COMPLEX STIFFNESS TEST DATA FOR THREE VISCOELASTIC MATERIALS BY THE DIRECT COMPLEX STIFFNESS METHOD

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An integral part of the Damping and Metal Matrix for Precision Structures (DAMMPS) program involves the acquisition and dissemination of complex stiffness data for several viscoelastic material (VEM) specimens. Three such specimens have been tested by the Lockheed Missiles and Space Company, Inc. DAMMPS team: 3M Y-966, Soundcoat DYAD-606, and 3M ISD-112. These particular materials were chosen to demonstrate usable loss factor amplitudes which span the anticipated frequency and temperature range of operation for the structure studied under the contract. Future testing will characterize these and other selected specimens in more detail to provide an accurate material properties database for the detailed design task. Test data were collected very efficiently utilizing the Direct Complex Stiffness (DCS) method and manipulated/reduced using the VEMINT program. In this paper, salient aspects of the test and data reduction procedures are presented, as well as several forms of the complex modulus data.

INTRODUCTION

This paper documents the test, data reduction, and characterization of three viscoelastic materials performed under the current phase of the Damping and Metal Matrix for Precision Structures (DAMMPS) program. The three materials were 3M's Y-966, Soundcoat's DYAD-606, and 3M's ISD-112. The materials were tested using a Direct Complex Stiffness (DCS) method, and the data were reduced using a state-of-the-art characterization method. A more complete description of the test methodology, hardware, and characterization software is found in other technical papers [1,2].

The objective of the preliminary testing under this task was to screen the properties of three viscoelastic materials (VEMs) for potential incorporation into the Demonstration Structural Article (DSA) identified for study and proof-of-concept exercises in the DAMMPS program [3]. These engineering data were collected over temperature and frequency ranges particular to the expected operational environment of the structure. In general, the volume and breadth of the data obtained in this phase of testing is less than what will be produced for the next phase of the DAMMPS effort, where testing will lead to more complete characterizations, resulting in complex modulus data over broader temperature and frequency ranges.

Raw data were obtained using a testing system developed by CSA Engineering which operates on the principle of DCS measurements, a nonresonant technique. The VEM specimens were tested in shear and their properties were measured directly, not inferred indirectly, from the raw data. Although nonresonant methods place more stringent requirements on the instrumentation, it has been shown to be more accurate and versatile than the resonant testing options.

Since it is impractical to test a VEM at every combination of temperature and frequency, specimens are tested at discrete temperatures and frequencies, and a relationship is developed which characterizes the material at all other combinations of temperature and frequency. This process, referred to as characterization, was performed on the material test data by using a state-of-the-art characterization program which is currently under development. The characterization process employed the "Spline Fit of Slope" temperature shift function and the "Ratio of Factored Polynomials (Collocation)" complex modulus model [4].

DIRECT COMPLEX STIFFNESS TEST METHOD

The DCS test method, often called the impedance technique, is a nonresonant test method that uses a simple test specimen, called a lay-up, as shown in Figure 1. Transducers measure input force and the resulting displacement of the center block directly. Input and response signals are digitized and processed, usually by discrete Fourier transform methods, to obtain the impedance at the force input point. After subtracting the inertia contribution due to the known mass of the center block, this quantity is normalized by the specimen stress area and thickness to obtain the complex modulus of the VEM as a function of frequency and temperature.

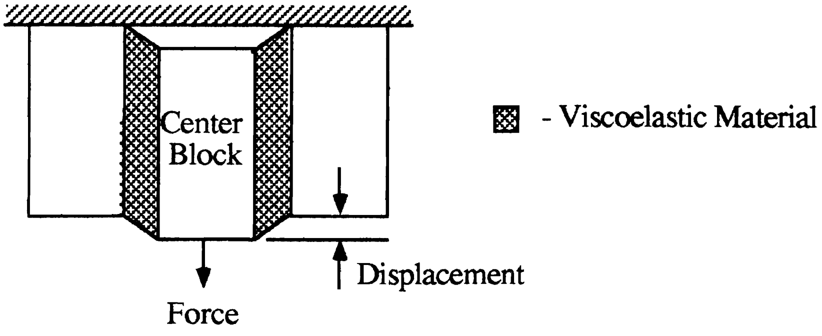

Figure 1 - Direct Complex Stiffness Testing Method

Direct stiffness methods require much care in the design of the apparatus to insure that fixture resonant frequencies are as high as possible. Likewise, operator experience is important in lay-up assembly and in interpretation of data to identify and correct any anomalies immediately. When done properly, measurements can be accurate and repeatable for frequencies from about 0.01 Hz. to an upper limit dictated by the dynamics of the fixture. Advantages with respect to speed, accuracy, temperature control, frequency range, frequency resolution, data format, and specimen generality make the direct complex stiffness technique the method of choice for most applications.

The test system used to perform the complex modulus tests described herein was designed and built by CSA Engineering. Using the principles of DCS measurements, a known dynamic force (usually a random burst) is applied in such a way that shear deformation is produced in a small VEM specimen which is held at a known temperature. The force and resulting shear are transduced, and the frequency response between input force and output displacement is calculated by means of a discrete Fourier transform. This complex function of frequency is then processed to obtain the complex shear modulus of the material.

DATA COLLECTION

A single specimen of each of the three VEMs was used to acquire the preliminary material data for each material. Since any DCS test system can accommodate only a finite range of specimen stiffnesses, each VEM specimen can only be used when the associated stiffness is compatible with the dynamic range of the machine. Accurate measurements of the complex modulus are complicated by the large changes in stiffness which occur in the transition region, since specimen stiffness varies directly with modulus. Judgement is required to estimate the room temperature modulus of each material and its approximate location within the transition regions (e.g., glassy, rubbery, or transition). For example, if a material is known to be in the rubbery region at room temperature and target frequencies, area and thickness values would be chosen to minimize specimen stiffness so that temperatures could be decreased to approach transition without exceeding the stiffness range accommodated by the test apparatus. In the worst case, extra specimens must be made to accommodate the wide stiffness variations of transition and/or inaccurate estimates of material stiffness and transition regions.

Specimen stiffness limitations are controlled by two phenomena. The upper limit for specimen stiffness on the test equipment is limited by the absence of sufficient transducer output and/or the rigidity of the test fixture. Conversely, lower stiffness limits are controlled by the increased ratio of inertia to the total force. The latter limitation occurs when the decreasing specimen stiffness causes resonant frequencies of the constant-mass center block on the VEM "spring" to shift down near the measurement band.

Nearby resonances violate the assumptions of DCS tests since force-deflection properties are determined by inertia as well as stiffness. The intent of this and any direct stiffness test is to measure the stiffness properties of a specimen, not the inertia effects produced by a nearby resonance. At some point, the analytical mass correction will not be able to nullify the increasing inertia forces. For the testing under consideration here, inertia force magnitudes were tracked and recorded during data acquisition. Unwanted or inaccurate data were purged during characterization since this process presents additional methods of error identification.

VISCOELASTIC DATA REDUCTION AND PRESENTATION

The preceding section described the test method that was used to obtain shear modulus and loss factor data at a number of temperatures and frequencies. Because of the impracticality of testing a viscoelastic material at every combination of temperature and frequency, a relationship is developed which characterizes the material at any combination of temperature and frequency. This process is referred to as characterization. The data are "shifted" using a temperature shift function and "fitted" using a complex modulus model.

For the data reduction presented in this test report, the "Spline Fit of Slope" temperature shift function (α_T) was used to reduce experimental data [4]. In this method, the slope of α_T is defined by a spline fit through "knots" at N evenly spaced temperature intervals.

Once α_T has been obtained, complex modulus (G^*) curves are superimposed upon the reduced data in the International plot. The following "Ratio of Factored Polynomials" model was used to draw these curves.

$$G^* = G_e \prod_{k=1}^{N} \frac{1 + \left(\dfrac{2\pi j f_R}{r_k/e^2}\right)^{1/2}}{1 + \left(\dfrac{2\pi j f_R}{r_k e^2}\right)^{1/2}}$$

where G^* = complex modulus,

G_e = storage modulus rubbery asymptote,

G_g = storage modulus glassy asymptote,

$f_R = \alpha_T f_i$ = reduced frequency,

r_k = breakpoint reduced frequency, and

$e = (G_g/G_e)^{\frac{1}{2N}}$

Once the material is characterized, the program provides a superset of the plots and data described in reference 5. These are listed below and presented for each of the tested materials in the following sections.

1. Plots of $\log(G^*_R(f,T))$ and $\log(\eta)$ vs. reduced frequency with constant temperature lines and an experimental frequency axis (International plot) in both English and S.I. units,
2. Plots of $\log(\eta)$ vs. $\log(G^*_R(f,T))$ (Wicket plot) in English and S.I. units,
3. A plot of $\log(\alpha_T)$, $d(\log(\alpha_T))/dT$, and apparent activation energy vs. temperature,
4. Plots of log(frequency) vs. temperature in English and S.I. units,
5. A plot of $\log(G^*_R(f,T))$ and $\log(\eta)$ vs. temperature, and
6. An updated tabulated data file.

3M ISD-112 CHARACTERIZATION DATA

This material is an acrylic pressure sensitive adhesive, not marketed as a stand-alone damping material. It is generally sold as a part of a final 3M-designed damping solution. The test specimen was obtained from Lockheed Missiles & Space Company, Inc., Space Systems Division, identified by the manufacturer as 2105 NVB TYPE 1205 on the packing slip and 2105 1NVB964A3618 (label affixed to the roll itself). Prior to testing, the material was exposed to approximately 40% relative humidity (RH) at 75°F for one month. This environment also represents ambient test conditions. (Published information indicates a one year shelf-life at 50% RH and 70°F.) Since the test specimen was only 0.005 in. thick, special care was taken to ensure that the bonding substrates associated with the test fixture were flat to within 0.001 in. over the entire specimen area. The surfaces were then degreased with a solvent (e.g., trichloroethane or toluene). The test specimen was constructed by bonding the material between aluminum blocks at 75°F with a pressure of between 2 to 5 psi, applied for only a few seconds, since bonding occurred instantaneously. An initial specimen was constructed with area and thickness of 0.99 in^2 and 0.0113 in., respectively. Handling may have damaged the article since it was too compliant, necessitating the construction of a second specimen with an area of 6.00 in^2 and thickness of 0.0105 in. Only data from the second article are presented in this report. This second series of tests commenced at CSA Engineering on October 1, 1990, using a proprietary DCS method test system coupled with a Zonic 6080/6081 FFT Analyzer. Although a strain linearity check was not performed, strain levels during testing were maintained at approximately 2% and the maximum loss factor observed was 1.25 (32°F < T < 96°F - eight discrete values, and 0.9 Hz. < f < 1000 Hz.). Figures 2 - 6 provide final detailed characterization data.

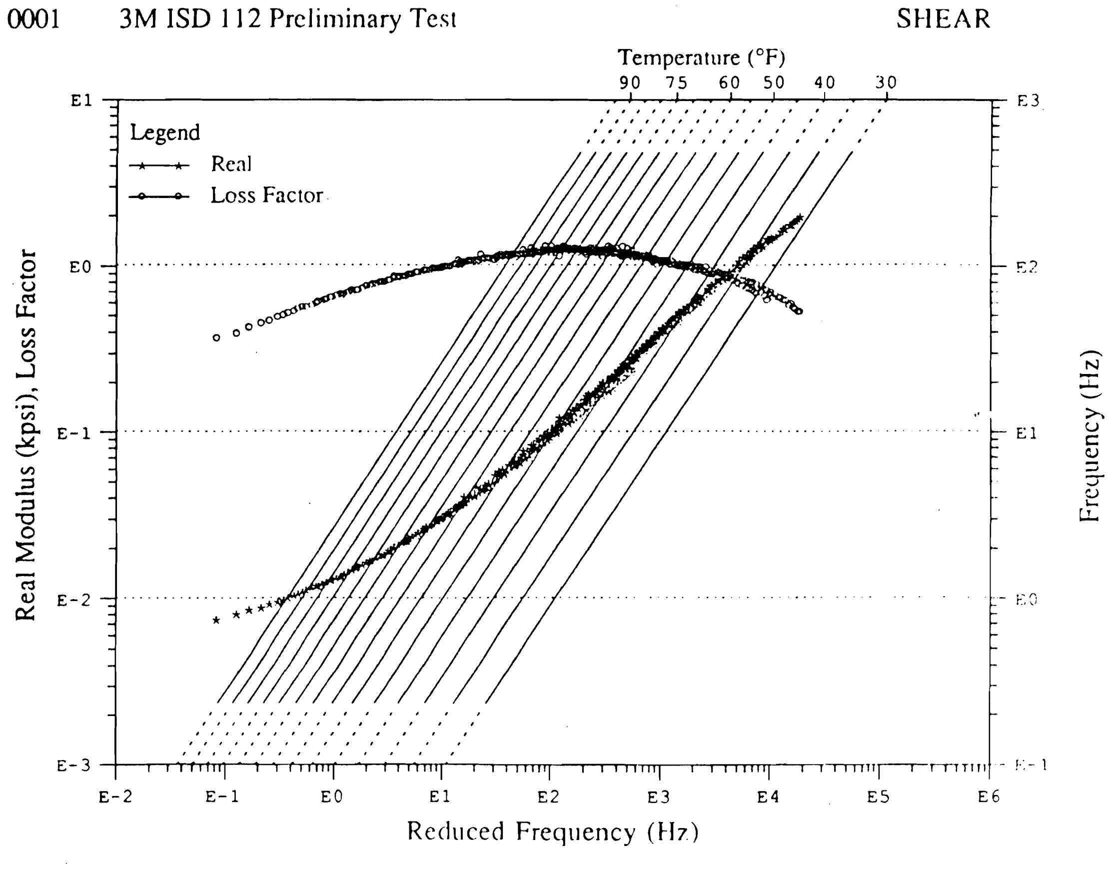

Figure 2. International plot for 3M ISD-112 (English units)

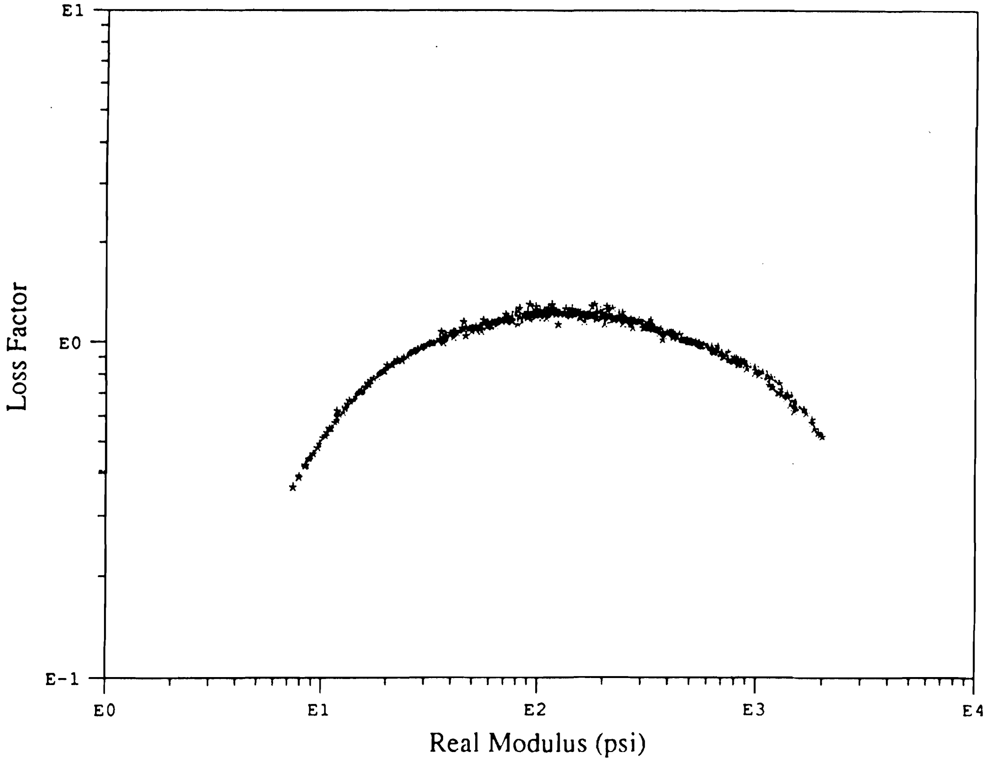

Figure 3. Wicket plot for 3M ISD-112 (English units)

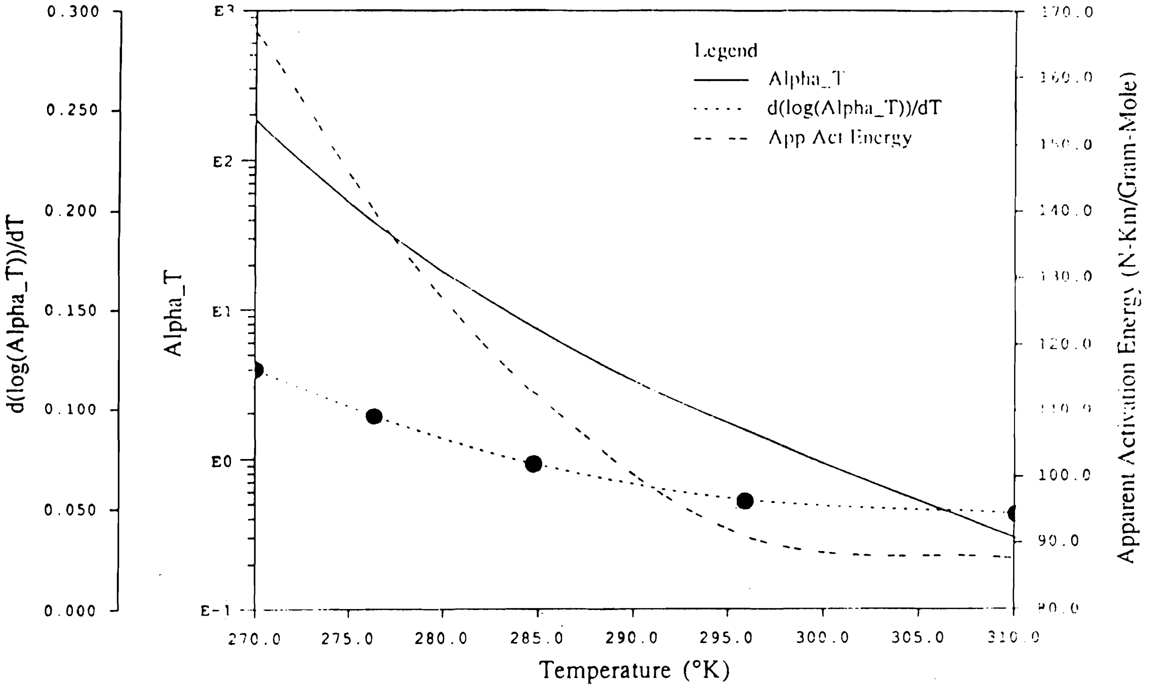

Figure 4. Log(α_T), d(log(α_T))/dT, and apparent activation energy vs. temperature for 3M ISD-112

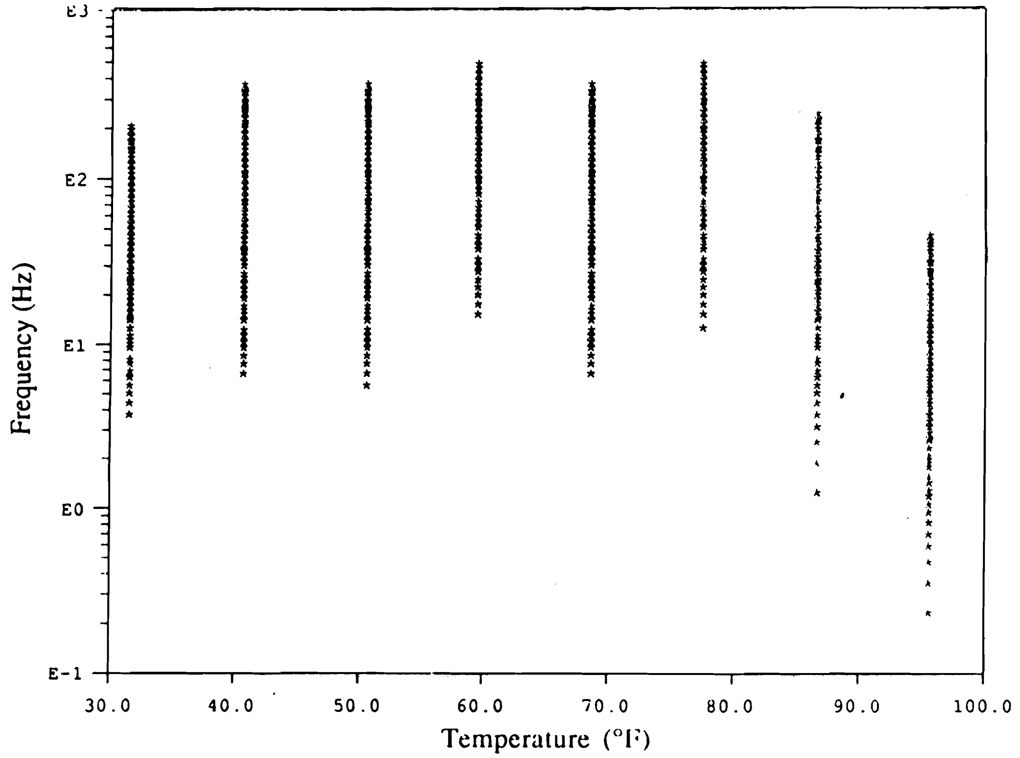

Figure 5. Log(frequency) vs. temperature for 3M ISD-112 (English units)

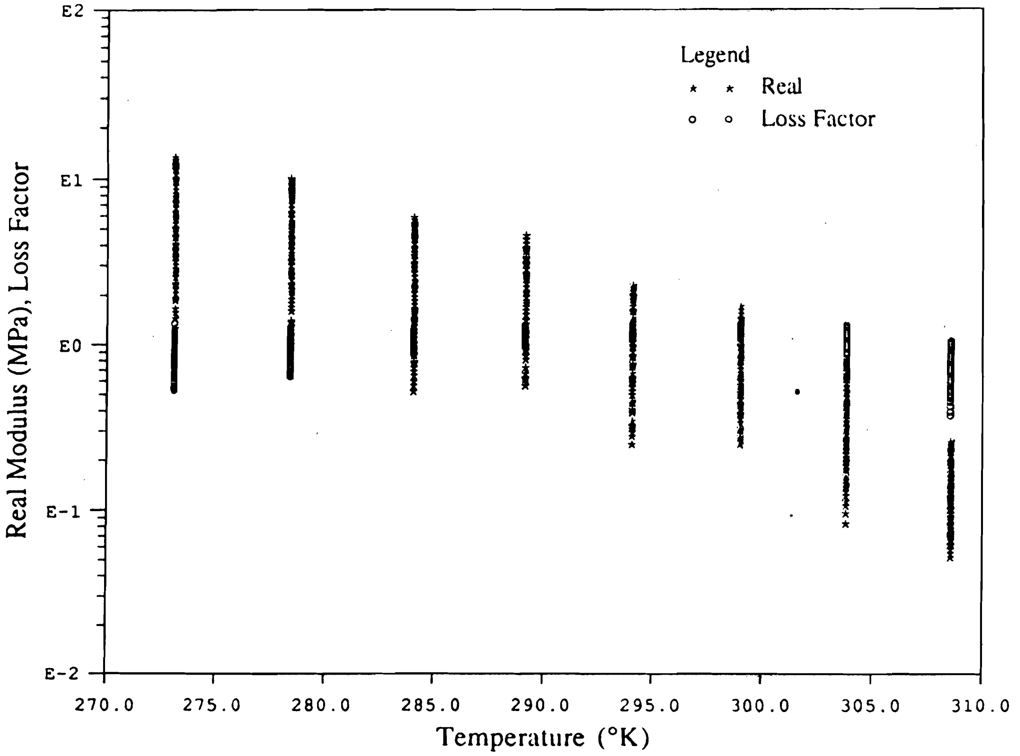

Figure 6. log($G^*_R(f,T)$) and log(η) vs. temperature for 3M ISD-112 (S.I. units)

3M Y-966 CHARACTERIZATION DATA

This material is also an acrylic pressure sensitive adhesive, obtained from the sales office of R.S. Hughes, Sunnyvale, CA. The ambient test environment and published shelf-life is identical to that of ISD-112. Since this test specimen was also very thin, similar precautions were exercised to ensure the flatness of the bonding substrates. The surfaces were degreased with a solvent, and the material was bonded to the fixture blocks. This material is generally sold with a nominal thickness of 0.002 in. To decrease the stiffness of the layup (and thus extend the upper end of measurable frequencies), the VEM was doubled to obtain a thickness of 0.0046 in. The total VEM area was 2.32 in^2. Testing was performed on September 25, 1990, using the fixturing and data acquisition system described above. Strain levels during this battery of tests were maintained at approximately 5% and the maximum loss factor observed was 1.27 (59°F < T < 113°F - eight discrete values, and 0.1 Hz. < f < 1000 Hz.). Figures 7 - 11 provide final detailed characterization data.

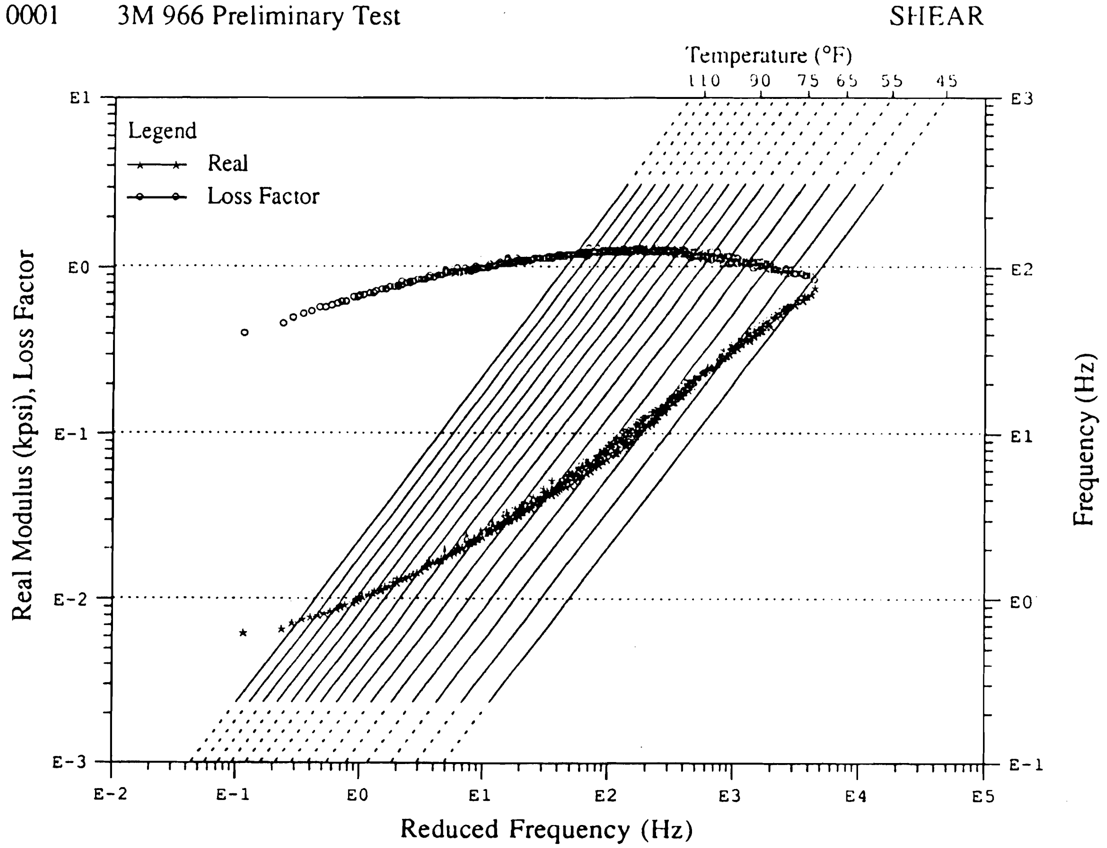

Figure 7. International plot for 3M Y-966 (English units)

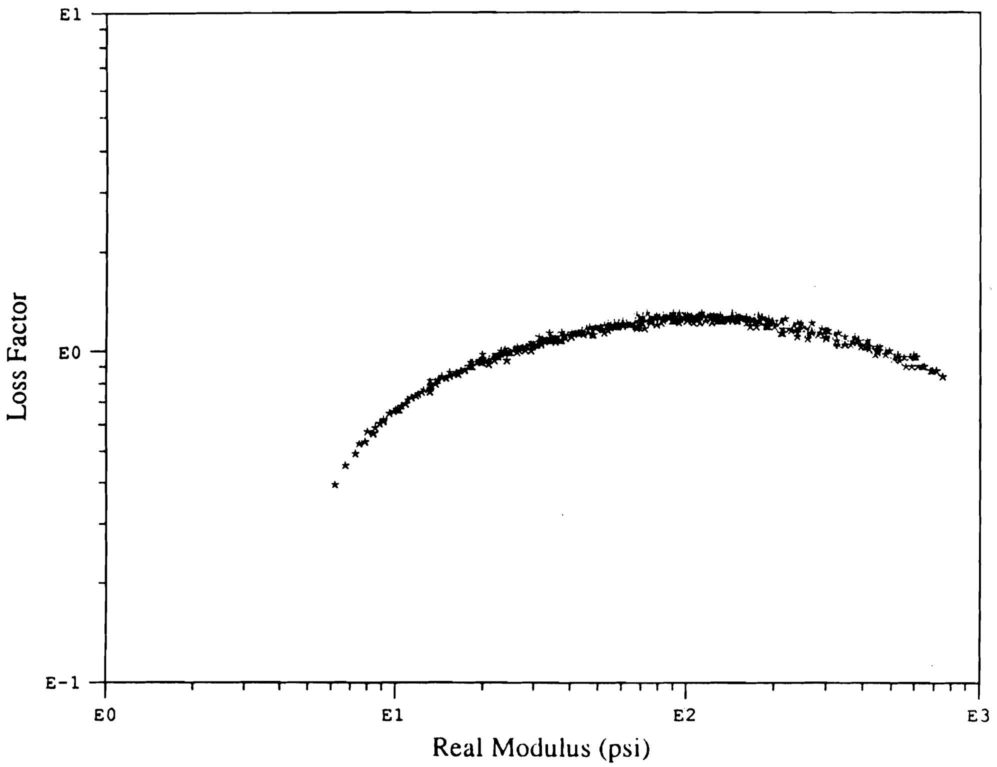

Figure 8. Wicket plot for 3M Y-966 (English units)

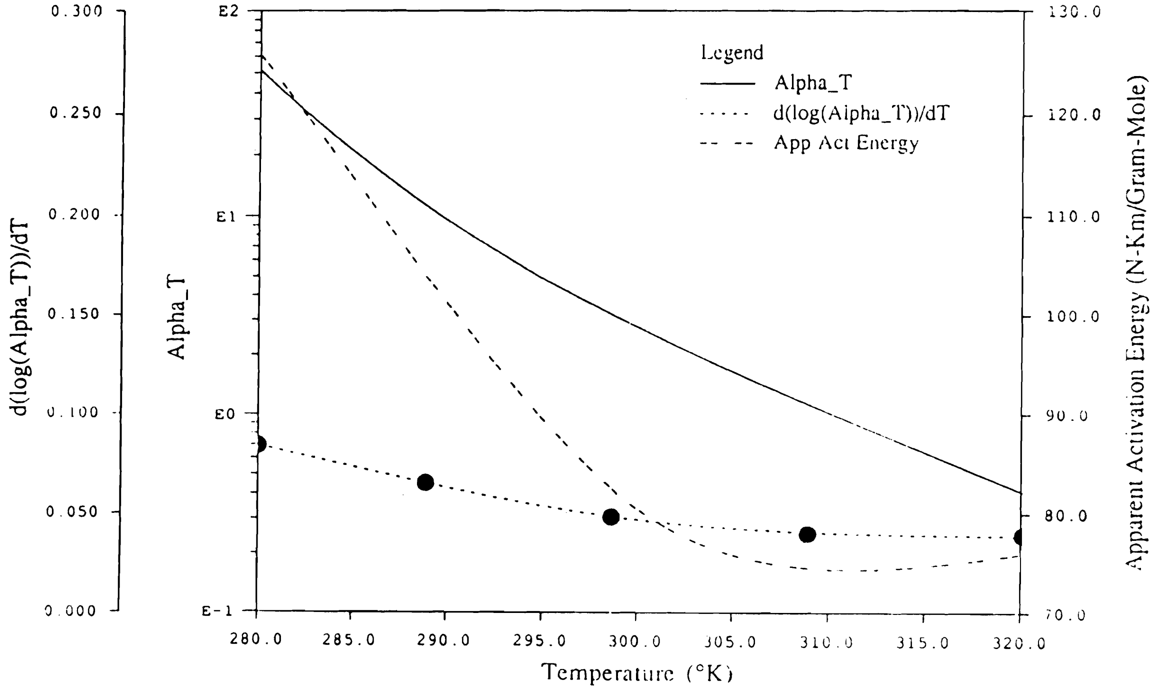

Figure 9. Log(α_T), d(log(α_T))/dT, and apparent activation energy vs. temperature for 3M Y-966

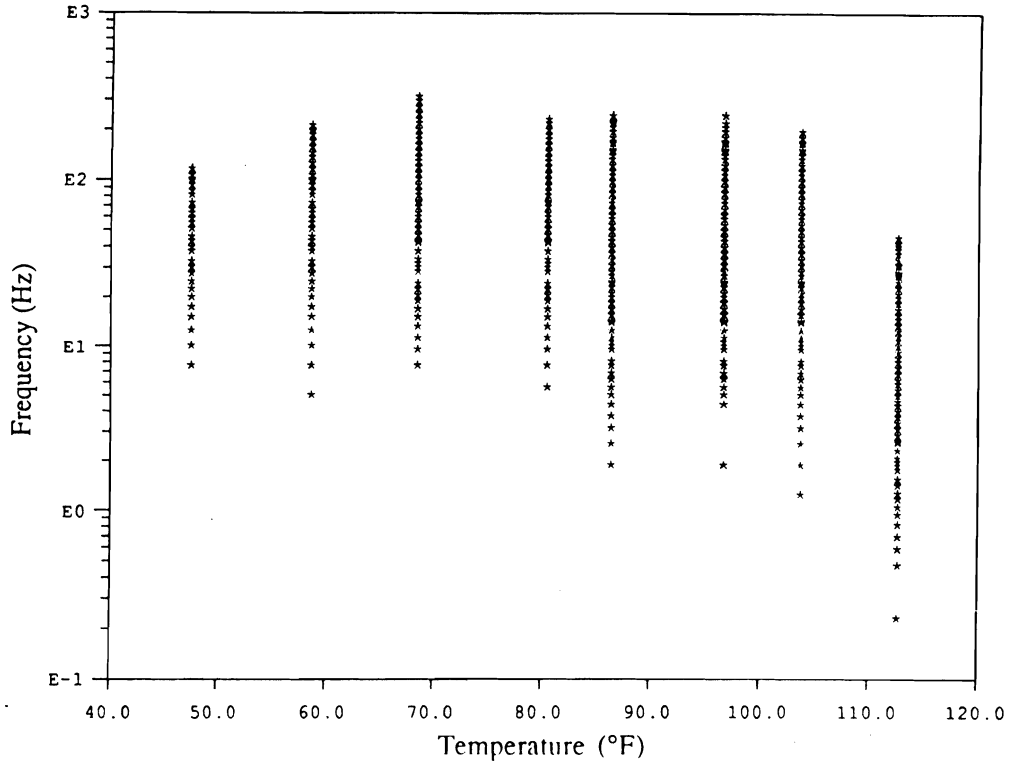

Figure 10. Log(frequency) vs. temperature for 3M Y-966 (English units)

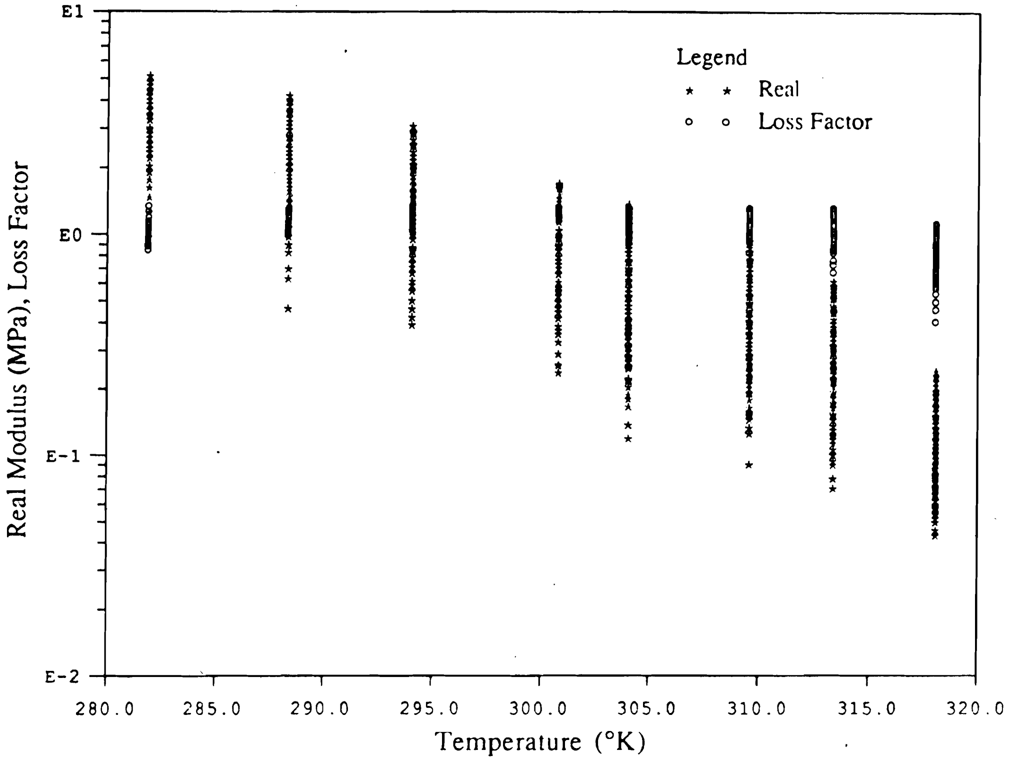

Figure 11. log($G^*_R(f,T)$) and log(η) vs. temperature for 3M Y-966 (S.I. units)

SOUNDCOAT DYAD-606 CHARACTERIZATION DATA

The third material test was performed on DYAD-606, a polyurethane manufactured by Soundcoat and obtained directly from their sales office in Santa Ana, CA. It is sold pre-cast in sheet form specifically for vibration damping applications. The test specimen was constructed by bonding the material to degreased aluminum blocks with 3M-1838 epoxy, which was allowed to cure at 75°F for two days. The final specimen area was 3.76 in^2 with a thickness was 0.050 in. Testing was performed on October 2, 1990, utilizing the fixturing and data acquisition system as before. Strain levels during this battery of tests were maintained at approximately 0.4% and the maximum loss factor observed was 1.06 (80°F < T < 126°F - six discrete values, and 0.2 Hz. < f < 1000 Hz.). Figures 12 - 16 provide final detailed characterization data.

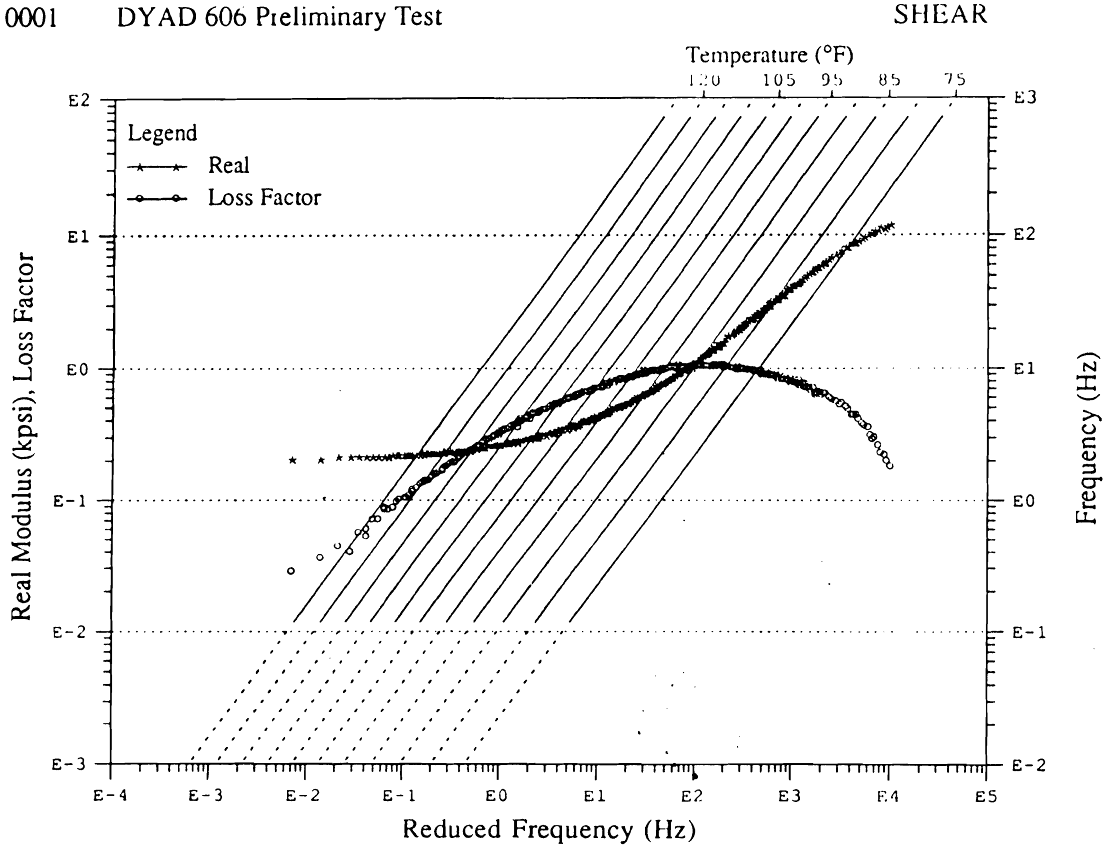

Figure 12. International plot for DYAD 606 (English units)

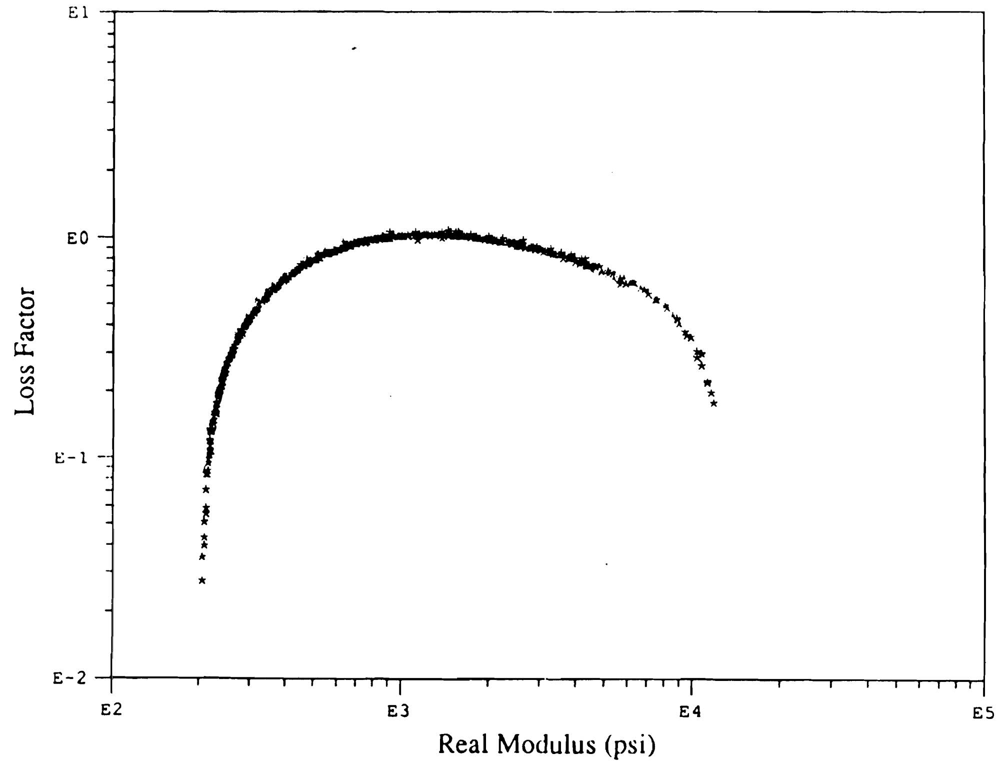

Figure 13. Wicket plot for DYAD 606 (English units)

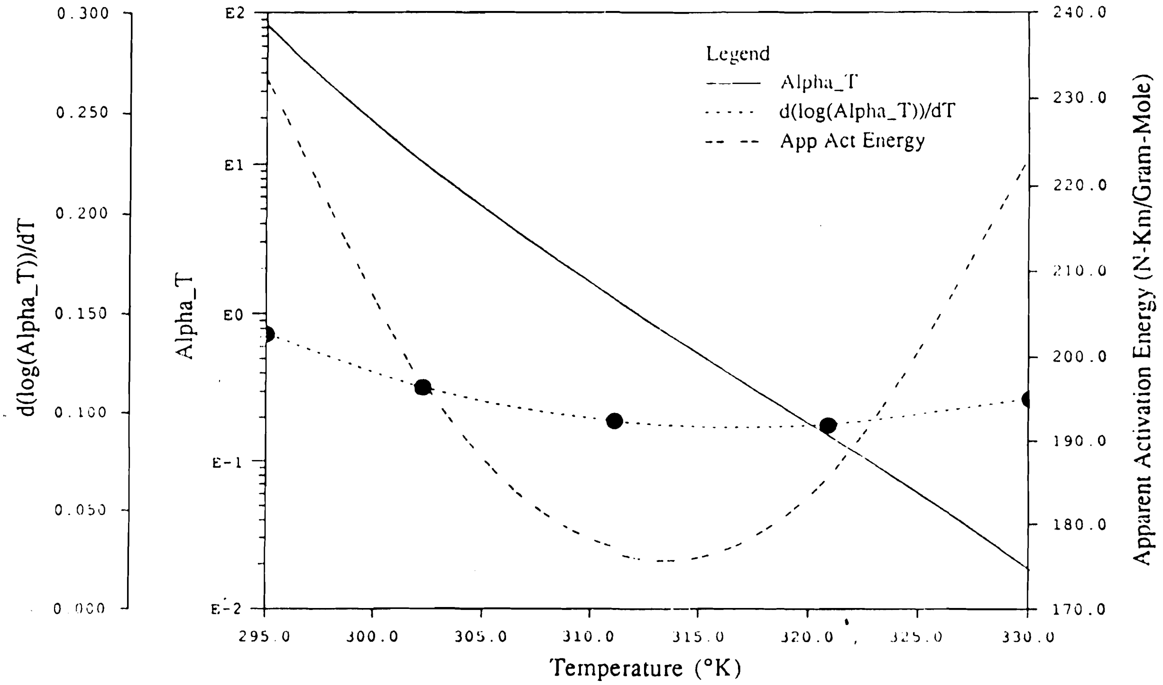

Figure 14. Log(α_T), d(log(α_T))/dT, and apparent activation energy vs. temperature for DYAD 606

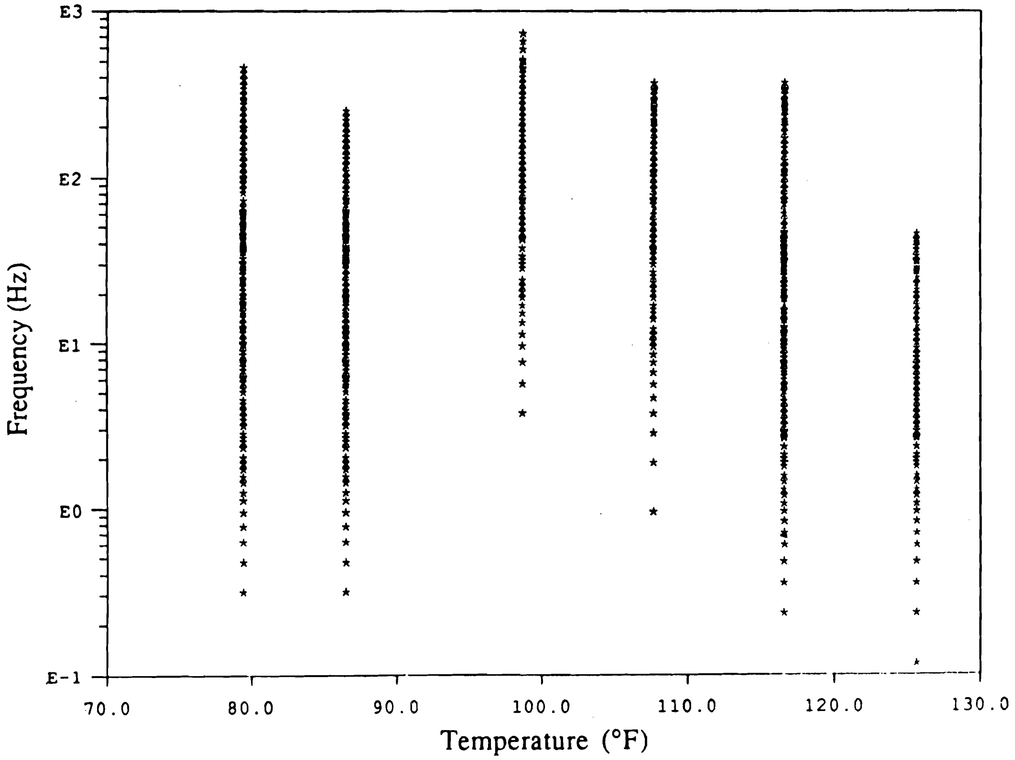

Figure 15. Log(frequency) vs. temperature for DYAD 606 (English units)

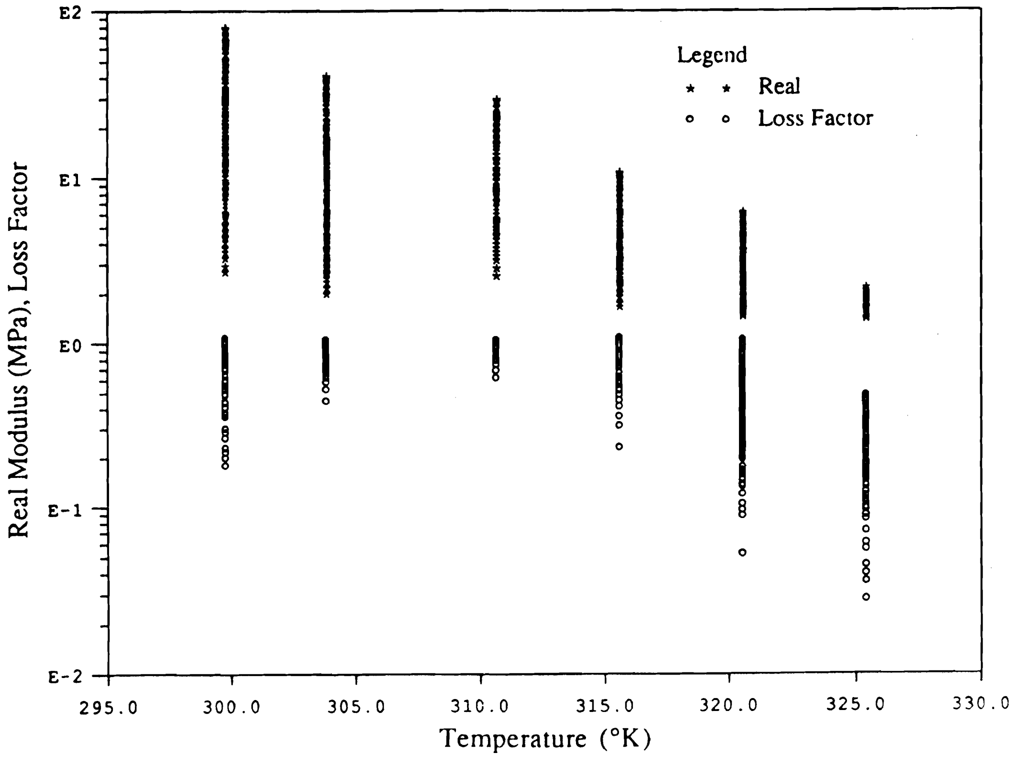

Figure 16. log($G^*_R(f,T)$) and log(η) vs. temperature for DYAD 606 (S.I. units)

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