31.0		
45	8.8	44.0	11.4	38
70	11.1	55.5		
94	12.5	62.5		
118	12.9	64.5	20.0	67
189	15.6	78.0		
286	17.9	89.5	26.4	89
358	18.9	94.5		
426	21.4	107.0	31.4	103
522	22.5	112.5		
594	22.8	114.0	36.4	121
665	23.6	118.0		
762	24.6	123.0	37.7	126
858	25.3	126.5		
930	25.8	129.0	40.0	134
1120	26.8	134.0	42.2	142
1192	27.1	135.5		
1338	28.0	140.0	43.1	145
1434	28.2	141.0		
1506	28.8	144.0	44.5	149
1602	29.3	146.5		
1674	29.8	149.0	46.5	156
1770	30.0	150.0		

Test still in progress. (April 21, 1958)

TABLE 10. CREEP TEST DATA

Subject Creep Test: Aluminum Alloy Conductor Cable

By: D. Koupal & T. Gerard Date: December 1, 1956

Column Number: 5 Lot Number: 2

Series Number: 3 Lever Multiplication: 22.0 to 1

Gage Length: 200 in. Overall Length: 24 ft approx

Preload: 75% of Ultimate tensile strength (6825 lb) 3000 hr

Test Load: 25% of Ultimate tensile strength (2275 lb)

OBSERVATIONS

ELAPSED TIME hours	STRAIN GAGE READING 0.001 in.	UNIT ELONGATION micro-inches/in.	SCALE READING inches	OVERALL ELONGATION thousands in.
		(Preload)		
0.0	0.0	0.0	0.00	0.00
1.0	2.0	10.0	0.05	2.27
2.0	2.6	13.0	0.09	4.09
3.0	3.1	15.5	0.12	5.45
4.0	3.3	16.5	0.13	5.90
5.0	3.8	19.0	0.14	6.36
6.0	4.1	20.5	0.15	6.81
7.0	4.2	21.0	0.16	7.27
8.0	4.5	22.0	0.16	7.27
9.0	4.7	23.5	0.16	7.27
10.0	4.9	24.5	0.16	7.27
11.0	5.0	25.0	0.16	7.27
12.0	5.0	25.0	0.19	8.63
13.0	5.4	27.0	0.19	8.63
14.0	5.6	28.0	0.19	8.63
15.0	5.7	28.5	0.9	8.63
16.0	5.8	29.0	0.20	9.09
17.0	5.8	29.0	0.20	9.09

TABLE 10. (cont.)

OBSERVATIONS				
ELAPSED TIME hours	STRAIN GAGE READING 0.001 in.	UNIT ELONGATION micro-inches/in.	SCALE READING INCHES	OVERALL ELONGATION thousands in.
18.0	5.9	29.5	0.20	9.00
19.0	6.0	30.0	0.20	9.09
20.0	6.1	30.5	0.21	9.54
21.0	6.2	31.0	0.23	10.45
22.0	6.3	31.5	0.23	10.45
23.0	6.7	33.5	0.23	10.45
24.0	6.9	34.5	0.23	10.45
36.0	8.3	41.5	0.27	12.45
48.0	8.3	41.5	0.29	13.13
60.0	8.9	44.5	0.31	14.09
72.0	8.9	44.5	0.31	14.09
84.0	9.1	45.5	0.31	14.09
96.0	9.1	45.5	0.31	14.09
108.0	9.7	48.5	0.32	14.54
120.3	9.7	48.5	0.35	15.90
132.0	9.8	49.0	0.35	15.90
144.0	9.9	49.5	0.35	15.90
156.0	10.0	50.0	0.38	17.27
168.0	10.0	50.0	0.39	17.72
181.3	10.4	52.0	0.39	17.72
192.5	10.6	53.0	0.39	17.72
217.5	10.9	54.5	0.39	18.72
240.0	11.0	55.0	0.43	19.54
264.0	11.3	56.5	0.44	20.00
288.0	11.7	58.5	0.45	20.45
312.3	11.7	58.5	0.47	21.36
336.0	11.9	59.5	0.42	19.09
360.0	12.0	60.0	0.43	19.54
384.0	12.1	60.5	0.44	20.00
408.0	12.1	60.5	0.48	21.81
429.5	12.2	61.0	0.44	20.00

TABLE 10. (cont.)

OBSERVATIONS				
ELAPSED TIME hours	STRAIN GAGE READING 0.001 in.	UNIT ELONGATION micro-inches/in.	SCALE READING inches	OVERALL ELONGATION thousands in.
453.5	12.2	61.0	0.44	20.00
462.0	12.4	61.0	0.48	21.81
477.5	12.4	62.0	0.45	20.45
499.5	12.4	62.0	0.43	19.54
526.5	12.4	67.0	0.45	20.40
550.0	12.8	64.0	0.46	20.95
574.0	12.8	64.0	0.47	21.40
602.5	12.9	64.5		
623.5	12.0	65.0	0.48	21.80
645.5	13.0	65.0	0.48	21.80
677.5	13.0	65.0	0.48	21.80
693.5	13.0	65.0		
717.5	13.2	66.0	0.48	21.80
765.5	13.2	66.0	0.48	21.80
789.5	13.3	66.5	0.48	21.80
814.0	13.4	67.0	0.48	21.80
840.0	13.3	66.5		
887.5	13.3	66.5		
916.0	13.3	66.5	0.49	22.25
936.0	13.5	67.5		
960.5	13.5	67.5		
984.0	13.4	67.0		
1008.0	13.5	67.5	0.49	22.25
1032.0	13.4	67.0		
1055.5	13.4	67.0		
1079.0	13.6	68.0		
1104.0	13.7	68.5		
1128.5	13.7	68.5		
1151.5	13.7	68.5		
1175.5	13.7	68.5	0.52	23.60
1200.0	13.8	69.0		
1223.5	13.9	69.5		

TABLE 10. (cont.)

OBSERVATIONS				
ELAPSED TIME hours	STRAIN GAGE READING 0.001 in.	UNIT ELONGATION micro-inches/in.	SCALE READING inches	OVERALL ELONGATION thousands in.
1248.0	13.9	69.5		
1271.5	14.0	70.0		
1296.0	14.0	70.0		
1319.5	14.0	70.0		
1343.5	14.1	70.5	0.55	25.00
1368.0	14.1	70.5		
1391.5	13.9	69.5		
1417.5	14.0	70.0		
1440.0	13.9	69.5		
1464.0	13.9	69.5		
148800	13.9	69.5		
1513.5	14.3	71.5	0.54	24.55
1536.0	14.0	70.0		
1549.5	14.1	70.5		
1585.5	14.1	70.5		
1608.0	14.3	71.5		
1632.0	14.1	70.5		
1656.0	14.3	71.5		
1680.0	14.2	71.0		
1708.0	14.7	73.5	0.54	24.55
1726.5	14.8	74.0		
1757.0	14.5	72.5		
1776.0	14.7	73.5		
1800.0	14.8	74.0		
1824.0	14.8	74.0		
1847.5	14.8	74.0		
1872.0	14.8	74.0	0.54	24.55
1899.0	14.7	73.5		
1923.5	14.8	74.0		
1946.5	14.8	74.0		
1968.0	14.8	74.0		
1995.5	14.8	74.0		
2016.5	14.9	74.5		

TABLE 10. (cont.)

OBSERVATIONS				
ELAPSED TIME hours	STRAIN GAGE READING 0.001 in.	UNIT ELONGATION micro-inches/in.	SCALE READING inches	OVERALL ELONGATION thousands in.
2040.5	14.9	74.5	0.53	24.08
2068.5	14.9	74.5		
2092.0	14.9	74.5		
2112.0	15.0	75.0		
2140.5	14.9	74.5		
2160.0	14.9	74.5		
2187.0	14.9	74.5		
2208.0	14.8	74.0	0.55	25.00
2232.5	14.9	74.5		
2260.0	14.9	74.5		
2280.0	14.9	74.5		
2304.0	15.0	75.0		
2328.0	15.0	75.0		
2352.0	15.1	75.5		
2376.0	15.0	75.0		
2400.0	15.0	75.0	0.55	25.00
2424.0	15.1	75.0		
2450.0	15.0	75.0		
2471.0	15.0	75.0		
2499.0	15.1	75.5		
2519.0	15.1	75.5		
2566.0	15.1	75.5	0.57	25.90
2589.5	15.1	75.5		
2613.5	15.1	75.5		
2637.5	15.1	75.5		
2661.5	15.1	75.5		
2713.5	15.1	75.5	0.55	25.00
2733.5	15.3	76.5		
2757.5	15.2	76.0		
2783.0	14.9	74.5		
2810.5	15.5	77.5		
2830.5	15.4	77.0		

TABLE 10. (cont.)

OBSERVATIONS				
ELAPSED TIME hours	STRAIN GAGE READING 0.001 in.	UNIT ELONGATION micro-inches/in.	SCALE READING inches	OVERALL ELONGATION thousands in.
2856.0	15.5	77.5		
2880.0	15.6	78.0	0.58	26.40
2902.5	15.7	78.5		
2927.5	15.7	78.5		
2905.8	15.7	78.5		
2978.0	15.8	79.0		
3002.0	15.9	79.5		
3024.0	15.5	77.5		
3048.0	14.9	74.5	0.60	27.22
3074.0	15.4	77.0		
3095.5	15.0	75.0		
3123.0	15.4	77.0		
3146.0	15.4	77.0		
3171.0	15.7	78.5		
3193.0	15.4	77.0		
3263.5	15.4	77.0	0.59	26.80
3291.5	15.4	77.0		
3314.0	15.3	76.5		
3339.0	15.4	77.0		
3410.0	15.4	77.0	0.60	27.22
3431.5	15.7	78.5		
3458.5	15.7	78.5		
3480.0	15.4	77.0		
3512.0	15.7	78.5		
3530.0	15.4	77.0		
3557.5	15.6	78.0	0.61	27.70
3578.5	15.5	77.5		
3626.0	15.7	78.5		
3650.0	15.8	79.0		
3675.0	15.8	79.0		
3706.0	15.8	79.0		
3718.5	15.8	79.0		

TABLE 10. (cont.)

OBSERVATIONS				
ELAPSED TIME hours	STRAIN GAGE READING 0.001 in.	UNIT ELONGATION micro-inches/in.	SCALE READING inches	OVERALL ELONGATION thousands in.
3742.5	15.9	79.5	0.59	26.80
3772.0	15.9	79.5		
3795.0	15.9	79.5		
3819.0	15.8	79.0		
3843.0	15.8	79.0		
3866.0	15.8	79.0		
3888.0	15.9	79.5		
3914.0	15.9	79.5		
3939.5	15.9	79.5		
3983.5	15.8	79.0	0.58	26.4
4008.5	15.9	79.5		
4056.0	15.4	77.0		
4087.5	15.9	79.5		
4103.5	15.9	79.5		
4153.0	15.9	79.5		
4179.0	15.9	79.5		
4253.	15.8	79.0		
4273	15.8	79.0		
4297	15.6	78.0		
4325	15.7	78.5		
4350	15.7	78.5		
4401	16.1	80.5		
4420	16.1	80.5	0.58	26.4
4492	16.0	80.0		
4582	16.0	80.0		
4659	16.1	80.5		
4105	16.2	81.0		
4781	16.1	80.5	0.58	26.4
4827	16.1	80.5	0.58	26.4
4871	16.2	81.0		
4942	16.2	81.0		

TABLE 10. (cont.)

OBSERVATIONS				
ELAPSED TIME hours	STRAIN GAGE READING 0.001 in.	UNIT ELONGATION micro-inches/in.	SCALE READING inches	OVERALL ELONGATION Thousands in.
4991	16.2	81.0		
5086	16.1	80.5		
5170	16.2	81.0	0.57	25.9
5307	16.2	81.0	0.58	26.44
5401	16.2	81.0	0.58	
5475	16.2	81.0	0.54	24.64
5517	16.3	81.5		
5307	15.9	79.5		
5786.5	16.0	80.0		
5835.3	16.4	82.0		
5925.5	16.2	81.0		
6054.5	16.2	81.0		
6189.0	16.4	82.0		
6262.4	16.4	82.0		
6509.8	16.6	83.0		
6669.3	16.4	82.0		
6866.0	16.2	81.0		
7107.2	16.4	82.0		
7294.3	16.4	82.5		
7346.1	16.8	84.0		
7499.3	18.0	90.0		
7596.6	18.0	90.0		
7893.6			0.68	30.9
7965.[illegible]	17.5	87.5	0.66	30.0
8037.4	17.5	87.5	0.66	30.0
8133.9	17.8	89.0	0.61	27.7
8205.9	17.8	89.0	0.70	31.8
8301.8	17.8	89.0	0.69	31.4
8397.7	17.8	89.0	0.67	30.4
8469.8	17.7	88.3	0.67	30.4
8542.0	17.6	88.0		
8637.4	18.1	90.5	0.70	31.8

TABLE 10. (cont.)

OBSERVATIONS				
ELAPSED TIME hours	STRAIN GAGE READING 0.001 in.	UNIT ELONGATION micro-inches/in.	SCALES READING inches	OVERALL ELONGATION thousands in.
8708.0	18.1	90.5		
8804.6	18.1	90.5	0.70	31.8
8876.8	18.1	90.5		
8948.7	18.1	90.5	0.69	31.4
9020.6	18.1	90.5		
9112.6	18.1	90.5	0.69	31.4
9188.6	18.1	90.5		
9363.6	18.2	91.0	0.69	31.4
9457.6	18.1	90.5		
9685.8	18.3	91.5		
9739.3	18.3	91.5	0.68	30.9
9828.6	19.0	95.0		
9960.6	18.8	94.0		
10014	18.8	94.0	0.71	32.3
10126	20.9	104.5		
10222	20.9	104.5		

Test Concluded January 31, 1958

TABLE 11. CREEP TEST DATA

Subject Creep Test: Aluminum Alloy Conductor Wire

By: T. Gerard Date: January 12, 1958

Column Number: 6 Lot Number: 1

Series Number: 2 Lever Multiplication: None

Gage Length: 200 in. Overall Length: 24 ft 2 in.

Preload: None

Test Load:

OBSERVATIONS

ELAPSED TIME hours	STRAIN GAGE READING 0.001 in.	UNIT ELONGATION micro-inches/in.	OVERALL ELONGATION thousands in.	OVERALL UNIT ELONGATION micro-inches/in.
0.0	0.0	0.0		
0.83	1.7	8.5		
1.83	2.9	14.5		
2.83	3.8	19.0		
3.83	4.7	23.5		
4.83	5.5	27.5		
5.83	6.3	31.5		
6.85	7.1	35.5		
7.83	7.4	37.0		
8.83	8.1	40.5		
9.83	8.5	42.5		
10.83	8.7	43.5		
11.83	9.1	45.5		
20.3	11.8	59.0		
30.3	12.8	64.0		
52	15.4	77.0		
72	16.9	84.5		
95	18.2	91.0		

TABLE 11 (cont.)

OBSERVATIONS				
ELAPSED TIME hours	STRAIN GAGE READING 0.001 in.	UNIT ELONGATION micro-inches/in.	OVERALL ELONGATION thousands in.	OVERALL UNIT ELONGATION micro-inches/in.
192	21.9	109.5		
288	24.1	120.5		
360	26.9	134.5		
456	28.8	144.0		
528	29.8	149.0		
624	30.7	153.5		
695	31.7	158.5		
791	32.6	163.0		
863	33.4	167.0		
1031	34.5	172.5		
1127	34.9	174.5		
1199	35.8	179.0		
1270	35.8	179.5		
1367	36.7	183.5		
1463	36.9	184.5		
1555	37.9	189.5		
1725	38.5	192.5		
1797	38.6	193.0		

Test ended due to failure of apparatus March 28,1958

TABLE 12. CREEP TEST DATA

Subject Creep Test: Aluminum Alloy Conductor Wire

By: T. Gerard Date: October 5, 1957

Column Number: 6 Lot Number: 2

Series Number: 3 Lever Multiplication: None

Gage Length: 200 in. Overall Length: 23 ft 3½ in.

Preload: None

Test Load:

OBSERVATIONS

ELAPSED TIME hours	STRAIN GAGE READING 0.001 in.	UNIT ELONGATION micro-inches/in.	SCALES READING inches	OVERALL ELONGATION thousands in.
0.0	0.0	0.0		
1.3	6.5	32.5		
2.1	7.9	32.5		
3.1	9.8	46.0		
10.2	14.9	74.5		
19.5	19.0	95.0		
33.2	22.7	113.5		
42.1	24.0	120.0		
43.0	25.7	128.0		
67.0	27.7	138.5		
104.3	32.2	161.0		
201.0	37.9	189.5		
239.0	38.2	191.0		
282.0	39.1	195.5		
377.5	42.7	213.5		
431.0	42.9	214.5		
474.9	44.1	220.5		
570.9	47.1	235.5		
642.9	47.7	238.5		

TABLE 12. (cont.)

OBSERVATIONS				
ELAPSED TIME hours	STRAIN GAGE READING 0.001 in.	UNIT ELONGATION micro-inches/in.	SCALE READING inches	OVERALL ELONGATION thousands in.
738.9	48.5	242.5		
810.9	49.0	245.0		
906.9	50.5	252.5		
1002.9	51.8	259.0		
1074.9	52.5	262.5		
1146.9	53.1	265.5		
1242.9	53.5	267.5		
1314.9	54.3	271.5		
1410.9	54.7	273.5		
1482.9	55.7	278.5		
1554.9	55.7	278.5		
1626.9	56.7	283.5		
1722.9	57.5	287.5		
1794.9	57.7	288.5		
1969.1	59.3	296.5		
2064.1	60.0	300.0		
2136.1	60.6	303.0		
2251.6	61.2	306.0		
2345.0	60.9	304.5		

Test Concluded January 11, 1958