RESEARCH REPORT

(NASA-CR-155420) DEVELOPMENT OF LIFE-TEST METHODOLOGY FOR LONG-LIFE MECHANICAL COMPONENTS. PHASE 1: DEVELOPMENT OF METHODOLOGY. PHASE 2: DEMONSTRATION OF METHODOLOGY (Battelle Columbus Labs., Ohio.) 00/38 | N78-72674 | Unclas | 57592

Columbus Laboratories

~~(NASA-CR-120267) DEVELOPMENT OF LIFE-TEST METHODOLOGY FOR LONG-LIFE MECHANICAL COMPONENTS. PHASE 1: DEVELOPMENT OF (Battelle Columbus Labs., Ohio.) 41 p LIMIT GOVT.+NASA CONTR. CSCL 14D G3/15 X74-10184 Unclas 16960~~

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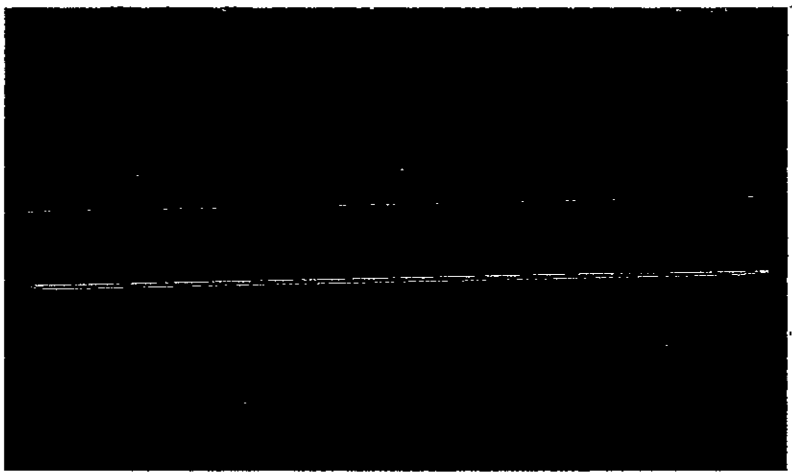

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N78-72674

SUMMARY REPORT

on

DEVELOPMENT OF LIFE-TEST METHODOLOGY FOR LONG-LIFE MECHANICAL COMPONENTS
PHASE I: DEVELOPMENT OF METHODOLOGY
PHASE II: DEMONSTRATION OF METHODOLOGY

to

NATIONAL AERONAUTICS AND SPACE ADMINISTRATION
GEORGE C. MARSHALL SPACE FLIGHT CENTER

April 18, 1974

by

D. B. Hamilton, Project Manager for Phase I
K. F. Dufrane, Project Manager for Phase II

and

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B. G. Brand, W. Berry, and J. W. Kissel

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CONCLUSIONS

A short-term life-test methodology has been developed for mechanical components for space applications with lifetime requirements up to 10 years. The reliability of the methodology is at least as high as if prototypes were life tested by running for the design lifetime under the intended duty cycle. The basic approach requires studying the failure mechanisms of individual components to ensure that each component has the required reliability for its duty cycle with consideration given to all operating conditions.

The methodology developed was successfully demonstrated using an arbitrarily selected miniature needle valve as an model mechanical component. When the failure mechanisms of each component of the valve were studied in detail, operating conditions were selected which represent the extremes of those expected in service. If the valves were operated in a given application under conditions less rigorous than these extremes, high reliability would be expected. With known requirements over the course of a mission (cycles or time), the results obtained from the life-test methodology can be used to predict whether failures will occur.

INTRODUCTION

The purpose of this program was to develop short-term life test methodology for mechanical components for space applications with lifetime requirements up to 10 years. Life testing of mechanical components for space applications has traditionally been performed by operating one or more individual components under the required duty cycle for the required lifetime. This method becomes impractical for long lifetimes such as those in excess of 1 year. Statistical mechanical reliability analysis, in which confidence limits and percentage reliability figures are used, is also impractical since sufficiently large samples of mechanical space components are not normally available. Therefore, a need exists for reliable short-term life-test methodology for long-life components.

The scope of the program was defined to cover specifically valves and associated equipment; however, the methodology developed was to be applicable to mechanical components in general. The program was divided into two phases. Phase I covered the development of life test methodology. Phase II covered the life testing of a specific component to demonstrate the methodology and to modify the approach, if warranted.

Since the field of valves for space applications comprises hundreds of different functions and valve configurations, the program scope was defined by NASA project personnel by selecting three specific components and providing detailed drawings and specifications for each. The components selected were a 2-inch recirculation valve, a 4-inch vent valve, and a calibration gas-supply-module assembly. Some general information was also received for two other units. Since these valves were considered representative of typical designs, subsequent evaluation and development of specific life tests were based on these components. No actual valves were available for demonstration of the methodology in Phase II, therefore, a miniature needle valve was chosen for demonstration purposes.

The program plan for Phase I was first to perform a literature search to determine the state of the art of life testing of mechanical components and to establish the range of environments to which components will probably be subjected in space missions in the near future. The next step was to analyze the detailed drawings and specifications for the three representative components to determine the range of materials of interest, the relevant material aging processes, and the relevant component failure modes. The final step was to develop or specify appropriate life testing procedures for the various failure modes and aging processes. Since it is not possible in a limited program to cover all possible failure mechanisms and aging processes, the program ultimately focussed on nonmetallic wear and creep as the most critical and least understood failure mechanisms.

The plan for Phase II was to demonstrate the approach developed in Phase I by using an actual component. The miniature needle valves chosen have a Teflon (PTFE) stem packing and Kel-F seats; both of these polymer materials are used in typical NASA valves. Since no specific application existed for the valves, the operating conditions were chosen arbitrarily.

SUMMARY

Phase I: Development of Methodology

The program was concentrated on valves and associated equipment. Three components were selected by NASA project personnel as representative.

- A 10.15 cm (4-inch) electric-motor-operated vent valve for air, gaseous nitrogen, and gaseous oxygen.
- A 5.08 cm (2-inch) pneumatically actuated, normally open recirculative valve for LOX and LH_2.
- A calibration gas-supply-module assembly to be used in the Metabolic Activity System of the Orbital Workshop. This system included solenoid valves, a pressure regulator, and a gas bottle.

During the development of the life-test methodology, these components were considered representative of aerospace valves with respect to design, materials, service media, operating condition, duty cycle, failure modes, and failure mechanisms. However, the life-test methodology developed is considered valid for all long-term mechanical space components.

Effort in Phase I consisted of a literature study to determine the range of environments to which components may be exposed and to determine available life test techniques, analysis of detail drawings and specifications of the three representative components to determine possible failure mechanisms, and laboratory experiments of wear and creep to evaluate short-term tests for wear and creep of nonmetallic materials.

From the literature, the range of environmental parameters were established for the various environments to which mechanical components for space applications are exposed.

The detail drawings and specifications associated with the three representative components were analyzed thoroughly to establish the potential failure mechansims for each component. Critical failure mechanisms identified included structural fatigue; crevice, galvanic, and stress corrosion of certain materials; fretting of bearing balls and races; metallic wear; and nonmetallic wear and creep of seats, bushings, and seals. Of these, the mechanisms of nonmetallic wear and creep were judged to be the most critical with respect to performance. In addition, these mechanisms are those about which the least is known; consequently, appropriate accelerated life-test methodology had not been developed. Experimental studies of both wear and creep of nonmetallic materials were conducted to examine the validity of possible short-term tests.

The wear study involved cryogenic and room-temperature wear experiments of virgin polytetrafluoroethylene (PTFE), glass-filled PTFE, chlorotrifluoroethylene (KEL-F), and a polyester material (Mylar). These nonmetallics represented the materials identified during the analysis of the three representative components. The wear study showed

(1) Initial creep during the wear process generally exceeds total wear. Therefore, life tests for wear must be conducted after the initial creep has occurred.

(2) Wear and wear rate at cryogenic temperatures is sufficiently different from that at room temperature that life tests for wear of cryogenic components must be conducted at cryogenic temperatures.

(3) Short-term life tests are best performed by increasing speeds up to a factor of 100. Life testing by extrapolation of short-term wear does not appear feasible.

The creep study involved a literature analysis and room temperature creep experiments with virgin PTFE (Halon G-700). The study showed

(1) Accelerated life tests for creep are feasible using temperature as the accelerating factor, provided that temperatures where material transitions occur are avoided during testing.

(2) Creep properties of polymers vary significantly from batch to batch and within batches. An initial short-term test should be performed on material samples to establish properties before performing life testing. A microhardness-type indentation test was evaluated as an initial short-term test; however, results were inadequate. A short-term creep test of, perhaps, 2 weeks duration is recommended instead.

As a result of the literature study, the experimental studies, and BCL's experience, a general life-test methodology has been defined for mechanical components. The elements of this methodology are

(1) Establish life cycle of component

(2) Establish the possible failure mechanisms for the component and its elements or parts

(3) Conduct (separately, if necessary) life tests for each critical failure mechanism.

Specific short-term life test procedures have been developed for wear and creep of nonmetallic materials, and recommendations have been made for short-term life test procedures for the other failure mechanisms identified during the analysis of the three representative components.

Phase II: Demonstration of Methodology

The general approach to life-test methodology was followed for demonstration purposes using a forged miniature needle valve having a Teflon stem packing and a Kel-F seat. A review of the drawings was made to predict likely failure mechanisms, which included wear and creep of the Teflon and Kel-F and thread wear. A life-test facility was constructed to cycle the valves automatically for the purpose of studying the failure mechanisms. At very high closeing torques, e.g., 2.82 N·m (25 inch-pounds), failure occurred from creep of the Kel-F seat and from thread wear. Specific experiments to study these failure mechanisms established that a reasonable maximum closing torque of 0.65 N·m (5.8 inch-pounds) would permit extended operation with only mild thread wear and acceptable creep of the Kel-F. Leakage through the stem packing coincided with advanced thread wear. Normally, stem leakage would occur primarily from creep of the Teflon. Creep experiments on bulk specimens of Kel-F and Teflon were performed so that the times at which undesirable levels of creep would occur could be predicted. The results generally confirmed those obtained from valve testing.

PHASE I: DEVELOPMENT OF METHODOLOGY

The details of the Phase I efforts were described in the Phase I Interim Report.* A summary of the recommended life-test methodology is presented below. Data on the concepts of mechanical failure, operating environments, critical failure mechanisms for the three representative NASA valves, available life-test methods, and creep and wear of nonmetallic materials can be obtained from the Phase I Interim Report.

General Considerations and Discussions

The following assumptions were made in developing the life-test methodology.

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* Interim Report on "Development of Life-Test Methodology for Long-Life Mechanical Components. Phase I: Development of Methodology", July 31, 1973.

(1) The component to be life tested has been designed according to the current state of art.

(2) The component (or its prototype) has passed proof, qualification, and acceptance tests and is capable of operating satisfactorily for at least a short period of time.

(3) The component design effort has been completed. Therefore, design modifications cannot be made to facilitate life testing.

Although the developed methodology presumes that the component design is completed (Assumption No. 3), the following recommendations should be considered in new designs:

- Consideration of life testing should begin during the design phase as soon as the component configuration is established and materials are selected. At that time, possible failure mechanisms should be established.
- For those failure mechanisms that are not well understood, key laboratory experiments should be performed to assess their relevance.
- Considerations should be given to starting life tests on specific elements or parts (such as valve seats, bearings or gears) as soon as possible.
- Because of the difficult nature of life testing, the component should be designed, whenever feasible, around the need to be life tested. For example, sufficient information of proprietary processes or materials is sometimes not available to permit accurate life tests to be devised.
- Parts and materials should be used that are as well understood and well characterized as possible.

The recommended methodology involves first establishing the various failure mechanisms whereby the component parts or elements may fail, then performing life tests for each critical failure mechanism. Since quantitative accelerated tests are not available for most failure mechanisms, predicting the service life of the component is usually impossible. However, conducting life tests to demonstrate that the component will last at least as long as its intended lifetime is frequently possible. The recommended methodology is based on demonstrating that the component minimum life is at least as long as the required lifetime.

If the recommended sequence of determining the critical failure mechanisms and conducting separate life tests is correctly and successfully carried out, the component will be judged 100 percent reliable with respect to the failure mechanisms considered. Component failure would be possible only if a failure mechanism were overlooked, if the duty cycle input information were inaccurate, or if the component were installed improperly. In practice, completely accurate life tests are not yet available for every failure mode. Nevertheless, the developed methodology appears to be the most effective way to life test; and if it is applied to a component, the results will be at least as good as the present method of running a component for its intended life-time under its intended duty cycle. Furthermore, the present method of life testing one or a few components of a production run does not guarantee that no failures will occur in space. Manufacturing tolerances on alignment, dimensions, and materials are such that component failure in space is possible even though life tests have been successful.

Recommended Life-Test Sequence

The specific elements of the recommended life-test methodology are

(1) Establish Component Life Cycle

(2) Determine Possible Failure Mechanisms

(3) Conduct Life Tests for Each Failure Mechanism

Each is discussed separately below.

Establish Component Life Cycle

Establishing the component life cycle involves establishing the environments and operating conditions to which the component and its elements are exposed during the various phases of its existence. The various possible phases include:

- Construction. Practices during construction may affect the long-term performance of component elements. For example, insufficient cleaning of contaminants may prematurely corrode or age either metals or nonmetals. Residual contaminants from plating baths have been known to corrode materials in bearings, rings, and brushes in slip-ring assemblies for despun antennas for communications satellites.
- Qualification and Acceptance Testing. If the individual component to be life tested has been subjected to such tests, then the conditions under which testing was performed and the test duty cycle should be defined.
- Transportation. Temperature extremes and environmental composition can vary widely throughout the United States. Vibrations on railcars have been known to brinell rolling bearing races.
- Storage. Components may be stored for several years. Corrosion of critical metals will depend on humidity and degree of salinity of the atmosphere. Nonmetals may also be deleteriously affected; for example, adsorption of salt-air humidity during the storage phase, followed by exposure to ultraviolet radiation during a subsequent phase could degrade polymers.
- Prelaunch. After withdrawing from storage, components may be exposed to uncontrolled environmental conditions either before or after installation.
- Launch. Shock and vibration are extremely important in this phase.

- Operational Phase. The component duty cycle must, of course, be established for this phase. For launch vehicles, of course, the launch phase is the operational phase.
- Reentry. High temperatures and other environmental extremes may occur.
- Parking Awaiting Reuse. Environmental control during this phase may be less than during storage or other phases.

The environmental parameters to be considered include

- Atmosphere: mist, fog, water, salt, sand, dust, corrosive gases, outgassed material
- Corrosive cleaning agents
- Ambient temperature: level and variation
- Vibration and shock
- Radiation type and exposure time: optical ultraviolet, beta, gamma, alpha, protons, X-rays, neutrons
- Meteoroids.

After establishing the range of environments, the component duty cycle for the operational phases must be defined. Subsequently, the environmental and duty cycle information must be used to define the operating conditions of the elements in the component for each phase. Defining the operating conditions of the elements is essential in order to establish critical failure modes for each element. Important operating conditions include:

- Cycle rate
- Pressure
- Response time
- Temperatures - level and variation
- Flow rate (for valves, regulators, etc.)
- Tolerable leakage (for valve seats or seals)
- Power consumption and friction
- Loads (for bearings, gears, seals, etc.)
- Shock and vibration levels
- Environmental composition

Determine Possible Failure Mechanisms

Using the life cycle information established previously, the critical failure mechanisms for each component element must be determined. This can be done in two ways: by a forecasting study in which specialists in various fields review the component design, and by experimental operation of individual components followed by a thorough failure analysis of both failed and unfailed parts. Analysis of retrieved space hardware is also an attractive possibility; however, such hardware is not likely to be available.

Forecasting Study. This involves the following steps:

(1) Assemble a team of experts with experience with the specific component type in the following areas:
   - (a) Structural failure
   - (b) Wear
   - (c) Metallic materials corrosion and aging
   - (d) Nonmetallic material aging, creep, and fracture
   - (e) Radiation damage of materials
   - (f) Lubricant degradation.

(2) This team should review detail drawings, specifications, qualification and proof tests, and other data relevant to the component.

(3) Develop list of possible failure mechanisms on the basis of joint discussions.

(4) Laboratory experiments. In some cases, potential failure mechanisms may not be sufficiently well understood to assess their relevance. In these cases, key short-term laboratory experiments may be possible to establish criticality of the failure mechanisms.

Experimental Failure Analysis. An individual component should be run under the normal duty cycle and its elements disassembled and examined for incipient failure mechanisms. This, in itself, may be insufficient to identify latent failure mechanisms, since the single component may not be representative because of tolerances, misalignments, etc. In order to encourage such failure mechanisms to manifest themselves, we recommend running another individual component under slightly more rigorous operating conditions. Specifically, the following sequence is recommended:

(1) Operate a component under its normal duty cycle for a significant period (for example, 1 month)

(2) Operate another component under conditions somewhat more severe than the normal duty cycle: higher speeds, higher loads, higher flow rates, slightly higher temperatures, etc. These conditions should be selected such that as few as possible new failure mechanisms are introduced.

(3) For critical or poorly understood failure mechanisms identified in the forecasting study, elements such as seats or bearings may be withdrawn from the component and run individually. If time and funds permit, components or elements may be instrumented during operation to detect incipient failures. Material specimens should, in some cases, be exposed to environmental conditions if reactions are suspected, but not verified.

(4) If available, obtain retrieved hardware.

(5) Failure Analysis. The various elements should be disassembled and analyzed carefully. If failures occur, the causes (mechanisms) of failure should be clearly established. It is, perhaps, more likely that failures will not occur. However, careful surface examination can reveal incipient failures. Surface-analysis techniques that can be employed as warranted include

  (a) Optical microscopy
  (b) Scanning electron microscopy
  (c) X-ray or electron diffraction
  (d) Ion microanalysis
  (e) Ion scattering spectrometry

(f) Metallographic sectioning

(g) Infrared and mass spectrometry

(h) Optical emission spectrometry

(i) Atomic absorption spectrometry

(j) Ellipsometry for identification of organic films.

In addition, physical property measurements of elastomers and plastics may be performed to evaluate aging.

(6) On the basis of the forecasting study and the failure analyses, the list of critical failure mechanisms requiring life testing may be developed.

Conduct Short-Term Life Tests for Each Critical Failure Mechanism

Consideration of Possible Testing Approaches. A variety of types of life tests were identified in the literature study:

(1) Run component for intended lifetime. This is obviously not usually feasible.

(2) Statistical mechanical reliability analysis. Although popular at one time, this methodology is not now considered valid, since a statistically significant sample is not usually available for mechanical components.

(3) Signature analysis. This includes sonic (acoustic), torque ripple, infrared, thermal contact resistance, electromagnetic emission and other signature techniques. In general, these have not progressed to the point where they are dependable. For some specific components (such as bearings), however, they hold future promise.

(4) Acceleration. This is the best possible short-term test technique, because a quantitative correlation is drawn between test time and real time. Unfortunately, accurate accelerated tests are not yet available for most failure mechanisms.

(5) Extrapolation. For cumulative damage failure mechanisms for which the damage rate is known either to remain constant or to decrease with time, it is possible to

get an estimate of life by running for a short period, then extrapolating linearly to the desired lifetime.

(6) Time compression of duty cycle to reduce inoperative periods. Subject to equilibration of thermal or other processes, this is, perhaps, the simplest effective life test technique. For valves and other components which operate intermittently, the required number of cycles for cycle-dependent failure mechanisms (such as fatigue or wear) can sometimes be obtained in a short time. However, time-dependent mechanisms, such as aging or corrosion must be treated independently.

(7) Minimum-life testing. In this case, the component is run under a single set of conditions at least as severe as those in the normal duty cycle. The life test is then speeded up or accelerated in some manner, so that a successful component is determined to have a lifetime at least as long as the desired lifetime. Actual life is not determined. Most life testing involves using this technique in conjunction with one of the previous techniques.

Specific Recommended Short-Term Life Tests. Recommendations for specific failure modes are given below. Following life testing, the components or elements should be disassembled and examined carefully to make certain that new failure mechanisms were not introduced during testing.

(1) Low- and high-cycle metal fatigue. Fatigue life can frequently be estimated from published tensile data. If this is not possible, the following sequence should be carried out.

(a) Select test cycle. Examine duty cycle and select a test cycle (stress, temperature, time, rate) which is at least as severe as duty cycle. If several factors enter in, such as both stress level and pressure cycling, or temperature level and temperature cycling, it may be necessary to select more than one test cycle.

(b) Accelerate tests by increasing cycling rate to accumulate total cycles; condense inoperative periods. For materials with strain aging properties (steel, titanium) cycle rate must be adjusted to the diffusion mechanisms involved. For other materials maximum cycle rates are limited by heat buildup from internal friction.

(c) Synergistic effects dealing with degradation in mechanical properties should be evaluated independently.

(2) Metallic wear. This can be divided into two cases: mild wear or severe wear. If severe wear is expected, the component should be redesigned. Mild wear is defined as not leading to progressive roughening of the surface.

(a) Wear life test should run for at least a week for equilibration.

(b) Testing rate should be raised by raising speed. Increasing load may change the wear mechanism. The specific component or part should be analyzed to determine maximum speed permissible. Heat transfer analysis based on frictional heat generation and contact conditions should be carried out to provide the following information.

- Maximum surface temperature should not exceed the yield point drop.
- Surface temperature should not exceed critical temperature for boundary lubrication (boundary film desorption or decomposition temperature).
- For fluid lubrication, the shear rate of the lubricant film should be controlled to provide the same lubrication regime the component will see (hydrodynamic boundary, mixed, EHD).

(c) Determine total wear by extrapolation assuming linear wear rate.

(d) Particle debris. In mild metallic wear, small particles are librated which would not be expected to foul the component.

(3) Metallic corrosion

(a) Fretting fatigue. Use established tests to examine material tendencies toward fretting fatigue.

(b) Corrosion fatigue. This mechanism does not appear relevant to space valves.

(c) Hydrogen embrittlement. Standard tests are available. These involve electrolytically charging a piece of material with hydrogen, then measuring fracture toughness.

(d) Galvanic corrosion. Standard tables are available, however, this should not be a problem in spacecraft valves.

(e) Corrosion products restricting movement. This does not appear to be a significant problem, so in order to evaluate it, life testing could be conducted by grossly overestimating the environment.

(4) Radiation damage. A great deal of data are already available in this area, including synergisms with mechanical effects. Specific life tests are not recommended.

(5) Nonmetallic aging

(a) Evaporation of materials and differential evaporation (such as departure of plasticizer). Conduct TGA (thermogravimetric analysis - vacuum microbalance) tests to determine evaporation rate as a function of temperature, then extrapolate to desired lifetime.

(b) Cross-linking aging. Accelerated testing is possible by raising concentration of the active component (such as ozone) in the environment.

(c) Autochemical and autocatalytic reactions. DTA (differential thermal analysis) can be used to identify the existence of such reactions. Life testing can then be speeded up by increasing temperatures.

(6) Creep of nonmetallic materials. Because of batch-to-batch variations in material properties, and because of the dependence of the mechanical properties of a polymer upon past history, the long-term creep of nonmetallic materials is difficult to predict in a general way. The general methodology recommended is to conduct some short-term creep tests in order to identify the particular piece or material batch with respect to its creep properties. On the basis of these tests, temperature and stress acceleration factors can be determined for the particular material, and the long-term behavior predicted by temperature and/or stress superposition. Life tests for creep should be performed on the component elements withdrawn from the component.

The following sequence should be applied for the prediction of the long-term creep behavior of nonmetallic parts in the aerospace valves under consideration.

(a) The parts should be identified and a failure criterion defined for each. That is, how much creep can be tolerated? Is permanent set more important than total creep?, etc.

(b) The use history and environment of each part should be established. This history should include
- Stress
- Atmosphere
- Temperature

for each portion of the life cycle of a given part. For example, the stress profile might include several cycles of valve actuation where the part is alternately stressed and unstressed. Since the cumulative damage model is assumed to be operative here, the various cycles may be combined to provide an integrated and simplified profile. For example, if a valve component is stressed 1000 times for 1 minute each, separated by 1-day dwell intervals at a lower stress, this profile may be simulated by 100 minutes at the high stress and 10 days at the low stress, but at a higher temperature.

(c) The component or a sample from the same materials batch and fabrication run should be subjected to a short-term room-temperature pressure creep test. This test will yield a creep-compliance under standard conditions that will uniquely identify the mechanical/creep properties of that batch and will identify the set of creep compliance curves to be used.

(d) The material should then be subjected to an accelerated creep test based upon the principle of temperature-time, and/or stress-time, superposition. The stress profile described in Step 2 should be applied simultaneously with a temperature profile that yields the proper degree of acceleration while avoiding the critical material transition temperature ranges for that material. The measurement of creep versus time in this test will yield data reflecting the creep behavior of this material for the requisite extended time period.

(7) Nonmetallic wear; extent of wear. Prediction of the long-term wear behavior of the polymeric materials used in these valves is best carried out by a speed-accelerated test. In this type of test, the number of revolutions, oscillatory cycles, or total linear sliding distance for the expected life is determined. The material combination is then subjected to the equivalent number of cycles in a much shorter time period by increasing the rubbing or cycling

rate. For example, if a steel/filled PTFE friction interface in, say, a valve stand, is determined to undergo 6000 meters of total sliding at a load of 3.45 MN/m^2 (500 psi) at 77 K in 10 years, this service may be accelerated by sliding at a rate of 0.50 m/sec for 200 minutes at 77 K under a load of 3.45 MN/m^2.

The following sequence should be applied in determining the long-term wear behavior of nonmetallic materials in the valves of interest.

(a) The parts should be identified and a failure criterion defined for each. The failure criterion should be based upon allowable wear and the possible specific wear mechanisms such as scoring or wear debris jamming.

(b) The use-history and environment should be established for each part. This history should include

- Load/stress
- Atmosphere
- Temperature
- Number of wear cycles
- Linear sliding distance
- Relative speed of wear surfaces during sliding

A profile should be constructed for each parameter.

(c) For the component or for a specimen from the same material batch and fabrication run, a wear test should be carried out applying the stress-temperature profile defined in Step (2). The speed, or cycle rate, should be increased up to the upper limit defined for that material in order to achieve the requisite degree of acceleration. For example, if the filled PTFE gland just discussed spends 40 percent of its real-time life at 300 K under a load of 3.45 MN/m^2 (500 psi) and 60 percent of its real-time life at 77 K under a load of 13.8 MN/m^2 (2000 psi), then the 200 minute accelerated test should be run for 40 percent of 200 minutes (80 min) at 300 K and 3.45 MN/m^2 for 60 percent of 200 minutes (120 min) at 13.8 MN/m^2 and 77 K. The test should be carried out in such a way as to factor out initial creep effects.

(d) The total wear should then be measured and observations made of the nature of the wear track and the quantity and morphology of the debris. These data and observations should be interpreted as though the specimen or component had been exposed for the extended real-time period. The effects of wear and debris on component function should be determined by the comparison of the posttest data with the failure criterion for this particular part.

(8) Nonmetallic wear; wear debris. The failure mode of interest is the fouling of clearances in valves.

(a) Run part for a significant period and collect and observe wear debris.

(b) Compare size of debris particles with clearances in the valve. Debris should be either clearly larger or clearly smaller than valve clearances. If debris particles are of the same order of size as the clearances, then fouling is likely and alternative materials should be selected.

PHASE II: DEMONSTRATION OF METHODOLOGY

The approach to life-test methodology developed in Phase I was demonstrated in Phase II using miniature needle valves (hand operated; made to fit 0.64 cm (0.25 inch) tubing) as an arbitrary choice of hardware The following summary shows how the life-test methodology can be applied.

Step 1: Establish Component Life Cycle

Since miniature needle valves are hand operated and are used for a variety of purposes, the definition of the normal duty cycle must be made arbitrarily on the basis of a reasonable, typical application. Likewise, the definition of life (time or cycles to failure) must be made arbitrarily. Therefore, the following choices and assumptions were made.

(1) Operation with nitrogen gas at 6.89 newtons/mm^2 (1000 psi).

(2) Operation at a constant temperature of 49 C (120 F).

(3) Valves close both to a constant angular position and to a constant torque.

(4) Valve stems open and close at 9 rev/min.

(5) Seat failure defined by leakage of 30 bubbles per minute through a 0.051-cm (0.020-inch) orifice attached to the normal valve outlet.

(6) Stem packing failure defined by 30 bubbles per minute being released from stem and packing area.

In an actual application, many of the operating conditions would be defined. Also, the desired life would be known, which would provide the number of cycles expected before failure.

Step 2: Establish the Possible Failure Mechanisms for the Component and Its Elements or Parts

Forecasting Study

An initial review was made of the drawings of the valve components to forecast probable failure mechanisms. In order of importance, the following failure mechanisms appeared most likely to occur eventually in extended service.

(1) Wear of stem packing. Two Teflon wafers contained between three metal, noncontacting spacers form the stem seal. Wear of the wafers is expected from contact with the stem as it moves during opening and closing in a reversing, helical motion. In addition, any side loads applied to the stem during operation would increase the contact pressure against the wafers at one side and produce an expected increase in wear rate.

(2) Wear and fatigue of Kel-F seat. This particular valve design permits rotation between the stem seat and the valve stem, which prevents rotation between the seat and the valve body during closing. However, local motion occurs between the seat and body as the closing force imbeds the seat into the body. Degradation of the seat face is expected through wear and fatigue from contact with the body, which would lead to leakage across the seat.

(3) Wear of threads. The stem is coupled to the body by threads to produce the closing force during rotation of the valve stem. Thread wear is expected and could be involved in failures in two ways. First, if thread wear became sufficiently severe (galling) to seize the stem in the body, the function of the valve would be destroyed. Second, since the threads are located between the stem and seat, wear debris from the threads could accelerate stem and seat wear.

(4) Creep of stem packing and seat. Although the valve design minimizes creep of the stem packing and seat by containing the material well to minimize the directions for creep, localized creep is expected. Considerable creep of the seat could occur before leaking would result (assuming the stem can be turned further to compensate for the creep). A lesser amount of stem-packing creep could be tolerated.

(5) Erosion, corrosion, and metal fatigue. Other possible failure mechanisms, such as erosion, corrosion, and metal fatigue, could occur, depending on the operating media, pressures, and pressure drop. These mechanisms are considered as secondary possibilities.

Experimental Failure Analysis

In support of establishing the possible failure mechanisms, a life-test facility was constructed to cycle the valves automatically. Short-term experiments were performed to confirm the failure mechanisms predicted by the design review. Short-term life tests were then conducted to study each failure mechanism in detail.

Life-Test Facility. The life-test facility was constructed with the following operation capabilities to provide testing with the assumed operating conditions.

(1) Two valves closed to a constant angular position; two valves closed to a constant torque.

(2) Automatic cycling of all four valves simultaneously consisting of opening one revolution at 9 rev/min, immediate reversing, closing at 9 rev/min, and remaining at rest in the closed position for the remainder of the cycle. Operation could be conducted at a frequency of 1 cycle per minute and 2 cycles per minute.

(3) Operation under 49 C (120 F) water to provide constant temperature and continuous leak-test ability. A 0.051-cm (0.020-inch) diameter orifice attached to the exit of the valves provided a standard bubble size for observing seat leakage.

(4) Nitrogen gas supplied to the valves at 6.89 newtons/mm^2 (1000 psi).

Initial Experiments for Failure Analysis. The initial experiments were run with a deliberately high closing torque of 2.82 N·m (25 inch-pounds) to accelerate the failure mechanisms. This torque is approximately the maximum that can be applied by hand. The results are presented in Table 1. As expected, seat leaks developed first in the valves closed to a constant angular position (the initial angular position was that obtained by closing the valve to 2.82 N·m (25 inch-pounds)). Creep and wear of the Kel-F seat and wear of the threads lower the closing force, which is not held constant in this closing mode. Stem leakage was evaluated only in Valve No. 3, which was installed in the reverse direction so that the stem was exposed to nitrogen at 6.89 newtons/mm^2 (1000 psi) while the valve was closed.

A failure analysis of the disassembled valves showed that thread wear and seat wear and creep were the primary causes of failure. The Kel-F was worn at the seat contact and was extruded along the seat-retaining screw. The thread wear occurred on the brass body, which produced extensive wear debris within the valve. The surface finish of the stainless steel stem threads was rough from machining, which probably aggravated the wear of the threads in the brass body.

With the results of the initial experiments generally confirming the failure mechanisms predicted in the design review, experiments were conducted to study each failure mechanism in greater detail.

Step 3: Conduct Short-Term Life Tests for Each Critical Failure Mechanism

The preliminary valve life testing showed that failures occurred first from thread wear and seat wear and creep. Since these results confirmed some of the primary failure mechanisms predicted in the design review, experiments were designed to study each failure mechanism in greater detail. Experiments were also designed to study stem leakage from wear and creep of the Teflon stem packing, which was a primary predicted failure mechanism, but one which was not evaluated directly in the initial life testing. The specific failure mechanisms were studied both with actual valves in the Life-Test Facility and with bulk specimens of Kel-F and Telfon.

TABLE 1. INITIAL VALVE LIFE-TEST RESULTS

Valve	Cycles	Test Mode	Leakage	Inspection Notes
1.	3,600	Fixed angular position	Seat, from 40 to 160 bubbles/min	Minor Kel-F and Teflon extrusion. No thread wear or Kel-F wear debris.
2.	4,116	Ditto	Seat, excess of 160 bubbles/min	Extensive brass thread wear debris. Minor Kel-F and Teflon extrusion. Kel-F wear debris, and brass wear debris embedded in Kel-F.
3.	6,600	Constant torque of 2.82 newton meters (25 inch-pounds)	Occasional stem leakage	Extensive Kel-F creep and wear. Minor Teflon creep. No thread wear debris.
4.	6,600	Ditto	No leaks	Extensive Kel-F creep and wear. Fractured seat retainer. Minor Teflon creep. No thread wear debris.
5.	4,506	Fixed angular position	Seat, excess of 160 bubbles/min	Extensive brass thread wear debris. Minor Kel-F and Teflon creep. Some brass wear debris embedded in Kel-F.
6.	10,368	Ditto	Seat, excess of 160 bubbles/min	Extensive brass thread wear debris. Brass wear debris embedded in Kel-F. Extensive Kel-F wear debris, but minor Kel-F and Teflon creep.

Thread Wear

The Life-Test Facility was modified so that thread wear could be studied in one of the four valves. A lever-arm arrangement was used to apply a dead-weight load against the valve body. The load was transmitted to the stem threads, which supported the constant load throughout their cycling motion of opening and closing. This testing mode accelerated thread wear compared with normal operation, which applies a major load to the threads only during the limited rotation when the Kel-F seats against the body. The valves were installed so that the stem packing was exposed to 6.89 N/mm^2 (1000 psi) nitrogen continuously by blocking off the valve exit.

The results of the valves tested in this mode are presented in Table 2 (Valves 7, 8, 9, 11, 12, 15, 16, 17, 18, and 20), along with the results of the other valve tests conducted during the study. The loads were chosen from calculated valves of seat loads obtained during normal valve closing. The tests were very rigorous, as evidenced by the large number of gross thread failures. However, no failure occurred when a load of 889 N (200 lb) was applied continuously to the threads. Assuming a thread coefficient of friction of 0.1, this corresponds to a closing torque of approximately 0.65 N•m (5.8 in.-lb), which is a reasonable closing torque for a valve of this type. This is also a conservative estimate because a constantly applied load is more rigorous than a cycling load in this type of application. A cycling load permits redistribution of lubricant on the threads, whereas a constantly applied load denies the migration of lubricant to the sliding surfaces by keeping them in continuous contact. Therefore, the results of the thread tests indicate that operation of the valves at maximum closing torques of 0.65 N•m (5.8 in.-lb) will permit extended operation without deterioration by thread wear.

Seat Wear and Creep

The initial valve tests at very high closing torques of 2.82 N•m (25 in.-lb) produced a large amount of Kel-F extrusion along the seat retaining screw (the Kel-F was restricted by the valve body during closing, which caused

TABLE 2. LIFE-TEST RESULTS FOR CRITICAL FAILURE MECHANISMS

Valve	Cycles (120 per hour)	Mode	Thread Load Newtons	Thread Load pounds	Stem Leakage,* Bubbles per min	Inspection Notes
7	168	Thread wear	2670	600	>160	Threads completely worn out of body, Kel-F creep 0.038 cm (0.015 in.) from base of screw head.
8	36	Thread wear	2670	600	>160	Threads completely worn out of body, Kel-F creep 0.033 cm (0.013 in.) from base of screw head.
9	12	Thread wear	1340	300	>160	Threads completely worn out of body, Kel-F creep 0.031 cm (0.012 in.) from base of screw head.
10	0 (static for 240 hrs)	Seat creep, constant torque of 2.26 Nm (20 in. lb)	--	--	0	Kel-F creep 0.025 cm (0.010 in.) from base of crew head.
11	10,000	Thread wear	889	200	0	Mild wear on body threads; threads still serviceable. Kel-F creep 0.10 cm (0.040 in.) from base of screw head.
12	900	Thread wear	1340	300	>160	Threads and stem packing mutilated by motor failing to stop while unwinding stem. Kel-F creep 0.076 cm (0.030in.) from base of screw head.
13	3,890	Stem leakage	--	--	>160	Considerable thread wear, with debris embedded in Kel-F seat. Stem leakage from extrusion of Teflon along stem. Kel-F creep 0.051 cm (0.020 in.).
14	4,120	Stem leakage	--	--	>160	Threads completely worn out of body near outside end of travel from failure of motor-reversal system.
15	216	Thread wear	1340	300	>160	Thread wear caused jamming of stem. Kel-F creep 0.063 cm (0.025 in.) from base of screw head.
16	240	Thread wear	1340	300	>160	Threads in excellent condition. Stem leakage from Teflon extrusion along stem. Kel-F creep 0.13 cm (0.050 in.).
17	696	Thread wear	1340	300	120	Mild thread wear. Stem leakage from Teflon wear. Kel-F creep 0.13 cm (0.050 in.).
18	960	Thread wear	1340	300	7160	Heavy thread wear, Kel-F creep 0.15 cm (0.060in.) from base of screw head.
19	0 (static for 236 hrs)	Seat creep, constant torque of 1.13 Nm (10 in lb)	--	--	0	Kel-F creep 0.025 cm (0.010 in.) from base of screw head.
20	300	Thread wear	889	200	7160	Threads and stem packing destroyed by motor failing to stop.
21	1872	Fixed position	--	--	0	Mild thread wear, Kel-F creep 0.051 cm (0.020 in.) from base of screw head.
22	360	Fixed position	--	--	0	No visible thread wear, Kel-F creep 0.038 cm (0.015 in.) from base of screw head.
23	18,120	Constant torque 0.85 Nm (7.5 in lb)	--	--	0	Mild thread wear, retaining screw for Kel-F seat backed out, which caused excessive Kel-F wear.
24	12,120	Constant torque 0.85 Nm (7.5 in.-lb)	--	--	0	Mild thread wear. Kel-F creep 0.17 cm (0.065 in.) from base of screw head.

* Failure arbitrarily defined as 30 bubbles per minute.

a cylinder of Kel-F to form along the retaining screw). Since this extrusion process probably resulted from a combination of creep from high contact stresses and from local sliding along the seat during closing, a static experiment was performed to study creep only by applying a constant torque on two valves (Nos. 10 and 19). As seen in Table 2, the resulting creep of the Kel-F was very small compared with the creep of the Kel-F seats in the cycling tests that used a seat load maintained at a high level. Therefore, the extrusion of the Kel-F appeared to be more strongly influenced by the cyclic contact with the body rather than by creep alone. Creep of the seats studied further on bulk specimens is described below.

Stem Wear and Creep

All of the Valves 7 through 17 presented in Table 1 were installed so that a nitrogen pressure of 6.89 N/mm^2 (1000 psi) was applied continuously to the stem packing to evaluate stem leakage. All of the valves except for Valves 10, 11, 19, 21, 22, 23, and 24 had extremely high stem-leakage rates at the end of the test. However, these results are not considered to be valid for evaluation of stem packing creep and wear because all of the valves showing stem leakage had excessive thread wear. Since the stem is located radially by the threads as well as by the stem packing, excessive thread wear permits misalignments in the packing region. Such misalignments cause unrealistic loads on the packing, which probably was the direct cause of the high occurrence of stem leakage.

The operation of Valves 11, 23, and 24 for 10,000 cycles or more without stem leakage is a significant indication of the reliability of the stem packing providing the threads remain intact. Valves 13 and 14, which were intended to study stem leakage, were set up to close to a constant angular position established by an initial closing of 2.82 N·m (25 in.-lb). Apparently this high torque level was sufficient to cause thread wear, with the resulting deterioration of the stem packing. Valve 14 failed as a result of a failure of the motor-control system.

Bulk Creep Experiments

The creep characteristics of Teflon and Kel-F samples were evaluated using the Weissenberg Rheogoniometer. Dynamic mechanical tests were made using this equipment and the data obtained were calculated in terms of the storage (elastic) and loss (viscous) compliances. These data, presented in Tables 3 and 4, Columns 6 and 7, show that the Teflon materials, at constant applied load, can be expected to creep more than Kel-F. The difference in creep between the two materials is a factor of 2 or 3.

The storage compliance ($J'(\omega)$) and the loss compliance ($J''(\omega)$) can be used to construct master curves covering many decades of frequency. These master curves can then be used to determine the creep compliance ($J(t)$) of the materials. This is accomplished by the following approximate Equation (1)*

$$J(t) = J'(\omega) + 0.4\,J''(0.4\omega) - 0.014\,J''(10\omega) \qquad (1)$$

when ω is the angular frequency (radian/sec) in the dynamic mechanical tests, and t is the equivalent real time. The time t and frequency ω are related by

$$t = 1/\omega \qquad (2)$$

Equations (1) and (2) were used to calculate $J(t)$ from the experimentally measured $J'(\omega)$ and $J''(\omega)$. The resulting data, presented in Figures 1 and 2, show the shear creep compliances of Teflon and Kel-F, respectively.

These data were used to predict the service behavior of the Kel-F valve seat and Teflon valve stem packing. Each case is discussed separately below.

Kel-F Valve Seat Creep Predictions

In shutting the valve, a load is applied to the Kel-F seat. The result of the load will be extrusion of the Kel-F material into the clearance between the screw head and the orifice; the clearance is ≈0.25 cm (0.01 in.). The amount of material extruded will depend on the stress, the length of time applied, and the compliance of the material.

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*Reference on Page 37.

TABLE 3. DYNAMIC MECHANICAL MEASUREMENT OF KEL-F

SAMPLE- KEL-F AT ROOM TEMP. AND 500U AMP. ROD OF WIDTH, THICK, LENGTH 0.299X0.646X1.000(CM)

FREQUENCY (CYC/SEC)	COMPLEX MODULI (DYNES/CM↑2)	STORAGE	LOSS TANGENT	RELAXATION TIME (SEC)	STORAGE COMPLIANCE	LOSS COMPLIANCE	ANGULAR FREQUENCY (1/SECONDS)
0.0060	4.845E+09	4.843E+09	3.1345E-02	0.8315	2.063E-10	6.466E-12	0.038
0.0600	5.200E+09	5.197E+09	3.4823E-02	9.2370E-02	1.922E-10	6.692E-12	0.377
0.6000	5.536E+09	5.530E+09	4.5906E-02	1.2177E-02	1.805E-10	8.284E-12	3.770
6.0000	5.955E+09	5.945E+09	5.9270E-02	1.5722E-03	1.676E-10	9.935E-12	37.699

SAMPLE- KEL-F AT 49.5 C ROD OF WIDTH, THICK, LENGTH 0.299X0.646X1.000(CM)

FREQUENCY (CYC/SEC)	COMPLEX MODULI (DYNES/CM↑2)	STORAGE	LOSS TANGENT	RELAXATION TIME (SEC)	STORAGE COMPLIANCE	LOSS COMPLIANCE	ANGULAR FREQUENCY (1/SECONDS)
0.0060	4.160E+09	4.159E+09	2.5279E-02	0.6705	2.403E-10	6.075E-12	0.038
0.0190	4.268E+09	4.267E+09	1.0555E-02	8.8536E-02	2.343E-10	2.473E-12	0.119
0.0301	4.416E+09	4.412E+09	4.4525E-02	0.2357	2.262E-10	1.007E-11	0.189
0.0600	4.478E+09	4.478E+09	9.7412E-03	2.5839E-02	2.233E-10	2.175E-12	0.377
0.0951	4.566E+09	4.560E+09	5.3344E-02	8.9280E-02	2.187E-10	1.167E-11	0.597
0.1897	4.567E+09	4.566E+09	2.5123E-02	2.1073E-02	2.189E-10	5.499E-12	1.192
0.3007	4.539E+09	4.538E+09	2.7533E-02	1.4572E-02	2.202E-10	6.063E-12	1.889
0.6000	4.636E+09	4.634E+09	2.5112E-02	6.6613E-03	2.157E-10	5.416E-12	3.770
1.8974	4.596E+09	4.594E+09	2.4838E-02	2.0834E-03	2.175E-10	5.403E-12	11.921
6.0000	4.638E+09	4.636E+09	2.2116E-02	5.8665E-04	2.156E-10	4.768E-12	37.699

SAMPLE- KEL-F AT 68 C ROD OF WIDTH, THICK, LENGTH 0.299X0.646X1.000(CM)

FREQUENCY (CYC/SEC)	COMPLEX MODULI (DYNES/CM↑2)	STORAGE	LOSS TANGENT	RELAXATION TIME (SEC)	STORAGE COMPLIANCE	LOSS COMPLIANCE	ANGULAR FREQUENCY (1/SECONDS)
0.0060	1.749E+09	1.724E+09	0.1690	4.482	5.639E-10	9.527E-11	0.038
0.0190	2.531E+09	2.502E+09	0.1530	1.283	3.905E-10	5.974E-11	0.119
0.0301	2.627E+09	2.601E+09	0.1402	0.7418	3.770E-10	5.284E-11	0.189
0.0600	2.820E+09	2.797E+09	0.1281	0.3397	3.518E-10	4.505E-11	0.377
0.0600	2.795E+09	2.772E+09	0.1294	0.3433	3.549E-10	4.592E-11	0.377
0.0951	2.893E+09	2.871E+09	0.1229	0.2058	3.431E-10	4.218E-11	0.597
0.0951	2.908E+09	2.888E+09	0.1171	0.1960	3.416E-10	3.999E-11	0.597
0.1897	3.019E+09	3.002E+09	0.1072	8.9913E-02	3.293E-10	3.530E-11	1.192
0.3007	3.140E+09	3.125E+09	9.7611E-02	5.1662E-02	3.170E-10	3.094E-11	1.889
0.6000	3.241E+09	3.229E+09	8.7726E-02	2.3270E-02	3.073E-10	2.696E-11	3.770
1.8974	3.388E+09	3.381E+09	6.5827E-02	5.5217E-03	2.945E-10	1.938E-11	11.921
6.0000	3.509E+09	3.504E+09	5.1514E-02	1.3665E-03	2.846E-10	1.466E-11	37.699

SAMPLE- KEL-F AT 83.5 C ROD OF WIDTH, THICK, LENGTH 0.299X0.646X1.000(CM)

TABLE 3. -Continued.

FREQUENCY (CYC/SEC)	COMPLEX MODULI (DYNES/CM↑2)	STORAGE	LOSS TANGENT	RELAXATION TIME (SEC)	STORAGE COMPLIANCE	LOSS COMPLIANCE	ANGULAR FREQUENCY (1/SECONDS)
0.0060	1.060E+09	1.050E+09	0.1416	3.756	9.341E-10	1.323E-10	0.038
0.0190	1.185E+09	1.167E+09	0.1751	1.469	8.311E-10	1.455E-10	0.119
0.0301	1.267E+09	1.248E+09	0.1728	0.9145	7.779E-10	1.344E-10	0.189
0.0600	1.355E+09	1.331E+09	0.1984	0.4998	7.253E-10	1.367E-10	0.377
0.0600	1.440E+09	1.419E+09	0.1738	0.4611	6.843E-10	1.190E-10	0.377
0.0951	1.459E+09	1.433E+09	0.1906	0.3191	6.732E-10	1.283E-10	0.597
0.1897	1.615E+09	1.585E+09	0.1940	0.1628	6.079E-10	1.179E-10	1.192
0.3007	1.679E+09	1.648E+09	0.1947	0.1031	5.846E-10	1.138E-10	1.889
0.6000	1.813E+09	1.777E+09	0.2016	5.3465E-02	5.407E-10	1.090E-10	3.770
1.8974	2.102E+09	2.072E+09	0.1706	1.4306E-02	4.689E-10	7.998E-11	11.921
6.0000	2.382E+09	2.343E+09	0.1834	4.8653E-03	4.129E-10	7.574E-11	37.699

SAMPLE- KEL-F AT 100C ROD OF WIDTH,THICK,LENGTH 0.299X0.646X1.000(CM)

FREQUENCY (CYC/SEC)	COMPLEX MODULI (DYNES/CM↑2)	STORAGE	LOSS TANGENT	RELAXATION TIME (SEC)	STORAGE COMPLIANCE	LOSS COMPLIANCE	ANGULAR FREQUENCY (1/SECONDS)
0.0060	5.634E+08	6.610E+08	8.6361E-02	2.291	1.502E-09	1.297E-10	0.038
0.0190	5.993E+08	6.962E+08	9.4494E-02	0.7926	1.424E-09	1.345E-10	0.119
0.0301	7.261E+08	7.233E+08	8.8477E-02	0.4683	1.372E-09	1.214E-10	0.189
0.0600	7.570E+08	7.530E+08	9.5961E-02	0.2545	1.315E-09	1.262E-10	0.377
0.0600	7.405E+08	7.373E+08	9.4194E-02	0.2499	1.344E-09	1.266E-10	0.377
0.0951	7.756E+08	7.720E+08	9.7047E-02	0.1624	1.283E-09	1.245E-10	0.597
0.1897	7.984E+08	7.927E+08	0.1191	9.9912E-02	1.244E-09	1.481E-10	1.192
0.3007	8.232E+08	8.175E+08	0.1188	6.2865E-02	1.206E-09	1.433E-10	1.889
0.6000	8.647E+08	8.577E+08	0.1285	3.4080E-02	1.147E-09	1.474E-10	3.770
1.8974	9.512E+08	9.395E+08	0.1587	1.3312E-02	1.038E-09	1.648E-10	11.921
6.0000	1.087E+09	1.067E+09	0.1919	5.0894E-03	9.037E-10	1.734E-10	37.699

TABLE 4. DYNAMIC MECHANICAL MEASUREMENTS OF TEFLON

SAMPLE- TEFLON AT ROOM TEMP AND 500 U AMP — ROD OF WIDTH, THICK, LENGTH 0.327X0.636X1.000(CM)

FREQUENCY (CYC/SEC)	COMPLEX MODULI (DYNES/CM↑2)	STORAGE	LOSS TANGENT	RELAXATION TIME (SEC)	STORAGE COMPLIANCE	LOSS COMPLIANCE	ANGULAR FREQUENCY (1/SECONDS)
0.0060	1.863E+09	1.856E+09	8.7859E-02	2.331	5.347E-10	4.698E-11	0.038
0.0600	2.063E+09	2.054E+09	9.5418E-02	0.2531	4.826E-10	4.605E-11	0.377
0.6000	2.409E+09	2.394E+09	0.1125	2.9849E-02	4.125E-10	4.641E-11	3.770
6.0000	2.799E+09	2.786E+09	9.3900E-02	2.4908E-03	3.558E-10	3.341E-11	37.699

SAMPLE- TEFLON AT 50.5 C — ROD OF WIDTH, THICK, LENGTH 0.327X0.636X1.000(CM)

FREQUENCY (CYC/SEC)	COMPLEX MODULI (DYNES/CM↑2)	STORAGE	LOSS TANGENT	RELAXATION TIME (SEC)	STORAGE COMPLIANCE	LOSS COMPLIANCE	ANGULAR FREQUENCY (1/SECONDS)
0.0060	1.433E+09	1.432E+09	4.6608E-02	1.236	6.969E-10	3.248E-11	0.038
0.0190	1.470E+09	1.468E+09	5.5316E-02	0.4640	6.792E-10	3.757E-11	0.119
0.0301	1.525E+09	1.523E+09	5.8062E-02	0.3073	6.545E-10	3.800E-11	0.189
0.0600	1.544E+09	1.541E+09	5.7866E-02	0.1535	6.457E-10	3.742E-11	0.377
0.0600	1.562E+09	1.560E+09	5.7675E-02	0.1530	6.390E-10	3.686E-11	0.377
0.0951	1.562E+09	1.560E+09	5.9103E-02	9.8920E-02	6.390E-10	3.777E-11	0.597
0.1897	1.637E+09	1.633E+09	6.2436E-02	5.2373E-02	6.098E-10	3.808E-11	1.192
0.3007	1.637E+09	1.634E+09	5.9744E-02	3.1620E-02	6.099E-10	3.644E-11	1.889
0.6000	1.633E+09	1.630E+09	5.5896E-02	1.4827E-02	5.899E-10	3.297E-11	3.770
1.8974	1.758E+09	1.756E+09	5.1262E-02	4.2999E-03	5.681E-10	2.912E-11	11.921

SAMPLE- TEFLON AT 68.0 C — ROD OF WIDTH, THICK, LENGTH 0.327X0.636X1.000(CM)

FREQUENCY (CYC/SEC)	COMPLEX MODULI (DYNES/CM↑2)	STORAGE	LOSS TANGENT	RELAXATION TIME (SEC)	STORAGE COMPLIANCE	LOSS COMPLIANCE	ANGULAR FREQUENCY (1/SECONDS)
0.0060	1.216E+09	1.214E+09	5.5597E-02	1.475	8.212E-10	4.566E-11	0.038
0.0095	1.234E+09	1.232E+09	5.5575E-02	0.9301	8.093E-10	4.498E-11	0.060
0.0190	1.261E+09	1.258E+09	6.5587E-02	0.5502	7.915E-10	5.191E-11	0.119
0.0301	1.297E+09	1.294E+09	6.8903E-02	0.3647	7.693E-10	5.301E-11	0.189
0.0600	1.324E+09	1.321E+09	6.1380E-02	0.1628	7.539E-10	4.627E-11	0.377
0.0951	1.380E+09	1.378E+09	5.9148E-02	9.8995E-02	7.339E-10	4.341E-11	0.597
0.1897	1.433E+09	1.431E+09	5.7113E-02	4.7908E-02	6.965E-10	3.978E-11	1.192
0.6000	1.433E+09	1.431E+09	5.7122E-02	1.5152E-02	6.967E-10	3.979E-11	3.770
1.8974	1.497E+09	1.495E+09	5.6399E-02	4.7309E-03	6.668E-10	3.761E-11	11.921

SAMPLE- TEFLON AT 84.5 C — ROD OF WIDTH, THICK, LENGTH 0.327X0.636X1.000(CM)

FREQUENCY (CYC/SEC)	COMPLEX MODULI (DYNES/CM↑2)	STORAGE	LOSS TANGENT	RELAXATION TIME (SEC)	STORAGE COMPLIANCE	LOSS COMPLIANCE	ANGULAR FREQUENCY (1/SECONDS)

0.0060	1.012E+09	1.009E+09	7.5758E-02	2.036	9.857E-10	7.566E-11	0.038
0.0190	1.065E+09	1.062E+09	8.3561E-02	0.7009	9.441E-10	7.889E-11	0.119
0.0301	1.091E+09	1.088E+09	7.6345E-02	0.4041	9.140E-10	6.978E-11	0.189
0.0600	1.144E+09	1.140E+09	8.2015E-02	0.2176	8.710E-10	7.144E-11	0.377
0.0951	1.225E+09	1.222E+09	6.5961E-02	0.1104	8.147E-10	5.374E-11	0.597
0.1897	1.235E+09	1.233E+09	6.4039E-02	5.3717E-02	8.079E-10	5.174E-11	1.192
0.3007	1.271E+09	1.268E+09	6.2053E-02	3.2842E-02	7.854E-10	4.874E-11	1.889
0.6000	1.271E+09	1.269E+09	5.8494E-02	1.5516E-02	7.856E-10	4.596E-11	3.770
1.8974	1.332E+09	1.330E+09	5.6312E-02	4.7236E-03	7.498E-10	4.222E-11	11.921

SAMPLE- TEFLON AT 100.5 C ROD OF WIDTH,THICK,LENGTH 0.327X0.636X1.000(CM)

FREQUENCY (CYC/SEC)	COMPLEX MODULI (DYNES/CM↑2)	STORAGE	LOSS TANGENT	RELAXATION TIME (SEC)	STORAGE COMPLIANCE	LOSS COMPLIANCE	ANGULAR FREQUENCY (1/SECONDS)
0.0060	7.089E+08	7.028E+08	0.1320	3.502	1.399E-09	1.846E-10	0.038
0.0190	7.596E+08	7.548E+08	0.1137	0.9539	1.308E-09	1.487E-10	0.119
0.0301	7.854E+08	7.810E+08	0.1060	0.5610	1.266E-09	1.342E-10	0.189
0.0600	8.198E+08	8.156E+08	0.1020	0.2706	1.213E-09	1.238E-10	0.377
0.0951	8.458E+08	8.423E+08	9.1461E-02	0.1531	1.177E-09	1.077E-10	0.597
0.1897	8.805E+08	8.767E+08	9.2280E-02	7.7407E-02	1.131E-09	1.044E-10	1.192
0.3007	8.978E+08	8.945E+08	8.6803E-02	4.5941E-02	1.110E-09	9.632E-11	1.889
0.6000	9.361E+08	9.328E+08	8.3832E-02	2.2237E-02	1.065E-09	8.925E-11	3.770
1.8974	1.001E+09	9.978E+08	8.3480E-02	7.0025E-03	9.952E-10	8.308E-11	11.921

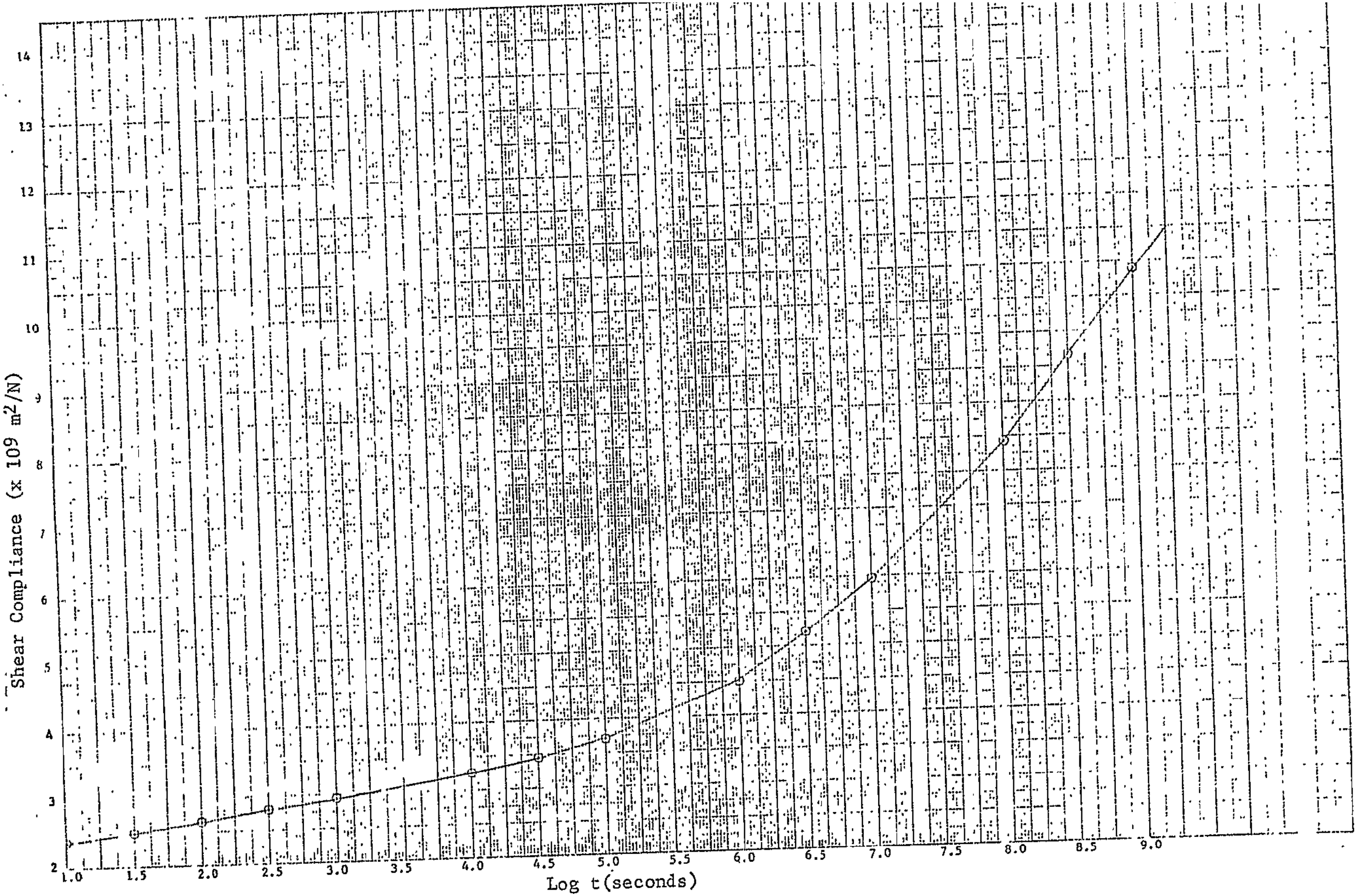

FIGURE 1. CREEP COMPLIANCE OF KEL-F AT 50 C

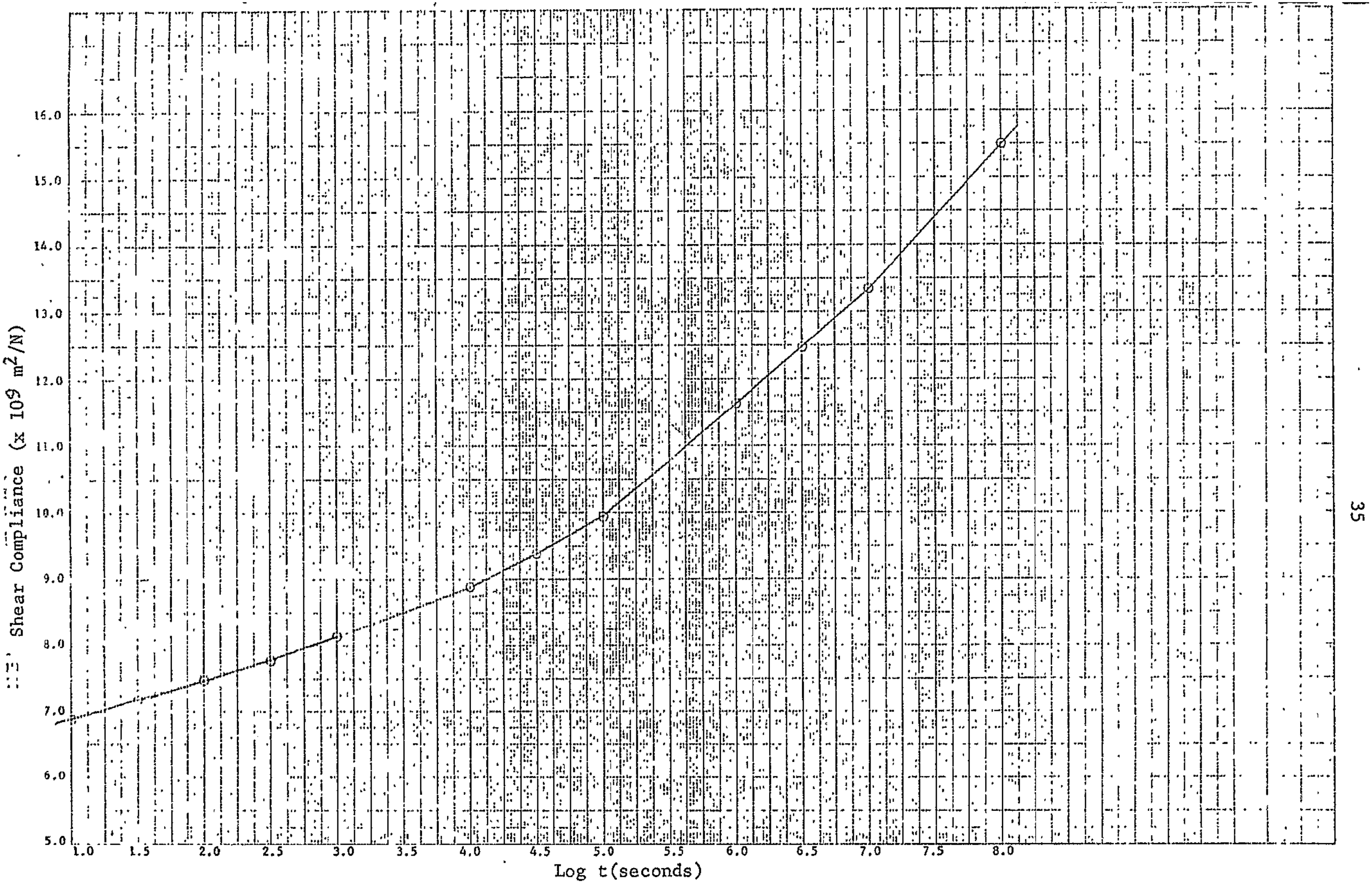

FIGURE 2. CREEP COMPLIANCE OF TEFLON AT 50 C

As an example, the case of a statically loaded valve will be considered. For the valve examined in this test (Valve 10), the applied load at 2.26 N·m (20 in.-lb) valve stem torque is approximately 755 N (170 lbs). Since the valve seat is on an angle, this force can be resolved into compressive and shear components, and the respective stresses can be calculated by dividing the loads by the area of application. These compressive and shear stresses are 8.3×10^7 N/m^2 (1.2×10^4 psi) and 7.3×10^7 N/m^2 (1.06×10^4 psi), respectively.

The amount of material extruded can be calculated from the creep compliance data, the applied stresses, and the geometry of the system. The stresses are assumed to act over a washer-shaped area with 3.81 cm (1.5 in.) inside diameter and 4.21 cm (1.7 in.) outside diameter. The shear compliance, J(t), for the Kel-F at 240 hr (8.64×10^5 sec) can be obtained directly from Figure 1 (at log t = 5.937) and is 445×10^{-9} m^2/N. The compressive compliance D(t) can then be calculated from the shear compliance by $D(t) = J(t)/2\ (1 + \nu)$ where ν is Poisson's ratio. Assuming $\nu = 0.35$, a typical value for thermoplastics, the compressive compliance is estimated to be 1.65×15^9 m^2/N.

Using the data on compliances, stresses, and the system geometry, the length of the extrudate is calculated to be 0.305 cm (0.012 in.). The experimentally observed extrudate length was 0.25 cm (0.01 in.). The agreement between experimentally observed and predicted behavior is good.

<u>Teflon Valve Stem Packing Creep Prediction</u>

The Teflon valve stem packing consists of Teflon washers sandwiched between metal spacers. A nut compresses the sandwich and forces the Teflon against the valve stem to effect a seal. The load required to effect a seal will depend on the initial clearance between the Teflon washer and the valve stem, the compliance of the material, and the applied load.

To calculate the load required to effect a seal, it will be assumed that a seal occurs when the Teflon just contacts the valve stem. The radial strain required is $\ln (L/L_o) = 0.0411$, and the compressive strain is $-0.0411/0.35 = 0.1175$ where 0.35 is Poisson's ratio. The creep compliance at 10 sec (assumed time required to tighten the assembly) can be calculated from the data in Figure 2 at log t = 1. The compressive compliance is $6.9 \times 10^{-9}/2.7 = 2.55 \times 10^{-9} m^2/N$. The stress area is 0.3 cm^2 (0.0465 $in.^2$). The required load, therefore, is $P = 1.38 \times 10^3 N$ (311 lbs). This compares favorably with the experimentally observed loads of $1.34 \times 10^3 N$ (302 lbs).

The load on the Teflon washer will decrease with time due to continued deformation and stress relaxation occurring in the material. After 150 hrs, the compliance (obtained from the data in Figure 2 at log t = 5.732 and calculated as above) has increased to $3.91 \times 10^{-9} m^2/N$. The load should decrease to 902 N (203 lbs). This compares with experimentally observed valves of 852 (192 lbs).

The above examples show that the creep compliance data can be used to predict this service behavior of polymeric valve components. The accuracy, however, depends on the assumptions made in the analysis. In the cases of the valve seat and valve stem packing, the agreement is good. In other cases the deformation may not be well defined and extensive approximations will be required. The agreement in such cases may not be as good.

REFERENCE

(1) Ferry, J. D., Viscoelastic Properties of Polymers, 2nd Ed., J. Wiley and Sons (1971).

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