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Ultrasonic Longitudinal Wave Velocity in Carbon-Carbon Pitch and Pitch/M2 Shape Stable Nosetip Material from 70°F to 5400°F

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Sandia National Laboratories
Albuquerque, New Mexico 87185 and Livermore, California 94550
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Ultrasonic Longitudinal Wave Velocity in Carbon-Carbon Pitch
and Pitch/M2 Shape Stable Nosetip Material
from 70° F to 5400° F (U)

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ABSTRACT

A pulse echo method was used in two notched rods of carbon-carbon Pitch material and one rod of Pitch/M2 shape stable nosetip material to measure the temperature dependence of the longitudinal wave velocity from room temperature to 5400° F. The velocity was constant to within 2% of the room temperature value for the Pitch parent material throughout the temperature range. For the Pitch/M2 material, the velocity increased to a maximum of 10% at 4000° F and then decreased rapidly. Room temperature velocities in the principal directions of the composite are also given for the two Pitch rods, which showed a 15% decrease in velocity near the ends of both rods and near the side of one rod.

MASTER

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ULTRASONIC LONGITUDINAL WAVE VELOCITY IN CARBON-CARBON PITCH
AND PITCH/M2 SHAPE STABLE NOSETIP MATERIAL
FROM 70°F TO 5400°F

Introduction

This work was requested by Lockheed Missiles & Space Company, Inc., in order to provide temperature dependent ultrasonic velocity data needed in use of the Ultrasonic Ablation Detector (UAD). The UAD is to be used to measure in-flight recession of the Shape Stable Nosetip (SSNT) on the DASO and the MK5 Flight Vehicle. The UAD provides measurements of recession at a given instant by recording the round trip delay time of an ultrasonic wave to traverse the length of the nosetip. Current nosetip length at that instant is determined by multiplying the known ultrasonic wave velocity by half the round trip delay time. In order to make the most accurate nosetip length measurements as the nosetip material heats up upon reentry, the ultrasonic wave velocity must also be known as a function of temperature. The temperature dependence of the ultrasonic longitudinal wave velocity in C/C Pitch parent material and in Pitch/M2 core material is presented here from 70°F to 5400°F.

The ultrasonic velocity versus temperature measurements were made with three separate 0.75 inch diameter rods which were machined from the full length Billet #8, PN 9139. One

rod, designated as ROD #2, contained the Pitch/M2 core material of 0.675 inch diameter along the center axis of the rod. The other two rods, designated as ROD #1 and ROD #3, consisted solely of the C/C Pitch parent material.

During the performance of these tests, it was determined that ROD #1 and ROD #3 were not uniform in material properties, and there were differences in the ultrasonic velocity from end to end as well as from side to side in both rods. These differences were extensively investigated in order to explain the temperature dependence variations between the two rods. The variations are shown to be due to the material property differences of the two rods and not due to errors in the measurement technique of the velocities. It is known that one of the rods was taken from the corner of the billet and the other rod was taken from near the side of the billet. The specific identity of each rod is otherwise lost.

Comparative ultrasonic velocity measurements taken at different locations along the length of the same rod changed by as much as 15%. Both rods exhibited these changes from end to end, but only ROD #3 varied significantly from side to side, i.e., along the diameter of the rod. These measurements showed that a significant edge effect of material properties existed in the original billet. However, the velocity values of ROD #1 were uniform throughout the indexed section of the rod which was used for the temperature measurements. Therefore, the temperature data of ROD #1 are representative of the Pitch parent material, but the temperature data of ROD #3 were influenced by the variation of the Pitch material properties in the transverse direction of that rod.

Experimental Methods

The ultrasonic velocity measurements versus temperature were made in the same way as described previously^{1,2}. The method uses the pulse echo technique, where an ultrasonic transducer is coupled to one end of an indexed rod. The indexed end of the rod is placed in the hot zone of a furnace and the transducer end of the rod is threaded into a watered-cooled brass holder to prevent excessive heating of the transducer during the test.

The indexed section of the rod is made by milling a right- cornered slot or notch into the side of the rod until a sufficient echo amplitude of the milled notch is present in the pulse echo wave trace. An indexed length from the notch to the end of the rod of 2.0 inches was provided in ROD #1 and ROD #3, and an indexed length of 1.5 inch was provided in ROD #2. The depth of the milled notch was kept at a minimum in order to reduce interference of the pulse echo reflection of the notch with that of the end of the rod.

The data from room temperature to 5400°F was obtained in two stages. First, the rod was placed into a nickel-chromium resistance wire element furnace where the temperature was recorded using a chromel-alumel thermocouple. The temperature was increased in approximately 125 degree increments between data points, from room temperature up to about 1100°F. The rod was then cooled to room temperature and placed in the high temperature furnace where the temperature was recorded using an optical pyrometer. Data was taken at approximately 125

degree increments from 1250°F to 1800°F and then in 400°F increments up to 5400°F. The optical pyrometer reading was corrected to an observed temperature value by adding the calibration correction of the pyrometer (calibrated on 11/7/84) plus the quartz window correction of the furnace to the pyrometer reading.

The ultrasonic velocity in the rod material is calculated at each temperature point by measuring the delay time difference between the correct pair of echo peaks from the notch and the end of the rod. The velocity is given by

$$V = \frac{2 L}{t} \quad (1)$$

where t is the measured delay time and L is the indexed length of the rod from the notch to the end of the rod. The length L at temperature is calculated by correcting the indexed length L_0 for thermal expansion. Data on the thermal expansion was supplied by Lockheed for the Z direction of the rod for both the Pitch and the Pitch/M2 material. A least squares polynomial fit of the thermal expansion data from billet #8060 was used for the calculations. For the Pitch material the following was used,

$$\begin{aligned} (L-L_0)/L_0 = & 0.0319724 \times 10^{-3} - 0.0904352 \times 10^{-5} T \\ & + 8.63546 \times 10^{-10} T^2 - 1.94355 \times 10^{-13} T^3 \\ & + 1.95864 \times 10^{-17} T^4 \end{aligned} \quad (2a)$$

and for the Pitch/M2 material the following was used

$$\begin{aligned}(L-L_0)/L_0 = & - 0.0770611 \times 10^{-3} + 0.12929 \times 10^{-5} T \\ & - 0.0250908 \times 10^{-8} T^2 + 1.95546 \times 10^{-12} T^3 \\ & - 5.29327 \times 10^{-16} T^4 + 4.84666 \times 10^{-20} T^5\end{aligned}\tag{2b}$$

where T is in degrees Fahrenheit.

The delay time measurement between the pair of echoes from the notch and the end of the rod was determined with the apparatus shown schematically in Figure 1. The ultrasonic waveform, including the pair of echoes of interest, was recorded independently by the boxcar integrator/x-y plotter system and by the Biomation/PDP 11/34 computer system. The x axis of the plotter in the boxcar integrator system was calibrated at one microsecond per centimeter, using the calibrated time mark generator as the reference source. The waveforms were digitized with the Biomation transient digitizer using a 0.05 microsecond sample interval.

An improved transducer pulsing technique (not used previously) was employed for these tests. The present pulsing technique allows excitation of the transducer with integral cycles of a pure sine wave at a set frequency. This allows efficient power input near the resonant frequency of the transducer, as well as a means of measuring the velocity in the dispersive material at a set frequency. For all the temperature dependent velocity measurements, the pulser was set to a frequency of 200 or 300 KHz with a pulse length of one cycle. The transducer used in the temperature tests was a

one-inch diameter, highly-damped, wide-band 500 KHz transducer.

The ultrasonic waveform at each temperature point was recorded on the x-y plotter and also digitized with the Biomation PDP 11/34 computer system. After completion of the test, a delay time measurement and the relative shift in delay time from the room temperature value was calculated from each waveform using a pair of echo peaks, one from the notch echo and another from the rod end echo. The relative shift in the delay time from the room temperature value was then used to calculate the correct delay time t at the given temperature which was used in Equation (1).

Preparation of the Test Specimens and Recorded Temperature Data

The procedure for preparing the rod specimens and measuring the temperature dependence of the ultrasonic velocity was identical for all three rods. Preliminary longitudinal pulse echo velocity determinations were made on the rods before the notches were machined in the rods. The frequency of the applied pulse was varied, and round trip delay time measurements were made to determine the room temperature velocity of the rod material, as well as check for optimum echo waveforms which could be used to make the temperature tests. Optimum waveforms were obtained when the frequency was set between 150 KHz to 300 KHz.

When the optimum waveform of the rod end reflection was obtained, an indexed length for machining the notch was

decided upon from the room temperature velocity value and the wave packet length of the rod end echo. The indexed length must be long enough so that excessive interference between the notch echo and the end echo is avoided, but it must be short enough so that the indexed length is well within the hot zone of the furnace. For the Pitch material and the Pitch/M2 material, indexed lengths of 2.0 and 1.5 inches respectively, met these requirements.

The rod with the transducer still attached was then mounted into the vice of a small milling machine. A notch was machined at the indexed length just deep enough so that the notch echo appearing in the waveform was distinct and of sufficient amplitude to be tracked during the temperature tests. After the milling process, the notched rod was placed into the furnace and the temperature tests were conducted.

The x-y plots of the initial pulse echo waveforms of the rod end reflections versus frequency, the sequential waveforms of the milling process, and the waveforms of the low and high temperature tests are all shown in Appendices A, B and C for ROD #1, ROD #2 and ROD #3 respectively.

Plots of the digitized waveforms, along with the measured relative shift of the notch echo and the rod end echo from the room temperature delay time value, are shown in Figures 2 through 6 for the three rods. The high-temperature, digitized data for ROD #1 is not included in these figures because an unexpected electrical interference problem existed between the Biomation digitizer and the high-temperature furnace controller. This problem was solved in subsequent high

temperature tests by momentarily turning off the furnace while the waveform was being digitized.

Temperature Test Results

The temperature data of the ultrasonic velocity as determined from the waveforms of the Appendices and Figures 2 through 6 are shown in Tables I, II, and III for the three rods. The normalized velocity value at each temperature is also given in the Tables where the room temperature velocity value for each rod was taken as the normalizing velocity. Table I contains data obtained with ROD #1 for a low temperature test at 200 KHz, a high-temperature test at 200 KHz, and second low-temperature test at 300 KHz. The second low-temperature test was conducted to check the system for errors, as well as confirm that the temperature dependence of the data of ROD #1 was slightly different from that of ROD #3.

Plots of the normalized velocity versus temperature for all the data in the Tables are shown in Figures 7, 8, and 9 for the three rods. As seen from Figures 7 and 9, a difference in the temperature dependence of ROD #1 and ROD #3 is observed, even though the rods are of the same parent material. Inconsistent room temperature values of ROD #3 between the pulse echo end reflection velocity (8.89 mm/microsecond), with the indexed length velocity value (9.83 mm/microsecond), indicated that this rod was not uniform in properties from end to end. In order to show that ROD #3 was anomalous and that the data of ROD #1 was representative of the Pitch parent material, an extensive study of the velocity variations in these two rods was undertaken.

Material Property Variations of ROD #1 and ROD #3

After all temperature tests were completed, ROD #1 and ROD #3 were machined with flat surfaces perpendicular to the X-direction of the C/C composite along the full length of the rods. This provided a constant thickness in the X- direction of the rod, through which ultrasonic through-transmission velocities could be determined at positions along the length of the rod.

Through-transmission delay time measurements were accomplished at locations along the rods using a pair of 500 KHz 0.25-inch diameter transducers and the Biomation/PDP 11/34 system. The waveforms of the 1st half cycle of the through-transmission pulse were recorded at 0.01 microsecond per sample interval, and the delay time of the peak was used for the velocity calculations. The waveforms recorded in the X-direction of the two rods, with an applied single cycle 300 KHz pulse as the transducers were moved along the length of the rod, are shown in Figures 10 and 11. The delay time measurement at each position is also listed in the Figures. The ultrasonic velocity calculated at each position along the rod is plotted in Figure 12 for both ROD #1 and ROD #3.

From Figure 12, the velocity in the X-direction is seen to decrease by 15% near each end of the rod. ROD #3 shows a larger change for the velocity in the indexed end of the rod than ROD #1. But this difference does not explain the apparent faster velocity in the Z-direction for the indexed region of ROD #3 as measured in Appendix C.

To investigate the material property differences further, the rods were also machined with flat surfaces perpendicular to the Y-direction of the composite. The through-transmission velocity values obtained in the indexed region of each rod using a 500 KHz applied pulse are shown in Figure 13. A 500 KHz applied pulse was used because it provided slightly more resolution of the peak than the 300 KHz pulse. A slightly higher velocity value was obtained at 500 KHz than at 300 KHz at the same location indicating the dispersion characteristics of the composite. In Figure 13, the velocities in the Y-direction on the notched side of ROD #3 are about 10% lower than they are in the other portions of the rod. ROD #1 is fairly uniform in this respect.

The lower velocities of ROD #3, as shown in Figure 13, imply that the velocity in the Z-direction may also be low at the notched side of the rod. To confirm this supposition, ROD #1 and ROD #3 were cut into three pieces with parallel faces machined perpendicular to the Z-direction of the rod. One piece contained the indexed top region of the rod and was about 1.7 inches long. The second piece of about 1.7 inch length was taken from the middle of the rod just below the notch of each rod. The third piece consisted of the bottom half of each rod, which was approximately 5.3 inches long. Accurate through-transmission velocity measurements at 500 KHz applied pulse were taken along the Z-direction of each piece at various axial locations. The results of these measurements are also shown in Figure 13.

From Figure 13, it is clearly shown that the material on the notch side of ROD #3 has a significantly lower velocity than the other portion of the rod. In comparison, the

velocities measured on ROD #1 are rather uniform from one side of the rod to the other. The slower velocity value measured on the notch side of ROD #3 is in agreement with the apparent fast velocity value of the indexed length as measured in Appendix C. As seen in Appendix C during the milling of the notch of ROD #3, the rod end reflection echo shifted by -1.3 microseconds. No shift of the end reflection echo is expected if the material in the rod is uniform from one side of the rod to the other side.

The -1.3 microsecond shift is explained by noting that the end reflection echo is a mixture of fast and slow velocity echoes with the slow velocity echo predominating. Then, by milling the notch, a large portion of the slow velocity end echo is being blocked and the fast velocity end echo becomes dominant. The notch echo is still from the slow velocity material, but the end echo is that of the fast velocity material; therefore, the calculation of the velocity in the indexed region of ROD #3 is not correct by using the delay time measurement between the notch echo and the end echo.

There is also evidence of a mixture of two echoes present in the end echo of ROD #3, which was observed during the high-temperature test illustrated in Figure 6. In this test from about 900°C to 3000°C, a confusion of double echo peaks appeared in the end reflection echo as if one set of echo peaks was moving from right to left through a second stationary set of echo peaks as a function of temperature. Waveforms were also taken in this test on decreasing temperature, which are displayed in Appendix C, where they show that the separation and merging of the double peaks was reversible. Although the delay time data for ROD #3 was

processed by tracking the notch echo peaks with the second rather stationary end echo peaks as well as possible, and the results are presented in this report, it is concluded that judging from the nonuniformity of material properties of ROD #3 from side to side, it is not representative of the interior Pitch parent material of a normal shape stable billet.

Measurement Errors

The delay time measurements at each temperature were made to ± 0.1 microsecond. This represents an error of approximately 1% for the velocity of the Pitch parent material and about a 0.5% for the velocity of the Pitch/M2 material. The temperature readings are estimated to be within 1% or better. A room temperature delay time measurement was taken before and after each temperature test, and the maximum shift recorded was 0.15 microseconds for the second low temperature test of ROD #1. Therefore, the maximum systematic error due to drift of the electronic equipment was no greater than 1.3%.

Summary and Conclusions

The longitudinal velocity was determined for Pitch parent material and Pitch/M2 material from 70°F to 5500°F. The velocity in the Pitch parent material was constant from room temperature to 5000°F, where a slight increase in velocity occurred. The velocity in the Pitch/M2 material was constant from room temperature to 1500°F, where it increased to a maximum at 4000°F, and then decreased rapidly for higher

temperatures. The maximum temperature for which the velocity in the Pitch/M2 material could be measured was about 4900°F, where the M2 material changed phase which prevented any additional measurements to be made.

Two rods of the Pitch parent material from the same billet displayed slightly different temperature dependence of the velocity. A thorough investigation of the velocity in the major axes of the rods, showed that the billet from which the rods were machined contained material property differences at the edges of the billet, which resulted in a 15% decrease in the ultrasonic velocity. The temperature dependence of the velocity for one of these rods was influenced by this material property difference.

References

1. J. H. Gieske, "Ultrasonic Shear and Longitudinal Wave Velocities in CMT Graphite and Carbon-Carbon (226) From 70[°] F to 5400[°] F," SAND76-0434, Sandia Laboratories, Albuquerque, New Mexico, April 1977.
2. J. H. Gieske, "Ultrasonic Shear Wave Velocity in CLF/CMT Graphite from Room Temperature to 2000[°] F," SAND80-1850, Sandia National Laboratories, Albuquerque, New Mexico, November 1980.

Figure 1. Schematic Diagram of Electronics to Record Pulse Echo Waveforms with the Analog System and the Digital System.

FIGURE 2 - DIGITIZED WAVEFORMS OF NOTCH ECHO AND END ECHO VERSUS TEMPERATURE FOR THE LOW TEMPERATURE TEST #2 OF ROD #1

FIGURE 3 - DIGITIZED WAVEFORMS OF NOTCH ECHO AND END ECHO VERSUS TEMPERATURE FOR THE LOW TEMPERATURE TEST OF ROD #2

FIGURE 4 - DIGITIZED WAVEFORMS OF NOTCH ECHO AND END ECHO VERSUS TEMPERATURE FOR THE HIGH TEMPERATURE TEST OF ROD #2

FIGURE 5 - DIGITIZED WAVEFORMS OF NOTCH ECHO AND END ECHO VERSUS TEMPERATURE FOR THE LOW TEMPERATURE TEST OF ROD #3

FIGURE 6 - DIGITIZED WAVEFORMS OF NOTCH ECHO AND END ECHO VERSUS TEMPERATURE FOR THE HIGH TEMPERATURE TEST OF ROD #3

FIGURE 7 - NORMALIZED LONGITUDINAL VELOCITY VERSUS TEMPERATURE
FOR ROD #1, $V_0 = 8.796$ mm/MICROSECOND

FIGURE 8 - NORMALIZED LONGITUDINAL VELOCITY VERSUS TEMPERATURE
FOR ROD #2, $V_0 = 4.187$ mm/MICROSECOND

FIGURE 9 - NORMALIZED LONGITUDINAL VELOCITY VERSUS TEMPERATURE
FOR ROD #3, $V_0 = 9.63$ mm/MICROSECOND

FIGURE 10 - THROUGH TRANSMISSION WAVEFORMS AND DELAY TIMES IN THE X-DIRECTION OF ROD #1 AT AXIAL LOCATIONS ALONG THE ROD. X DIMENSION EQUALS 0.625 INCHES.

FIGURE 11 - THROUGH TRANSMISSION WAVEFORMS AND DELAY TIMES IN THE X-DIRECTION OF ROD #3 AT AXIAL LOCATIONS ALONG THE ROD. X DIMENSION EQUALS 0.583 INCHES.

FIGURE 12 - VARIATION OF LONGITUDINAL VELOCITY IN THE X-DIRECTION OF THE COMPOSITE ALONG THE LENGTH OF ROD #1 and ROD #3

ROD #1

ROD #3

9.05	8.92	9.17
9.17	9.30	9.43
9.17	9.30	9.37
9.37	9.30	9.30

7.29	7.76	7.44
9.35	9.35	7.67
9.35	9.59	7.44
9.35	9.47	8.30

Y-DIRECTION

Notch

Notch

Velocity Values in mm/microsecond

Z-DIRECTION

9.66	9.57	9.49
9.37	9.65	9.37
9.33	9.41	9.21

Notch
Side

9.39	9.71	9.04
9.39	10.0	9.23
9.27	9.47	9.00

Notch
Side

Top of Rod

9.43	9.72	9.39
9.72	9.81	9.72
9.35	9.55	9.59

Middle of Rod

9.45	9.80	8.97
9.58	10.1	9.22
9.45	9.67	9.16

Bottom of Rod

9.40		
9.27	9.27	9.27
9.27		

9.29
9.42 9.55 9.04
9.35

Figure 13. Longitudinal Velocity Determinations at Various Locations in the Y-Direction and Z-Direction for ROD #1 and ROD#3.

TABLE I

Longitudinal Velocity Temperature Data for ROD #1 Pitch Parent Material

Corrected Temperature (°C)	Corrected Temperature (°F)	Corrected Index length, 2L (mm)	Measured Delay Time, t (μsec)	Calculated Velocity, V (mm/μsec)	Normalized Velocity, V/V ₀
LOW TEMPERATURE TEST #1					
22	71	101.597	11.55	8.796	1.000
67	152	101.591	11.55	8.796	1.000
103	217	101.587	11.60	8.758	0.996
155	311	101.583	11.60	8.757	0.996
219	426	101.579	11.55	8.795	1.000
270	518	101.577	11.55	8.795	1.000
318	604	101.576	11.60	8.757	0.995
369	696	101.576	11.60	8.757	0.995
410	770	101.576	11.60	8.757	0.995
464	867	101.578	11.55	8.795	1.000
510	950	101.580	11.55	8.795	1.000
536	996	101.581	11.60	8.757	0.996
580	1076	101.584	11.60	8.757	0.996
605	1121	101.586	11.60	8.757	0.996
26	78	101.597	11.60	8.758	0.996
HIGH TEMPERATURE TEST					
21	69	101.597	11.55	8.796	1.000
693	1279	101.593	11.40	8.912	1.013
736	1356	101.598	11.55	8.796	1.000
835	1535	101.609	11.60	8.759	0.996
864	1587	101.612	11.55	8.798	1.000
1049	1920	101.638	11.55	8.800	1.000
1224	2235	101.665	11.60	8.764	0.996
1424	2595	101.701	11.65	8.730	0.992
1641	2985	101.744	11.45	8.886	1.01
1822	3311	101.783	11.35	8.968	1.019
1964	3567	101.818	11.45	8.892	1.011
2134	3873	101.864	11.55	8.819	1.003
2270	4118	101.906	11.35	8.979	1.021
2280	4136	101.909	11.70	8.710	0.990
2437	4418	101.965	11.65	8.752	0.995
2573	4663	102.021	11.45	8.910	1.013
2584	4683	102.026	11.55	8.833	1.004
2771	5019	102.119	11.40	8.958	1.018
2885	5225	102.185	11.25	9.083	1.033
2989	5412	102.253	11.30	9.049	1.029
3041	5505	102.290	11.25	9.092	1.034

TABLE I continued;

3051	5523	102.297	11.30	9.053	1.029
26	78	101.597	11.50	8.834	1.004
LOW TEMPERATURE TEST #2					
21	69	101.597	11.55	8.796	1.000
83	181	101.589	11.50	8.834	1.004
133	271	101.584	11.55	8.795	1.000
180	356	101.581	11.50	8.833	1.004
240	464	101.578	11.50	8.833	1.004
284	543	101.576	11.55	8.794	1.000
330	626	101.576	11.60	8.757	0.995
382	719	101.576	11.55	8.794	1.000
428	802	101.577	11.60	8.757	0.995
479	894	101.578	11.60	8.757	0.995
525	977	101.581	11.65	8.719	0.991
570	1058	101.583	11.60	8.757	0.996
620	1148	101.587	11.55	8.795	1.000
29	84	101.596	11.55	8.796	1.000
LOW TEMPERATURE TEST (Biomation Data)					
21	69	101.597	11.55	8.796	1.000
83	181	101.589	11.60	8.758	0.996
133	271	101.584	11.70	8.682	0.987
180	356	101.581	11.65	8.719	0.991
240	464	101.578	11.65	8.719	0.991
285	545	101.576	11.70	8.682	0.987
330	626	101.576	11.75	8.645	0.983
382	719	101.576	11.75	8.645	0.983
428	802	101.577	11.75	8.645	0.983
479	894	101.578	11.75	8.645	0.983
525	977	101.581	11.65	8.719	0.991
570	1058	101.583	11.75	8.645	0.983
620	1148	101.587	11.75	8.646	0.983

TABLE II

Longitudinal Velocity Temperature Data for ROD #2 Pitch/M2 Material

Corrected Temperature (°C)	Corrected Temperature (°F)	Corrected Index length, 2L (mm)	Measured Delay Time, t (μsec)	Calculated Velocity, V (mm/μsec)	Normalized Velocity, V/V ₀
LOW TEMPERATURE TEST					
23	73	76.200	18.20	4.187	1.000
20	68	76.200	18.10	4.210	1.006
67	152	76.205	18.20	4.187	1.000
108	226	76.208	18.30	4.164	0.995
151	303	76.210	18.25	4.176	0.997
207	404	76.212	18.25	4.176	0.997
264	507	76.212	18.25	4.176	0.997
296	564	76.212	18.15	4.199	1.003
346	654	76.212	18.15	4.199	1.003
400	752	76.211	18.15	4.199	1.003
448	838	76.212	18.20	4.187	1.000
509	948	76.213	18.15	4.199	1.003
548	1018	76.214	18.10	4.211	1.006
603	1117	76.217	17.90	4.258	1.017
23	73	76.200	18.40	4.141	0.989
25	77	76.201	18.50	4.119	0.984
LOW TEMPERATURE TEST (Biomation Data)					
25	77	76.201	18.20	4.187	1.000
151	303	76.210	18.20	4.187	1.000
207	404	76.212	18.20	4.187	1.000
264	507	76.212	18.10	4.211	1.006
296	564	76.212	18.10	4.211	1.006
346	654	76.212	18.20	4.187	1.000
400	752	76.211	18.20	4.187	1.000
448	838	76.212	18.20	4.187	1.000
509	948	76.213	18.20	4.188	1.000
548	1018	76.214	18.05	4.222	1.008
603	1117	76.217	18.00	4.234	1.011
HIGH TEMPERATURE TEST					
25	77	76.201	18.20	4.187	1.000
25	77	76.201	18.25	4.175	0.997
704	1299	76.225	18.25	4.177	0.998
778	1432	76.233	18.30	4.166	0.995
945	1733	76.260	18.15	4.202	1.004
1085	1985	76.289	17.95	4.250	1.015
1270	2318	76.334	17.85	4.276	1.021
1346	2454	76.353	17.75	4.302	1.027

TABLE II continued

1491	2715	76.388	17.60	4.340	1.037
1594	2901	76.411	17.30	4.417	1.055
1712	3113	76.435	16.95	4.509	1.077
1974	3585	76.480	16.65	4.593	1.097
2165	3929	76.513	16.45	4.651	1.111
2364	4287	76.567	17.15	4.465	1.066
2458	4456	76.607	17.25	4.441	1.061
2573	4663	76.677	17.45	4.394	1.050
2604	4719	76.701	17.50	4.383	1.047
2698	4888	76.790	17.85	4.302	1.027
HIGH TEMPERATURE TEST (Biomation Data)					
25	77	76.201	18.20	4.187	1.000
694	1281	76.224	18.05	4.223	1.009
778	1432	76.233	18.15	4.200	1.003
965	1768	76.264	18.05	4.225	1.009
1105	2021	76.294	17.90	4.262	1.018
1270	2318	76.334	17.80	4.288	1.024
1346	2452	76.353	17.65	4.326	1.033
1501	2733	76.390	17.40	4.390	1.049
1609	2928	76.414	17.15	4.456	1.064
1747	3176	76.442	16.85	4.537	1.084
1974	3585	76.480	16.70	4.580	1.094
2195	3983	76.520	16.60	4.610	1.101
2364	4287	76.567	17.10	4.478	1.069
2458	4456	76.607	17.15	4.467	1.067
2604	4719	76.701	17.50	4.383	1.047

TABLE III

Longitudinal Velocity Temperature Data for ROD #3 Pitch Parent Material

Corrected Temperature (°C)	Corrected Temperature (°F)	Corrected Index length, 2L (mm)	Measured Delay Time, t (μsec)	Calculated Velocity, V (mm/μsec)	Normalized Velocity, V/V ₀
LOW TEMPERATURE TEST					
25	77	101.597	10.55	9.630	1.000
72	161	101.591	10.55	9.629	1.000
120	248	101.586	10.60	9.584	0.995
159	318	101.582	10.60	9.583	0.995
203	397	101.579	10.45	9.721	1.009
253	487	101.577	10.35	9.814	1.019
303	577	101.576	10.30	9.862	1.024
348	658	101.576	10.25	9.910	1.029
395	743	101.576	10.25	9.910	1.029
433	811	101.577	10.20	9.959	1.034
496	924	101.579	10.20	9.959	1.034
550	1022	101.582	10.15	10.008	1.039
606	1122	101.586	10.15	10.008	1.039
660	1220	101.590	10.20	9.96	1.034
23	73	101.597	10.55	9.63	1.000
LOW TEMPERATURE TEST (Biomation Data)					
25	77	101.597	10.55	9.630	1.000
72	161	101.591	10.55	9.629	1.000
120	248	101.586	10.45	9.721	1.009
159	318	101.582	10.50	9.675	1.005
203	397	101.579	10.40	9.767	1.014
253	487	101.577	10.30	9.862	1.024
303	577	101.576	10.30	9.862	1.024
348	658	101.576	10.30	9.862	1.024
395	743	101.576	10.20	9.958	1.034
433	811	101.577	10.20	9.959	1.034
497	926	101.579	10.15	10.008	1.039
551	1023	101.582	10.20	9.959	1.034
606	1122	101.586	10.10	10.058	1.044
660	1220	101.590	10.20	9.960	1.034
HIGH TEMPERATURE TEST					
25	77	101.597	10.55	9.630	1.000
693	1279	101.593	10.30	9.863	1.024
704	1299	101.594	10.35	9.816	1.019
799	1470	101.604	10.35	9.817	1.019
850	1562	101.610	10.25	9.913	1.029

TABLE III continued

856	1572	101.611	10.35	9.817	1.019
904	1659	101.617	10.30	9.866	1.024
997	1826	101.630	10.25	9.915	1.030
1044	1911	101.637	10.25	9.916	1.030
1076	1968	101.642	10.15	10.014	1.040
1301	2373	101.679	10.20	9.968	1.035
1502	2735	101.716	10.15	10.021	1.041
1584	2883	101.732	10.25	9.925	1.031
1703	3097	101.757	10.30	9.879	1.026
1928	3502	101.809	10.30	9.884	1.026
2049	3720	101.840	10.55	9.653	1.002
2238	4060	101.896	10.55	9.658	1.003
2359	4278	101.936	10.30	9.897	1.028
2500	4532	101.990	10.25	9.950	1.033
2636	4776	102.050	10.15	10.054	1.044
2636	4776	102.050	10.10	10.104	1.049
2719	4926	102.091	10.15	10.058	1.044
2833	5131	102.154	10.10	10.114	1.050
3009	5448	102.267	9.90	10.330	1.073
3061	5541	102.305	9.95	10.282	1.068
3081	5577	102.320	9.90	10.335	1.073

HIGH TEMPERATURE TEST (Biomation Data)

25	77	101.597	10.55	9.630	1.000
693	1279	101.593	10.30	9.863	1.024
724	1335	101.596	10.35	9.816	1.019
799	1470	101.604	10.30	9.865	1.024
850	1562	101.610	10.30	9.865	1.024
866	1590	101.612	10.30	9.865	1.024
904	1659	101.617	10.30	9.866	1.024
987	1808	101.629	10.30	9.867	1.025
1066	1950	101.640	10.15	10.014	1.040
1296	2364	101.678	10.10	10.067	1.045
1497	2726	101.715	10.20	9.972	1.035
1584	2883	101.732	10.15	10.023	1.041
1703	3097	101.757	10.15	10.025	1.041
1928	3502	101.809	10.20	9.981	1.036
2049	3720	101.840	10.45	9.745	1.012
2238	4060	101.896	10.40	9.798	1.017
2359	4278	101.936	10.30	9.897	1.028
2500	4532	101.990	10.25	9.950	1.033
2636	4776	102.050	10.20	10.005	1.039
2719	4926	102.091	10.15	10.058	1.044
2833	5131	102.154	10.15	10.064	1.045
3009	5448	102.267	9.95	10.278	1.067
3081	5577	102.320	10.60	9.653	1.002
2573	4663	102.021	10.35	9.857	1.024

APPENDIX A

ROD #1 PITCH PARENT MATERIAL WAVEFORMS FOR;
THE INITIAL ROD VELOCITY, THE NOTCH MACHINING PROCESS,
LOW TEMPERATURE TEST #1, THE HIGH TEMPERATURE TEST,
AND LOW TEMPERATURE TEST #2

Pulse Echo Waveforms of Notch Machining Process and Low Temperature Test #1 for ROD #1

CC1 12/6/64

Pulse Echo Waveforms of High Temperature Test of ROD #1

Pulse Echo Waveforms of Low Temperature Test #2 of ROD #1

APPENDIX B

ROD #2 PITCH/M2 MATERIAL WAVEFORMS FOR;
THE INITIAL ROD VELOCITY, THE NOTCH MACHINING PROCESS,
THE LOW TEMPERATURE TEST, AND THE HIGH TEMPERATURE TEST.

12 11

peak to peak 1058-20 = 1038 μsec
 $\frac{2 L_0}{1038 \text{ } \mu\text{sec}} = .175 \text{ in}/\mu\text{sec}$

5 MHz 1.0 inch diameter
 Wide Band Transducer
 Core Material

12/11/84 applied pulse and
 End Reflection
 on bare rod $L_0 = 91''$
 Core
 150 MHz

Pulse Echo Waveforms of Unnotched ROD #2 and Notch Machining Process

Pulse Echo Waveforms of Low Temperature Test of ROD #2

Pulse Echo Waveforms of High Temperature Test of ROD #2

APPENDIX C

ROD #3 PITCH PARENT MATERIAL WAVEFORMS FOR;
THE INITIAL ROD VELOCITY, THE NOTCH MACHINING PROCESS,
THE LOW TEMPERATURE TEST, AND THE HIGH TEMPERATURE TEST.

Pulse Echo Waveforms of Unnotched ROD #3 and Notch Machining Process

Pulse Echo Waveforms of Notched ROD #3 from 150 KHz to 400 KHz Applied Pulse

Pulse Echo Waveforms of Low Temperature Test of ROD #3

Pulse Echo Waveforms of High Temperature Test of ROD #3

Pulse Echo Waveforms of High Temperature Test of ROD #3

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