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MASTER

ULTRASONIC THERMOMETRY IN LMFBR SYSTEMS

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Progress Report

Covering the Quarter Ending September 1969

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SUMMARY

The progress achieved during the eighth quarter, July-September 1969, may be summarized as follows:

1) An anodized aluminum coil was tested at 1000°F for 1000 hours with no signal degradation.

2) Attenuation in a $0.023''$ dia x $6''$ length of remendur wire was found to be negligibly small at 1000°F . A $0.5''$ transducer coil excited with an -5 psec current pulse width was used for this experiment.

3) A preliminary 3-hole hafnia insulator was made by GE. However, the web thickness between the three $0.012''$ dia holes was too small for structural integrity at elevated temperature.

4) A composite thermocouple/ultrasonic temperature probe was fabricated by GE. A field test was conducted on the composite probe at the GE-NSP facilities to a maximum temperature of 2347°C . Signals gradually degraded at high temperatures. Upon disassembly, it was found that the $\sim 0.025''$ dia rhenium sensor wire had adhered to the surrounding $\sim 0.027''$ ID hafnia insulator. When freed, the signals recovered the amplitudes and shapes they had at room temperature, before the test. It is now planned, if possible, to conduct a second test using a bare rhenium wire of smaller ($0.020''$) diameter. The diameter change should yield a larger end echo, by providing more clearance, and by providing a better impedance match to the lead-in line.

5) Preliminary designs were made of the ultrasonic system for the high temperature FFTF laboratory simulation tests. The designs were sent to T. Mulcahy at the Argonne National Laboratory for comment on the choice of materials and fabrication details.

6) Rhenium was calibrated to 4000°F at Engelhard Industries, Newark, New Jersey.

HIGH TEMPERATURE TRANSDUCER STUDIES

Lifetime. An anodized aluminum transducer coil was fabricated from sample wire obtained from an outside vendor. Typical wire size is 0.005" dia anodized to a depth of 0.0003", The coil, 1/2" long, was wound around an alumina single bore insulator and threaded over a ~6" length of magnetostrictive remendur wire (Fig. 1). The ends of the wire were prevented from unraveling by potting them in place with an Aremco* cement. The coil assembly weighs about 200 mg, Its OD is about 1/8", to fit easily inside the 1/4" dia SS tube in future ORTC tests and FFTF applications.

The fine leads are rather fragile, so it is planned in the future to tie them to terminal stakes potted in place at the coil ends, or to wrap and pot them with extension leads. Extension lead wire of SS, Cu, etc. would then be brought to the multi-pin feedthrough connector at the top of the ORTC capsule, or, subsequently, to the FFTF fuel pin feedthrough, in a manner similar to that used for thermocouples.

The transducer assembly was placed in an oven at 1000°F (air atmosphere) for a period of 1000 hours. It was energized using the Panatherm[®] 5010, and General Radio Pulse Generator 1398A and Pulse Amplifier 1397A during this period, and remendur reverberations were monitored. No magnets were used. No signal degradation was observed (Fig. 2). Subsequently, 12 additional coils were wound from the same wire. It is planned to use these or similar coils in the ORTC irradiation tests.

While this test was limited to 1000°F, the vendor's data indicate that 9000-hour lifetimes at 1200°F are possible. To verify this, some testing is planned at temperatures approaching 1200°F (aluminum melts at 1220°F).

*Ceramabond 503

Since the Curie point of remendur is nearly 1800°F, it should be possible to use it in an inert environment up to at least -1500°F, with an appropriate coil, e. g. , anodized tantalum, unless limited by attenuation.

For transducer operation to still higher temperatures, LiNbO₃ piezoelectric crystals, with a Curie point of ~2200°F, are of interest. If such temperatures become of real importance with respect to transducer survival, then "eddy sonic" or "transducerless" generation and detection of sound should also be investigated.^{1, 2}

It is to be noted, however, that from presently available information on ORTC or FFTF fuel pin temperature profiles, it is not yet certain that the temperature at the expected transducer location will exceed 1200°F.

Attenuation. The attenuation in remendur up to 1000°F was studied in a similar but separate experiment. A 1/2" anodized aluminum coil located 2" from one end of a 0.023" dia x 6" long remendur wire, was placed in an oven and heated to 1000°F (see Fig. 3a). The relative amplitudes of the end echoes remained essentially constant throughout the temperature range, indicating negligible attenuation in this length (Fig. 3b to 3h).

This is basically a differential path type attenuation experiment. The short path is 2 x 2" or 4"; the long path is 8". The attenuation coefficient α is

$$\begin{aligned}\alpha &= \frac{1}{\Delta x} \ln \frac{A}{B} \quad \text{nep/inch} \\ &= \frac{8.686}{8-4} \ln \frac{A}{B} = 2 \ln \frac{A}{B} \quad \text{db/inch}\end{aligned}$$

¹W. D. Wallace et al. , Rev. Sci. Instr. **39** (12) 1863-1864 (Dec. 1968).

²D. J. Meredith et al., J. Acoust. Soc. Amer. **45** (6) 1393-1401 (1969).

Since the first echo pair, A and B, are substantially of equal magnitude, α is negligibly small, for the remendur lengths anticipated in ORTC or FFTF applications. The third ("sum") echo is seen to have a magnitude essentially equal to the sum of the preceding pair, but is of opposite sign. The time between such sum pulses is that taken to traverse the line twice. The decay of individual or sum pulse reverberations is seen to be quite gradual, which again means α is small.

As a function of temperature, the time between echoes increases only slightly - about 4% for the temperature range 70 to 1000°F,

To obtain attenuation data to higher temperatures than previously achieved, in sensors such as rhenium, or possibly other refractory alloys such as tungsten/rhenium, the self-heating technique³ has been improved somewhat. As shown in Fig. 4, a 6" glass cross is evacuated with a fore pump to $\sim 1\mu$. The glowing specimen wire is in the form of a sharp-cornered U. This shape, rather than the straight line used previously, minimizes bowing of the sensor, without placing the sensor in excessive tension. Thus, the 0.015" dia sensor remains essentially straight despite ~ 1 to 2% expansion when heated to 5000°F.

In the photo, both lead-ins are of 0.020" dia tungsten, in a symmetrical arrangement. Pulses of the same width can be used to interrogate each side of the U (the sharp bend at the bottom gives almost complete reflection), for redundancy. In the future, coils of different lengths, e. g. , 1" and 2", and proportionately different pulse widths, will be used, to measure the dependence of α on pulse width. The shortest coil is desired for temperature localization and profiling consistent with attenuation limitations. Sensor lengths from about 2" to 6" can be accommodated, for differential path α determinations.

3L. C. Lynnworth et al., NASA CR-72339 (Aug. 1967), Figs. 42-44. Preliminary attenuation data in W, Re, Mo, W-5% Re and W-26% Re were obtained up to $\sim 4000^\circ\text{F}$.

Appendix A includes calibration measurements of transit time vs temperature to 4000°F. Data were obtained in Engelhard's thermo-couple calibration furnace, Newark, New Jersey.

Appendix B derives expressions for the reflection coefficient R and attenuation coefficient α appropriate for this work. Several numerical examples are included to illustrate how to use the derived results.

Composite Sensor

A preliminary 3-hole hafnia insulator sample was made by GE. It appears, however, that additional work is necessary to increase the hole spacing (web) to 0.006" to 0.007". Accordingly, two transducer assemblies were sent to GE in preparation for a field test on the so-called second design option. Each assembly included a previously tested anodized aluminum coil and a 0.023" dia x 11 inch long remendur wire with a low acoustical impedance termination (sharp bend). The field test was conducted on September 3rd and 4th, 1969, at the GE-NSP oven facility. The composite probe was heated in steps from room temperature to a maximum temperature of 2347°C and left overnight (—15 hours) at ~2225°C. A gradual signal degradation with time was observed at the high temperatures (Fig. 5). The probe was cooled to room temperature, then heated to -1645°C and brought back to room temperature with no observable signal recovery. Later, when the probe was disassembled it was found that the 0.025" dia rhenium sensor wire had adhered to the surrounding ~0.027" ID hafnia insulator. When freed, the signals recovered their original shapes and amplitudes. As a result, it was decided to perform a second test using a bare rhenium wire since no larger ID hafnia insulators were available. It was also agreed to use a rhenium wire of smaller (0.020") diameter in order to obtain an end echo of larger amplitude.

The diameter of the rhenium sensor had been chosen to be 0.025" to simplify joining the two thermocouple leads to it, one of said leads also serving as the ultrasonic lead-in for the composite sensor assembly. It was thought that the hafnia insulator would have had larger bores. To provide more clearance in the 0.027" ID hafnia, however, the smaller rhenium diameter, 0.020", is called for. It has now been found that the lead-in can in fact be attached with less difficulty than expected, into a rhenium sensor as small as 0.020" dia. Further, this yields a more favorable echo ratio. For a 0.009" dia tungsten or tungsten/rhenium lead-in, the theoretical extensional wave impedance ratios and corresponding joint-to-end echo ratios A/B are approximately as follows:

W or W/Re lead-in dia	Re sensor dia	$\frac{Z_1}{Z_2}$	$\{A/B\}$
0.009"	0.025"	0.13 (~1:8)	2.0
0.009"	0.020"	0.20 (1:5)	1.2
0.009"	0.018"	0.25 (1:4)	0.9

Integrated Sensor for Temperature Profiling. One of the attractive features of the thin-line ultrasonic thermometer is the possibility of measuring more than one temperature using only a single signal or information channel (lead-wire) from the sensed regions to the electronic instrument.

To determine the characteristics of lines containing several sensors in series, "integrated" sensors were built using (a) mushroom-shaped mass discontinuities on a line of otherwise constant diameter, and (b) discontinuities formed by diameter changes (Fig. 6). Case (a) has four sensors having length sequence: long/short; long/short. The paper clips represent the points at which the echoes originate. The oscillograms (Fig. 7) show the echo sequence for case (a), echoes

ABCDE. Echoes A, B, C, and D are of like sign and nearly of equal amplitude, since their discontinuities are all quite small and each represents an increase in impedance. End echo E is of opposite sign, and larger than the others. Since E is larger than the others, this suggests even more sensors could be put in series. Ten would appear to be a reasonable limit. At high temperature, of course, attenuation would further limit the practical maximum number of sensors.

FFTF Simulation. Preliminary designs were made of the ultrasonic system for the high temperature FFTF laboratory simulation tests. The designs (Figs. 8, 9) were sent to T. Mulcahy of Argonne National Laboratory who has commented on the choice of materials and fabrication details. The possibility of minimizing the length of magnetostrictive material is still under study, as are the details on electrical penetration.

The preferred sheath material, based on thermocouple studies with UO_2 and mixed oxide fuels, appears to be W-26% Re. Dimensions would be 0.062" OD x 0.007" wall x 32" long. Tantalum has been used at lower temperatures, and would be used in our laboratory for FFTF simulations for short periods of time, to check out the ultrasonic system, without incurring the costs of W-Re tubing.

The ultrasonic system for both the spacer wire and the fuel meat temperature measurements were designed for minimum fuel pin modification. As presently envisioned, the spacer wire temperature measurement would be accomplished by placing thin ultrasonic lead-in and sensor wires inside a spacer tube of the same OD as the spacer wire. The use of a spacer tube in lieu of a spacer wire had previously been contemplated by other investigators in connection with thermocouple measurements.⁴ It is proposed that all electrical connections to the ultrasonic transducers be made in the same manner as that envisioned for thermocouple usage.

⁴Design and Analysis of EBR-II Instrumented Subassembly System - ANL report Contract W-31-109-ENG 38 (January 1968).

Fig. 1. Coils of anodized aluminum wire, of the type tested to 1000°F for 1000 hours. Dime is shown for size comparison.

a) Room temperature 5V/cm , $20\mu\text{sec/cm}$.

b) At 1000°F after 1000 hr operation.
 5V/cm , $20\mu\text{sec/cm}$.

Fig. 2. Signal displays before and after 1000 hr operation at 1000°F .

(a) Experimental set-up

(b) Room temperature
0.5 V/cm, 20 μ sec/cm

(c) 500°F

(d) 600°F

(e) 700°F

(f) 800°F

(g) 900°F

(h) 1000°F

Fig. 3. Attenuation in remendur up to 1000°F

Fig. 4. Self-heating system for attenuation and cyclic studies.

Increasing temperature
on first run up,
September 3, 1969. $\sim 1300^{\circ}\text{C}$

$50 \mu\text{sec/cm}$ 2220°C

Echoes degrading at 1613°C
(1620 hrs)

Echoes muddled at 2347°C
(1630 hrs)

Echoes did not recover on
September 4, 1969 at room
temperature, after over-
night soak at -2200°C

Fig. 5. Oscillograms showing test results at GE-NSP for composite sensor.

Fig. 6. Integrated sensors for temperature profiling. Clips correspond to echoes generated at the discontinuities.

<u>Trace</u>	<u>Blanking Delay Position</u>	<u>Echo Polarity</u>	<u>Sensor Transit Time, psec</u>
1	-	-	-
2	4	AB	38.7
3	5	<u>BC</u>	29.1
4	6	<u>CD</u>	39.0
5	7	<u>DE</u>	24.2

Fig. 7. Oscillograms for integrated sensor consisting of four regions of equal diameter connected in series via weld upset (mush-room) discontinuities. Temperature profiling would be accomplished by scanning or switching through the sequence of "blanking delay."

Fig. 8. Proposed configuration for FFTF meat temperature simulation experiment. Lateral scale 1:8, Longitudinal scale 1:1.

SSF
8/14/69

APPENDCC A
CALIBRATION OF RHENIUM

by K. A. Fowler

This appendix summarizes the results of calibration measurements of the normalized sound velocity in rhenium as a function of temperature conducted at Englehard Industries on September 4 and 5, 1969.

I. Experimental

A. Equipment

1. Transducer: 5010-E5-14
2. Panatherm[®] 5010: Modified - 15V pulser, 60 cycle filter built-into receiver section
3. Sensor: 2.015" x 0.020" dia, rhenium wire (Rembar material)
4. "Blackbody" cavity:

5. Slight positive pressure - purified He atmosphere
6. Pulse width - ~ 10 psec or $f \cong 100$ kHz
7. Scope - Tektronix dual beam - Preamplifiers were not calibrated so that absolute amplitudes could not be measured.

11. Results

A. General

1. The calibration curve obtained in this test agreed substantially with that observed during the previous test in April.

2. The spread in the data obtained in April was greater than in this test. The reason for this is thought to be that in April the sensors were not centered in the cavity and, therefore, did not all see the same temperature within the cavity. Further, there was no cap on the cavity during the April test. Problems with noise pickup also contributed to uncertainty in the measured transit times.

3. The filter in the Panatherm receiver input completely suppressed the 60 cycle pickup problem.

4. Again the rhenium sound velocity at room temperature increased about 1% after a single heating cycle to $\sim 2000^{\circ}\text{C}$. Upon further reheating the room temperature transit time remained unchanged.

5. It was observed that, at high temperatures (2200°C), there was a definite tendency for the normalized transit time to be less when the time interval between the first and fifth echo was used instead of the first and second. This may be the result of increasing attenuation.

6. Reproducibility was good once the sensor was annealed.

7. The heating sequence was as follows:

- a. Heat to 1982°C and hold for ~ 10 minutes
- b. Heat to 2238°C
- c. Cool to 1573°C
- d. Heat to 2053°C
- e. Cool to room temperature
- f. Heat to 2025°C
- g. Cool to room temperature

8. Figure A1 shows the spread in the data from both the April and September tests. The spread for the April test represents the total spread for sensors 1-4. The mark midway on some of the bars indicates the spread without sensor #4 which was consistently high.

9. Figure A2 shows the reproducibility obtained by plotting the normalized transit time t_n between echoes A and E. All of the individual data points are plotted.

10. Figure A3 shows characteristic signal wave forms obtained at various temperatures.

B. Tabulated Data

Table A - I*

Temperature	A	B	C	R_{12}	a , N/cm
27°C	3.20	3.80	2.00	0.554	0.005
1181°C	3.80	4.15	2.25	0.574	0.006
1573°C	3.80	3.80	2.00	0.587	0.011
1982°C	3.80	3.00	1.40	0.610	0.026
2080°C	3.80	2.80	1.25	0.614	0.031

*Note: See Appendix B for derivation of these results.

Table A-11

Round trip transit time between echoes indicated, psec

<u>Temperature</u>	<u>AB</u>	<u>AC</u>	<u>AD</u>	<u>AE</u>
Room	22.3	44.7	66.8	89.2
Room	22.1	44.1	66.1	88.2
t_n	1.0090	1.0136	1.0106	1.0113
1982°C	29.1	58.4	87.4	116.7
t_n	0.7595	0.7551	0.7563	0.7558
2064°C	29.6	59.2	88.8	118.4
	0.7466	0.7449	0.7444	0.7449
2238°C	30.8	61.5	92.3	123.5
t_n	0.7175	0.7171	0.7161	0.7142
2080°C	29.7	59.4	89.0	118.9
t_n	0.7441	0.7424	0.7427	0.7418
1749°C	27.3	54.7	82.1	109.6
t_n	0.8095	0.8062	0.8051	0.8047
1573°C	26.5	53.1	79.6	
t_n	0.8340	0.8305	0.8304	
2053°C	29.6	59.2	88.7	118.5
t_n	0.7466	0.7449	0.7452	7.443
1097°C	25.1	50.3	75.3	100.6
t_n	.8805	.8767	.8778	.8767
1181°C	25.3	50.7	76.1-2	101.5
t_n	.8735	.8698	.8685	.8689
1418°C	26.0	52.0-1	78.0	104.2
t_n	.8500	.8481	.8474	.8464
1561°C	26.4	52.9	79.3	105.8
t_n	.8371	.8336	.8335	.8336
1823°C	27.7	55.6	83.3	111.4
t_n	.7978	.7931	.7935	.7917
2025°C	29.4	58.8	88.1	117.6
t_n	.7517	.7500	.7502	.7500

Figure A-1

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t_n for echoes A-E vs T

Rhenium Sensor #1

Englehard Test

Normalized Transit Time, t_n

Temperature, $^{\circ}\text{C}$

Figure A-2

#1 Rm. Temperature
22.3 psec

20 μ sec/cm

#2 1982⁰C

Same Vertical Sensitivity
as #1

#3 1982⁰C

Increased gain
of Panathern[®] 5010

Figure A-3

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#4 2238°C

Same gain as #3

#5 2238°C

I: d = of
Fanatherm

#6 2080°C

t_{AE} measured with
"B-boost" in

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#7 1573°C

#8 Rm. Temperature

#9 1097°C

Same gain as
#8

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#10 1832°C

#11 2025°C

APPENDIX B
CALCULATION OF ATTENUATION WHEN REFLECTION
COEFFICIENT IS UNKNOWN
by E. P. Papadakis

Statement of the Problem

When an ultrasonic round wire transmission line is terminated in a sensor (another round wire welded on or a continuation of the same wire etched to a smaller diameter or set off by a discontinuity) the junction is characterized by a reflection coefficient R and a transmission coefficient T . In the simple case where the transmission line (medium 1) and the sensor (medium 2) differ only in area A and/or in characteristic acoustic impedance ρv , the coefficients for particle displacement amplitude can be expressed simply as

$$R_{12} = \frac{Z_1 - Z_2}{Z_1 + Z_2} \quad (B1)$$

and

$$T_{12} = \frac{2Z_1}{Z_1 + Z_2} = 1 + R_{12} \quad (B2)$$

where $Z = \rho v_e A$ for extensional waves and $Z = \rho v_t A^2 / 2\pi$ for torsional waves. These are written for transmission into the sensor. For transmission out of the sensor,

$$R_{21} = \frac{Z_2 - Z_1}{Z_1 + Z_2} = -R_{12} \quad (B3)$$

and

$$T_{21} = \frac{2Z_2}{Z_1 + Z_2} = 1 + R_{21} = 1 - R_{12}. \quad (B4)$$

The material in the sensor is characterized also by an attenuation α per unit length. It is often necessary to measure this attenuation to determine whether adequate signals can be received from the sensor.

If R_{12} , R_{21} , T_{12} , and T_{21} were exactly equal to their theoretical expressions given in Eqs. (B1) through (B4), the attenuation could be found easily from the amplitudes of the echo from the junction and the echo from the end of the sensor. However, the coefficients depend upon the quality of the welded or bonded joint even in the simple case stated above. In more complicated cases involving notches, kinks, or lumps in the wire line of constant diameter, the coefficients are not known a priori. They can be expressed in terms of an effective impedance Z' of the wire including and beyond the discontinuity as seen from the point of view of the impinging wave. Since the wire is of constant diameter and material except for the discontinuity, $Z_1 = Z_2 = Z$, the coefficients are

$$R'_{12} = R'_{21} = \frac{Z - Z'}{Z + Z'} \quad (B5)$$

and

$$T'_{12} = T'_{21} = \frac{2Z}{Z + Z'} = 1 + R'_{12}. \quad (B6)$$

In both cases, all four coefficients can be expressed in terms of just one, R_{12} for the simple case or R'_{12} for the complicated case.

Thus there are pairs of variables to be determined, R_{12} and a in one case and R'_{12} and a in the other.

Solution of the Problem

Two measured quantities are needed to solve for **two** unknowns. The **two** quantities to be measured are the amplitudes of the first and second return signals B and C from the free end of the sensor normalized **by** the first reflection A from the junction. Let a wave of unit amplitude be incident upon the sensor **from** the wire transmission Line. Then the amplitude of the reflection A or A' is

$$A = R_{12}$$

or

(B7)

$$A' = R'_{12}.$$

The amplitude of transmission into the sensor is

$$T_{12} = 1 + R_{12}$$

or

(B8)

$$T'_{12} = 1 + R'_{12}.$$

After round trip transmission in the sensor of length L, both these quantities are multiplied by $\exp(-2aL)$. The transmitted portion, forming echo B or B' , is

$$B = T_{12}T_{21}e^{-2aL} = (1 - R_{12}^2)e^{-2aL}$$

or

$$B' = T'_{12}T'_{21}e^{-2aL} = (1 + R'_{12})^2 e^{-2aL}, \quad (B9)$$

while the reflected portion is

$$T_{12} R_{21} e^{-2aL} = -R_{12} (1 + R_{12}) e^{-2aL}$$

or

$$T'_{12} R'_{21} e^{-2aL} = R'_{12} (1 + R'_{12}) e^{-2aL} . \quad (B10)$$

After another round trip transmission in the sensor and transmission through the boundary, these quantities are multiplied by $\exp(-2aL)$ and T_{21} (or T'_{21}) to form echo C (or C').

$$C = -R_{12} (1 + R_{12}) T_{21} e^{-4aL} = -R_{12} (1 - R_{12}^2) e^{-4aL}$$

or

$$C' = R'_{12} (1 + R'_{12}) T'_{21} e^{-4aL} = R'_{12} (1 + R'_{12})^2 e^{-4aL} . \quad (B11)$$

Normalizing Eqs. (B9) and (B11) by division by Eq. (B7), one finds

$$B/A = \left[(1 - R_{12}^2) / R_{12} \right] e^{-2aL} ,$$

$$C/A = - (1 - R_{12}^2) e^{-4aL} ,$$

$$B'/A' = \left[(1 + R'_{12})^2 / R'_{12} \right] e^{-2aL} ,$$

and

$$C'/A' = (1 + R'_{12})^2 e^{-4aL} . \quad (B12)$$

The sign of these quantities indicates the polarity of the video pulse, and can be dropped in what follows if one writes $\tilde{B} = |B/A|$, $\tilde{C} = |C/A|$, $\tilde{B}' = |B'/A'|$, and $\tilde{C}' = |C'/A'|$.

Solving for the reflection coefficient and the attenuation, one finds

$$R_{12} = \pm \left[\tilde{C}/(\tilde{B}^2 + \tilde{C}) \right]^{1/2},$$

$$\alpha = \frac{1}{2L} \left\{ \ln \tilde{B} - \frac{1}{2} \left[\ln \tilde{C} + \ln (\tilde{B}^2 + \tilde{C}) \right] \right\},$$

or

$$R'_{12} = \frac{\tilde{C}' + \tilde{B}'\sqrt{\tilde{C}'}}{(\tilde{B}')^2 - \tilde{C}'},$$

$$\alpha = \frac{1}{2L} \left\{ \ln \tilde{B}' - \ln \tilde{C}' + \ln \left[\tilde{C}' + \tilde{B}'\sqrt{\tilde{C}'} \right] - \ln \left[(\tilde{B}')^2 - \tilde{C}' \right] \right\} \quad (B13)$$

Thus it is seen that both the attenuation and the reflection coefficient can be computed from the amplitudes of the first three signals returned from the sensor region. Changes in R and α can be measured versus temperature. R will change if the moduli of the wire transmission line and the sensor change at different rates with temperature. α may change for several reasons such as grain growth, dislocation unpinning, or interstitial motion.

An example of this procedure is given in Table A-I in which the attenuation and reflection coefficient of a rhenium sensor on a tungsten wire transmission line of different diameters are computed versus temperature. The data were taken from photographs made at the same time the delay measurements in Appendix A were recorded.