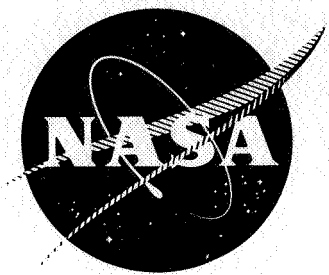


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ULTRASONIC MEASUREMENT OF CORE MATERIAL TEMPERATURE

by

M. S. McDonough, L. C. Lynnworth and E. H. Carnevale

prepared for

NATIONAL AERONAUTICS AND SPACE ADMINISTRATION

CONTRACT NAS 3-10284



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Waltham, Massachusetts 02154

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Phase II Report

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MATERIAL TEMPERATURE

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TABLE OF CONTENTS

	<u>Page</u>
ABSTRACT	ii
LIST OF FIGURES	iv
LIST OF TABLES	v
SUMMARY	1
INTRODUCTION	2
Statement of the Problem	2
Phase II Objective	2
EXPERIMENTAL INVESTIGATIONS	2
Background	2
Acoustic Isolation	3
Attenuation	3
Tests in Graphite	4
Sheath Materials	4
Tantalum Sheath Experiments	5
Tungsten Sheath Experiments	6
Sheath Design	7
CONCLUSIONS AND RECOMMENDATIONS	8
ACKNOWLEDGMENT	9
REFERENCES	11

LIST OF FIGURES

1. Ultrasonic line
2. Oscillograms showing acoustic isolation using 0.002" W spiral spacer wire.
3. Maximum attenuation vs pulse width for tungsten
4. Self-heating equipment
5. Oscillograms showing attenuation in a tungsten lead-in line and a rhenium sensor.
6. Oscillograms showing attenuation in a tantalum lead-line and a rhenium sensor.
7. Diffusion of carbon in tantalum and tungsten as a function of temperature and time.
8. Oscillograms of echoes in 0.03" dia x 2" long rhenium sensor in a tantalum tube at room temperature and at 4850°R.
9. Oscillograms of echoes in 0.030" dia x 2" long rhenium sensor in a tantalum tube at room temperature and at 5100°R.
10. Temperature vs clock time for a system heated to a temperature greater than 4800°R for three hours.
11. Oscillograms of echoes in 0.030" dia x 2" long rhenium sensor in a wrought W-2% ThO₂ tube at room temperature and at 4900°R.
12. Sheath system to protect a sensor from a carbon/hydrogen environment for one hour at 5300°R.
13. Sheath system consisting of stainless steel tubing and nickel wires.
14. Oscillograms of echoes in 0.056" dia x 4" long nickel sensor in a 0.096" x 8" long stainless steel tube.
15. Sheath system consisting of stainless steel tubing and nickel wires.
16. Oscillograms of echoes in 0.067" dia x 3" long nickel sensor in a 0.126" dia x 8" long stainless steel tube.

LIST OF TABLES

	Page
I. Melting or Eutectic Temperatures	10

SUMMARY

The main object of the second phase of this work was to design and test sheaths that would enable rhenium sensors to measure temperatures to 5300°R , to an accuracy of 50°R , in a graphite/hydrogen/nuclear environment.

High temperature ultrasonic measurements were conducted to 5300°R in a graphite environment using a Ta sheathed Re sensor. It was found that the system could measure a temperature of 5100°R in a graphite environment for 67 minutes, and this same system could measure temperatures greater than 4800°R for three hours. However, the sheath failed after three minutes at 5300°R . The tantalum sheath protected the Re sensor from the carbon environment provided the wall thickness of the sheath exceeded 0.010".

Similar ultrasonic tests were performed in a graphite atmosphere using either chemically vapor deposited tungsten tubing or wrought W-2% ThO_2 tubing in place of the tantalum tubing. The chemically vapor deposited tubing failed on several occasions after being heated for 3-5 minutes at a temperature of 5100°R . The wrought W-2% ThO_2 tubing operated satisfactorily for one hour at 4900°R .

It is recommended that a tantalum sheath clad with an outer layer of chemically vapor deposited metal be used in Phase III to protect the sensor from the graphite/hydrogen environment.

INTRODUCTION

Statement of the Problem

One of the most important measurements required in nuclear rocket engine technology is the measurement of temperature. This measurement has proven to be extremely difficult because of the high temperature involved ($> 5000^{\circ}\text{R}$), because of compatibility problems with some of the materials involved (graphite and hydrogen) and because of the intense transient and sustained neutron and gamma fluxes. Additional difficulties stem from the possibility of temperature overshoot, high pressure, flow, accessibility and geometrical restrictions, shock and vibration levels expected in some locations, etc.

Phase II Objective

The main objective of Phase II was to design and test sheaths that would enable rhenium sensors to measure temperatures to 5300°R in a carbon/hydrogen environment for one hour. Since the temperature goal of 5300°R is above the rhenium-carbon eutectic (4966°R), it follows that, if rhenium is to be used as the sensor, a sheath is required. Table I lists the eutectic temperatures for the materials that could be used in a complete sheath system. The design of the sheath also entails the satisfactory placement of a sensor in the sheath. Although there are no electrical shorting problems there are potential acoustic isolation problems.

EXPERIMENTAL INVESTIGATIONS

Background

In the ultrasonic temperature measuring system, temperature is determined by measuring the round trip transit time of the ultrasonic signal in a wire sensor. Transit time is determined by measuring the time between the signals reflected from the beginning and end of the sensor. For most materials, as temperature increases, transit time increases.

The transit time can be measured to $\pm 0.1 \mu\text{sec}$ with the Pana-Therm 5000, and at 5000°R the system will be able to measure temperature within $\pm 50^{\circ}\text{R}$.

In the present work the ultrasonic line usually consists of a Remendur transducer wire, a tungsten lead-in wire, and the rhenium sensor (Fig. 1). Joints were formed satisfactorily by flash butt welding. Echoes reflected by the various discontinuities, either welds or changes in diameter, were essentially equal to that predicted by theory.

Acoustic Isolation

In designing the sheath system, it is necessary to acoustically isolate the sensor and the lead-in wire from the sheath if satisfactory ultrasonic signals are to be obtained. Acoustic isolation has been realized by wrapping a spiral spacer wire around the sensor and lead-in wire. Investigations have shown that this isolation method is satisfactory if the diameters of the lead-in and sensor wires are at least ten times greater than that of the spacer wire. For this large impedance mismatch very little of the ultrasonic signal will be coupled out of the line. Also, since the wavelength of the ultrasonic signal is about two orders of magnitude greater than the diameter of the spiral spacer wire, the ultrasonic wave does not "see" the individual spiral spacer wire turns, i. e., the spiral spacer wire does not produce interfering echoes. For a 0.040" W lead-in line and a 0.030" Re sensor, a 0.002" W spiral spacer wire has been found to be satisfactory for pulse widths less than $30 \mu\text{sec}$ (Fig. 2).

Attenuation

Besides changes in transit time, as temperature increases, the amplitude of the sensor's echoes usually decreases, due to attenuation. For example, in Re, attenuation becomes increasingly more severe as the temperature increases above 3000°R . Attenuation depends on the material, vibrational mode, frequency and dampening external to the

wire. As reported previously, the attenuation decreases as the pulse width of the ultrasonic signal increases (Fig. 3).¹

To determine if attenuation would be a significant problem at temperatures greater than 4000°R and distributed as would be expected in a graphite furnace, measurements were made on a lead-in line and a sensor that were heated to 5100°R in a self-heated Ta tube (Fig. 4b). Figure 5 shows that when a 5 in. Re sensor and a 14 in. W lead-in line were heated to a temperature of 5100°R in a carbon-free vacuum, the sensor echoes, although attenuated, can be readily identified. The pulse width of the ultrasonic signal used was 25 μsec. This experiment demonstrates that ultrasonic echoes can be identified from the end of a line, 19 inches of which are essentially at a temperature of 5100°R. Note that the actual expected temperature distribution is probably not as severe as that simulated in this test.

Measurements were also performed to determine the feasibility of using a tantalum lead-in line in place of the tungsten lead-in. It may be desirable to use Ta in place of W, since Ta is more ductile than W and is more easily joined to a Ta sheath. Further, there are no Ta/C eutectics below 5300°R. A 5 in. Re sensor and a 14 in. tantalum lead-in line were placed in a 19 in. Ta tube that was self-heated. Graphite felt surrounded the Ta tube in the region where the Re sensor was located. Figure 6 shows that echoes from the sensor, which was heated to ~5250°R, although attenuated, can be readily identified.

Tests in Graphite

Sheath Materials

In order to measure temperatures up to 5300°R in a carbon/hydrogen/nuclear environment with a rhenium sensor, it is necessary to use a sheath, since 5300°R is above the Re/C eutectic. For this environment, the principal sheath materials are Ta and W. One of the sheath systems presently used by Los Alamos Scientific Laboratory to protect their thermocouples from hydrogen and carbon uses an outer

sheath of wrought W-2% ThO₂ tubing and an inner liner of tantalum. The outer sheath protects the system from hydrogen but not from carbon, while the inner sheath protects the temperature sensor from carbon. Tantalum forms a carbide at high temperatures and this carbide reduces the diffusion rate of carbon through the sheath. If the wall of tantalum liner is sufficiently thick very little carbon will diffuse through it (Fig. 7).² However, Westinghouse Astronuclear Laboratory has found that wrought W-2% ThO₂ tubing by itself works satisfactorily in a carbon environment at ~4700°R. Also, GE's Nuclear Materials and Propulsion Operation, Cincinnati, reported the successful use of a W sheath to 5080°R in a carbon/hydrogen atmosphere for one hour (W/Re thermocouple).³ GE's work contradicts phase diagrams which show a W-W₂C eutectic at ~4950°R (Table I). A sheath constructed of tungsten would be attractive because it avoids hydriding (tantalum hydrides in the temperature range 1200°R-2200°R). Tungsten's drawbacks, however, include lower carbon eutectic than Ta, more brittle, offers less resistance to carbon diffusion than Ta does; wrought tungsten tubing is more expensive than tantalum tubing.

Tantalum Sheath Experiments

Ultrasonic tests were conducted on a sheathed rhenium sensor to determine the maximum temperature at which the protected sensor could measure temperature for a period of at least one hour. The ultrasonic tests were performed in a helium atmosphere by self-heating a tantalum sheath that was surrounded by graphite felt (Fig. 4a). The transit time was measured automatically with the Pana-Therm 5000, from which temperature was determined. Figure 8 shows that the transit time can be measured in a Ta sheathed Re sensor, heated to 4850°R for 80 minutes. This sensor was maintained at a temperature greater than ~4800°R for two hours with no noticeable degradation of the ultrasonic signals.

After the sensor was cooled, it was reheated to a temperature of 5100°R for 67 minutes. Figure 9 presents the echoes from the beginning and end of the sensor at 5100°R . After running for over one hour at 5100°R , the system was cooled and then the temperature was increased to 5300°R . At this temperature, the system survived for three minutes, until the tantalum tube burned out. It should be observed that one ultrasonic sensor was used to measure temperatures greater than $\sim 4800^{\circ}\text{R}$ for three hours in a graphite environment (Fig. 10). Using the present experimental techniques, numerous high temperature measurements have been made relatively easily in a carbon environment using a tantalum sheathed rhenium sensor.

The tantalum tubing used in the experiments had a wall thickness of 0.012 in. This thickness seems sufficient to keep carbon from the rhenium sensor at a temperature of 5100°R for one hour. Measurements were also made using sheaths with wall thicknesses of 0.004 in. and 0.007 in.; these sheaths did not protect the sensor from the carbon at a temperature of $\sim 5000^{\circ}\text{R}$ for one hour. The Ta thicknesses thus found necessary to protect against carbon diffusion agree in general with those of LASL (Fig. 7).

Tungsten Sheath Experiments

Similar ultrasonic tests were also performed in a graphite/helium atmosphere using either chemically vapor deposited tungsten tubing or wrought W-2% ThO_2 tubing in place of the tantalum tube. The chemically vapor deposited tubing had a wall thickness of 0.011 in. and melted on several occasions after being heated for 3-5 minutes at a temperature of 5100°R . The tube melted due to the formation of either the tungsten-rhenium-carbon or the tungsten-carbon eutectic.

The wrought W-2% ThO_2 sheath that was surrounded by graphite felt was self-heated in a helium atmosphere. The tubing had a wall thickness of 0.011 in. Figure 11 shows that the transit time can be

measured in a W-2% ThO₂ sheathed Re sensor heated to ~4900°R for 60 minutes. The Re sensor was then heated to a temperature of 5300°R for ~3 minutes. After this period the tungsten tubing burned out. This demonstrates that wrought tungsten tubing will protect a Re sensor satisfactorily for one hour at ~4900°R.

These experiments show that at a temperature of 5100°R a tantalum sheathed rhenium sensor operates satisfactorily for one hour in a carbon environment. For temperatures below ~4900°R wrought tungsten (W-2% ThO₂) may also be used as a sheath.

Sheath Design

In measuring temperatures ultrasonically one can choose materials such that it may be sufficient to protect only the sensor itself from the carbon environment. It is not always necessary to protect the lead-in line from the carbon, since the capability of the sensor to measure temperature is essentially independent of any carbiding of the lead-in wire, provided lead-in eutectics or embrittlement do not create problems. This makes it possible to use a short sheath which protects the sensor only. The short sheath would typically be ~8 in. long.

A short sheath design which protects only the sensor is shown in Fig. 12. The sheath is a tantalum tube clad with an outer layer of chemically vapor deposited tungsten. The sheath dimensions are about 8 in. in length with a wall thickness of 0.010 to 0.030 in. Due to the short length of the sheath, it should be far less fragile, and less expensive to fabricate than a sheath several feet long fabricated of wrought tungsten tubing.

In order to ultrasonically evaluate the short sheath design inexpensively, stainless steel tubing and nickel wires were used. Two sheath designs were examined. For the first design the tubing was first tapered, in order to blend the tube into the ultrasonic line, and then silver brazed to the nickel wire. Various bonds were examined to

determine the effect of various tapers and amounts of silver braze on the ultrasonic signal (Fig. 13). It was found that the braze and the end of the tube caused echoes. The amplitude of the signal that was transmitted through the tube was found to be approximately independent of the size of the braze (length of braze \ll wavelength). The echoes from the end of the sensor and the tube can be readily identified, if the tube is 8 in. long and the sensor is 4 in. long (Fig. 14).

Figure 15 shows a second short sheath design. The tubing and the sensor were silver brazed to the lead-in line as shown in Fig. 15. Echoes from the end of the tube and the beginning and end of the sensor can be readily identified, if the sensor is 5 in. long and the tube is 8 in. long (Fig. 16).

Another design entails using a sheath that is several feet in length. The sheath would probably be very similar to the one used by LASL. The sheath system would consist of an outer sheath of wrought W-2% ThO₂ tubing and an inner liner of tantalum. Alternatively, one could use a Ta tube clad with chemically vapor deposited W. These systems' advantages include (1) the lead-in will not become embrittled by carbon diffusion, and (2) the only sheath weld in the hot zone occurs at the far end. Disadvantages are (1) difficulty of fabrication, and (2) high cost.

CONCLUSIONS AND RECOMMENDATIONS

The recommended metallic sheath system consists of a Ta tube, wall thickness greater than about 0.010 in., from about 8 in. long to possibly as long as the entire line, clad with an outer layer of chemically vapor deposited metal (Fig. 12). The sheath contains a Re sensor up to 0.030 in. dia x up to 5 in. long,* possibly a 0.002 in. W spiral spacer wire, and a W or Ta lead-in line or a combination of these materials or

*Either polycrystalline or single crystal tantalum or tungsten might also prove to be suitable for use as a sensor, if hysteresis effects can be eliminated.

other refractory materials, e. g. , Mo. Sheath materials are thus similar to those used for thermocouples in a carbon/hydrogen nuclear environment, but of geometry appropriate to the ultrasonic requirement. Due to new developments in the field of high temperature materials, subsequent sheath systems may be different from the one described above.

It is recommended that Phase III be performed. This involves testing in a combined hydrogen/graphite environment, up to the maximum temperature capability of available ovens, with 5300°R as a goal. It appears that the required oven is available at LASL for testing the ultrasonic system. Subsequently, if the tests in a hydrogen/graphite environment are successful, measurements should be made in a nuclear environment.

ACKNOWLEDGEMENT

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Table I

Melting or Eutectic Temperatures

Material	Temperature, °R	Reference
Re/WC	4649	Havell
Re/C	4966	Gonser
Re/Ta	5333	DMIC #152
Re/Ta/W	5333	DMIC #152
W/W ₂ C	5369	Hall
WC	5387	Nadler
W ₂ C	5405	Shaffer
Ta/Ta ₂ C (Ta-C)	5531	DMIC #152
Re/W	5576	DMIC #152
Ta	5884	Shaffer
Re	6226	Shaffer
Ta ₂ C	6611	Campbell
W	6629	Shaffer
TaC	7223	Campbell

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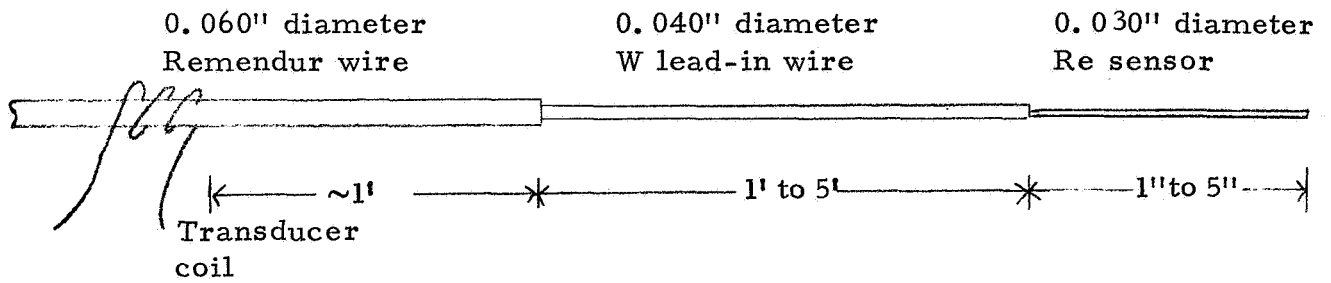
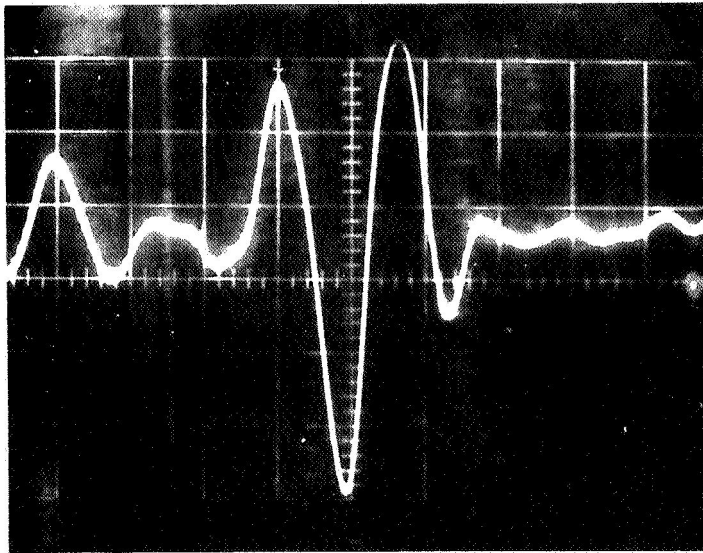
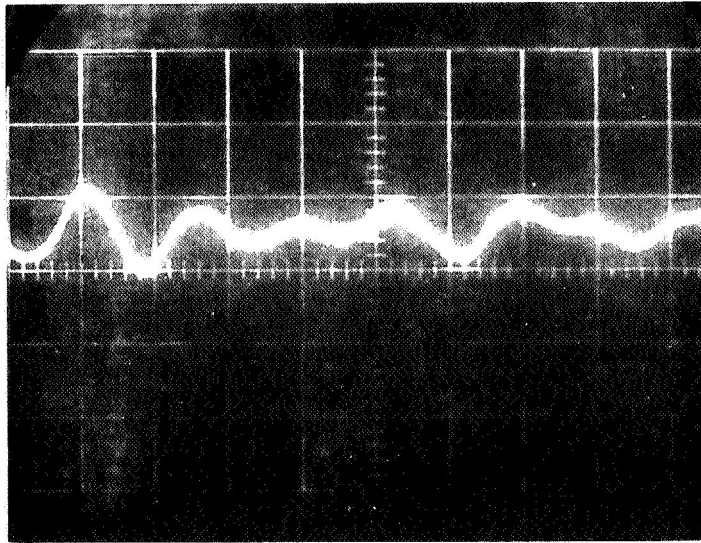


Figure 1. Ultrasonic line used to measure temperature. The ultrasonic echoes reflect from the beginning and end of the rhenium sensor. Dimensions shown approximate the typical values for the present program.



Room temperature
0.1 v/cm 10 μ sec/cm



$\sim 3900^{\circ}$ R
0.1 v/cm 10 μ sec/cm

Figure 2. Oscillograms of echoes in 0.030" dia x 4" long rhenium wire in a 22" long tantalum sheath. The diameter of the tungsten spiral spacer wire was 0.002". The lead-in line was 0.040" diameter W and the pulse width used was 10 μ sec.

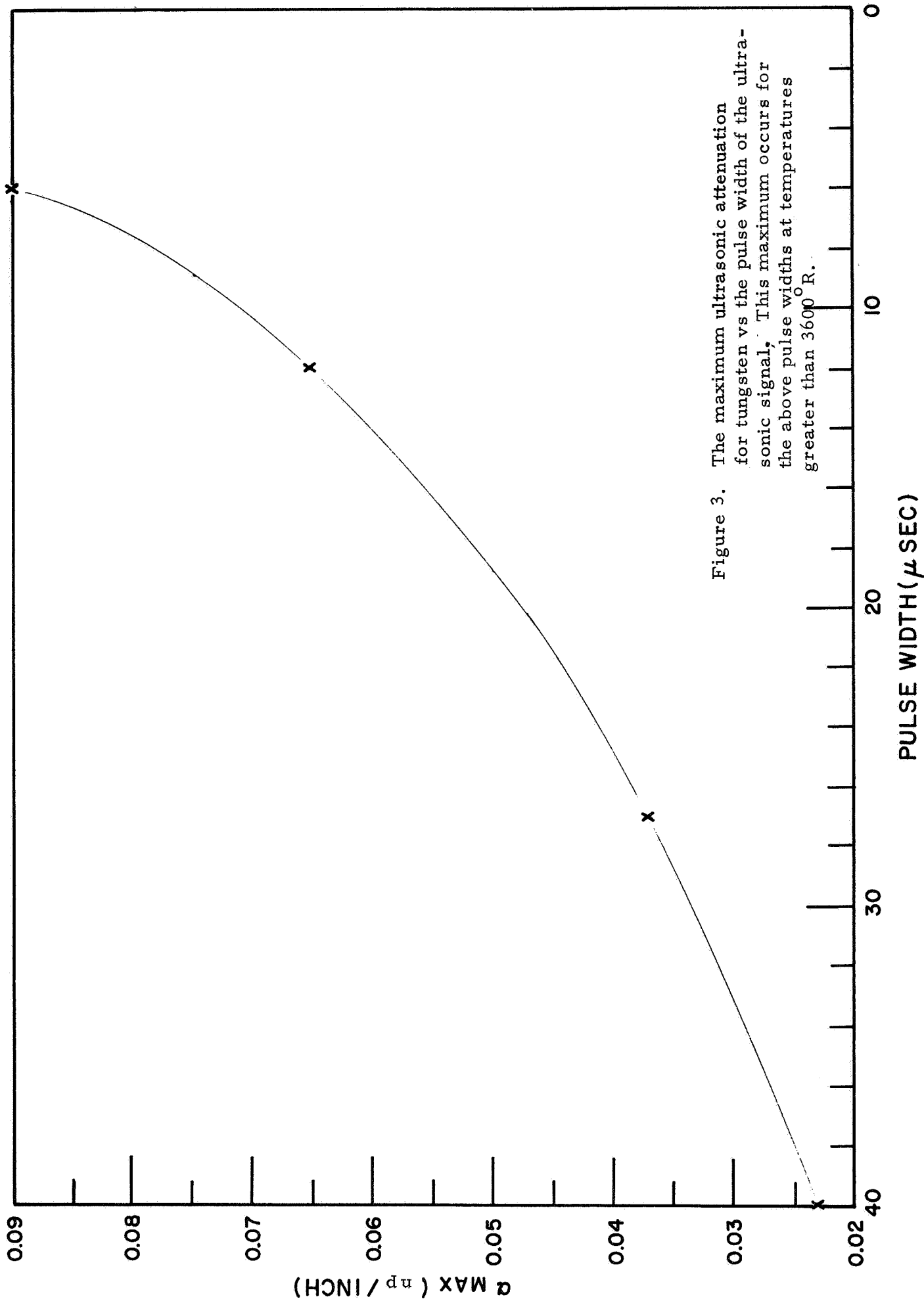


Figure 3. The maximum ultrasonic attenuation for tungsten vs the pulse width of the ultrasonic signal. This maximum occurs for the above pulse widths at temperatures greater than 3600° R.

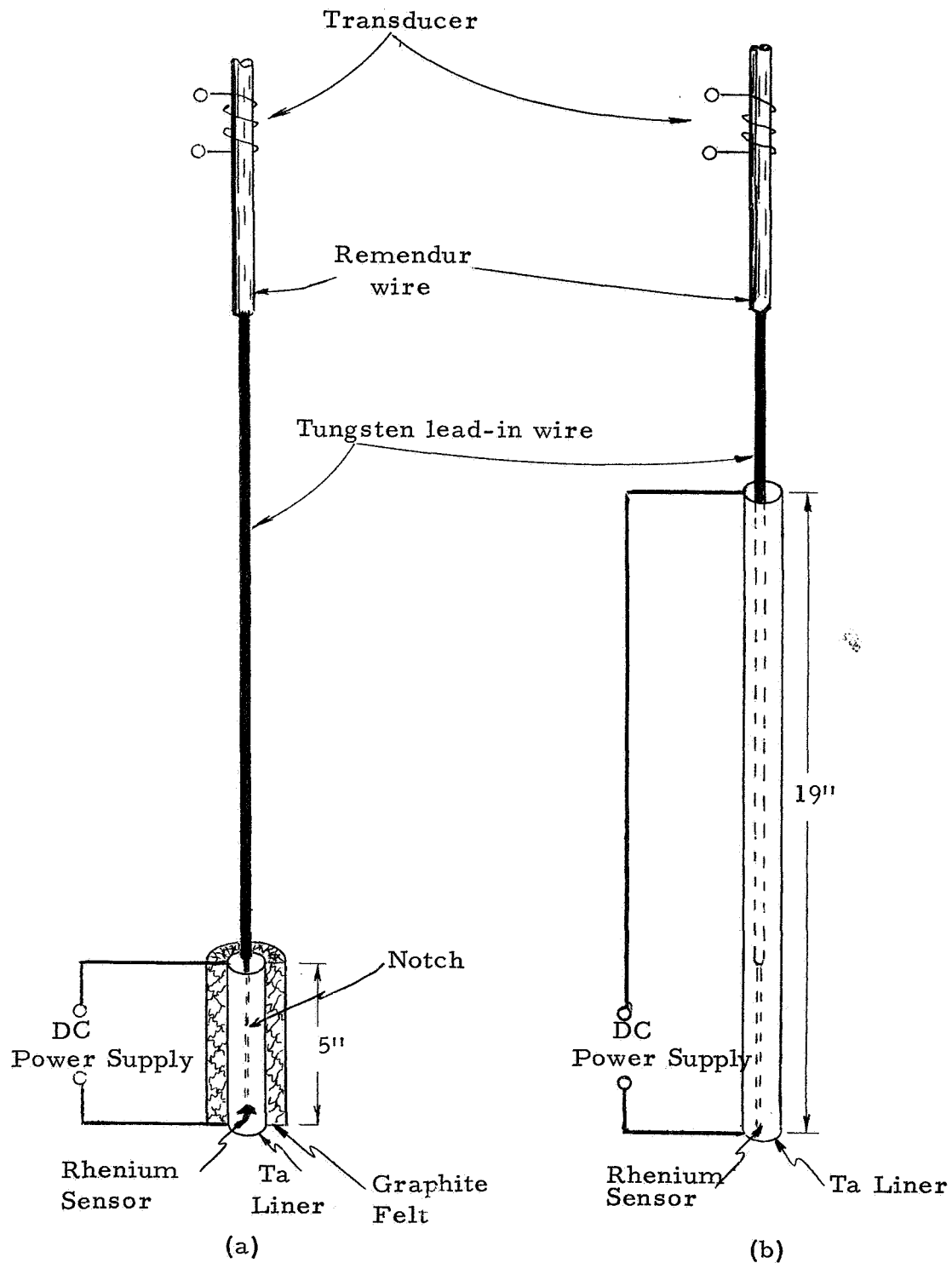
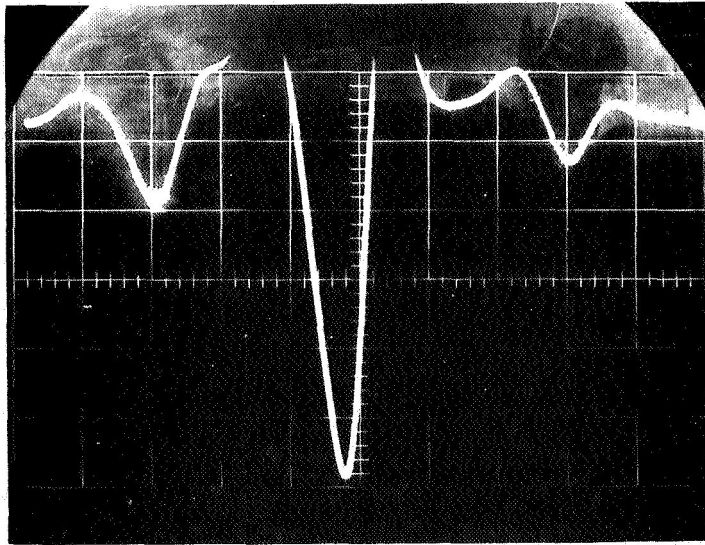


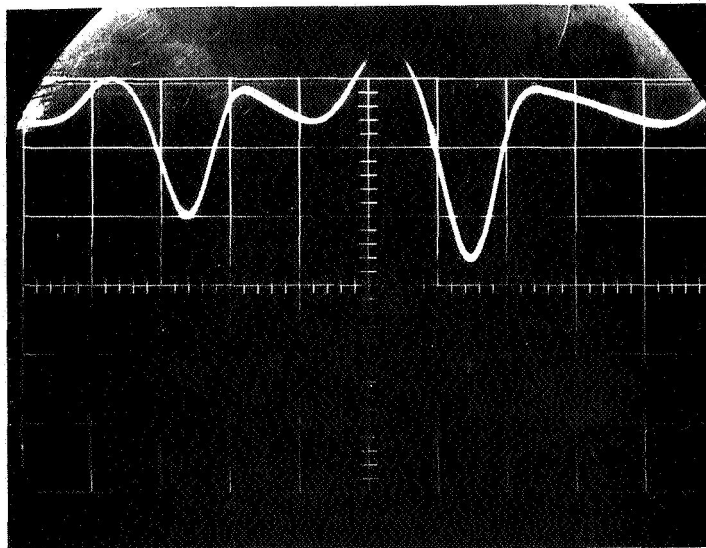
Figure 4. Ultrasonic line used to measure temperature in carbon and carbon-free environment. The ultrasonic echoes reflect from the beginning and end of the rhenium sensor.



Room Temperature

1 v/cm 20 μ sec/cm

Weld Echo End Echo

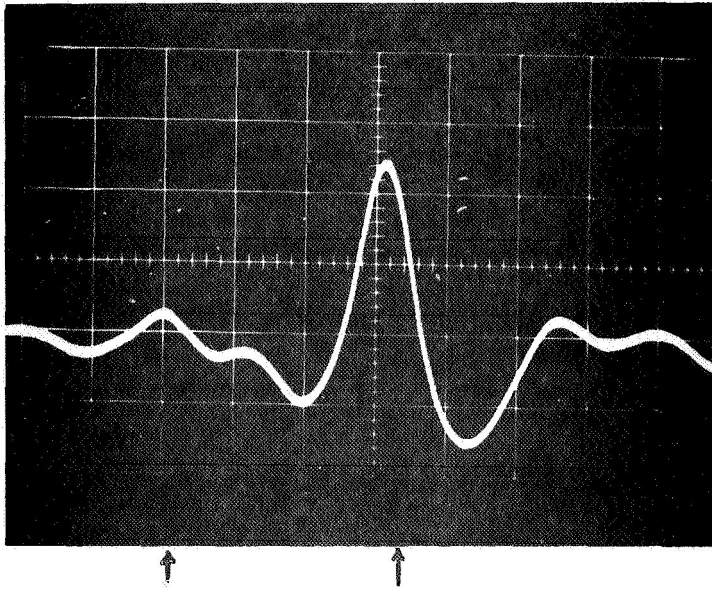


5100°R

1 v/cm 20 μ sec/cm

Weld Echo End Echo

Figure 5. Oscillograms of echoes in 0.030" dia x 4" long rhenium sensor in a 19" long tantalum sheath. The diameter of tungsten spiral spacer wire was 0.002". The lead-in was 0.040" dia tungsten and the pulse width was 25 μ sec.

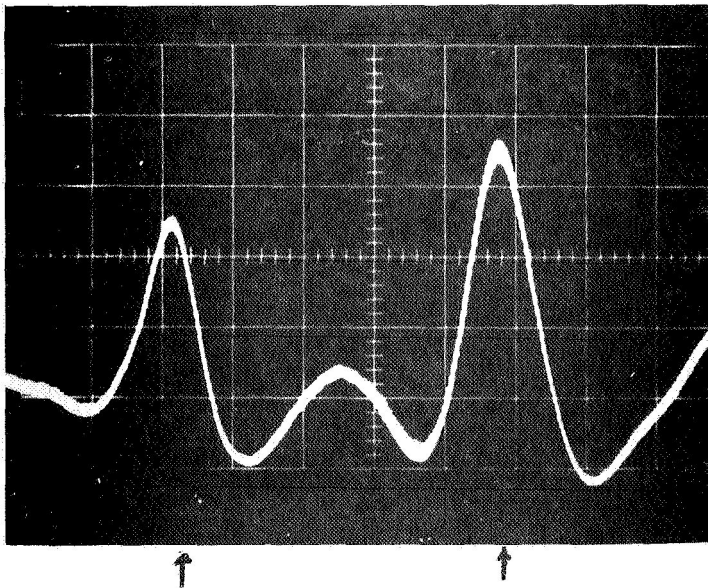


Room Temperature

0.5 v/cm . 20 μ sec/cm

Beginning
of Sensor

End of
Sensor



5250^oR

0.2 v/cm 20 μ sec/cm

Beginning
of Sensor

End of
Sensor

Figure 6. Oscillograms of echoes in 0.030" diameter x 5" long rhenium sensor in a self-heated 19" Ta sheath. The sheath was surrounded by graphite felt. The lead-in was 0.040" diameter tantalum.

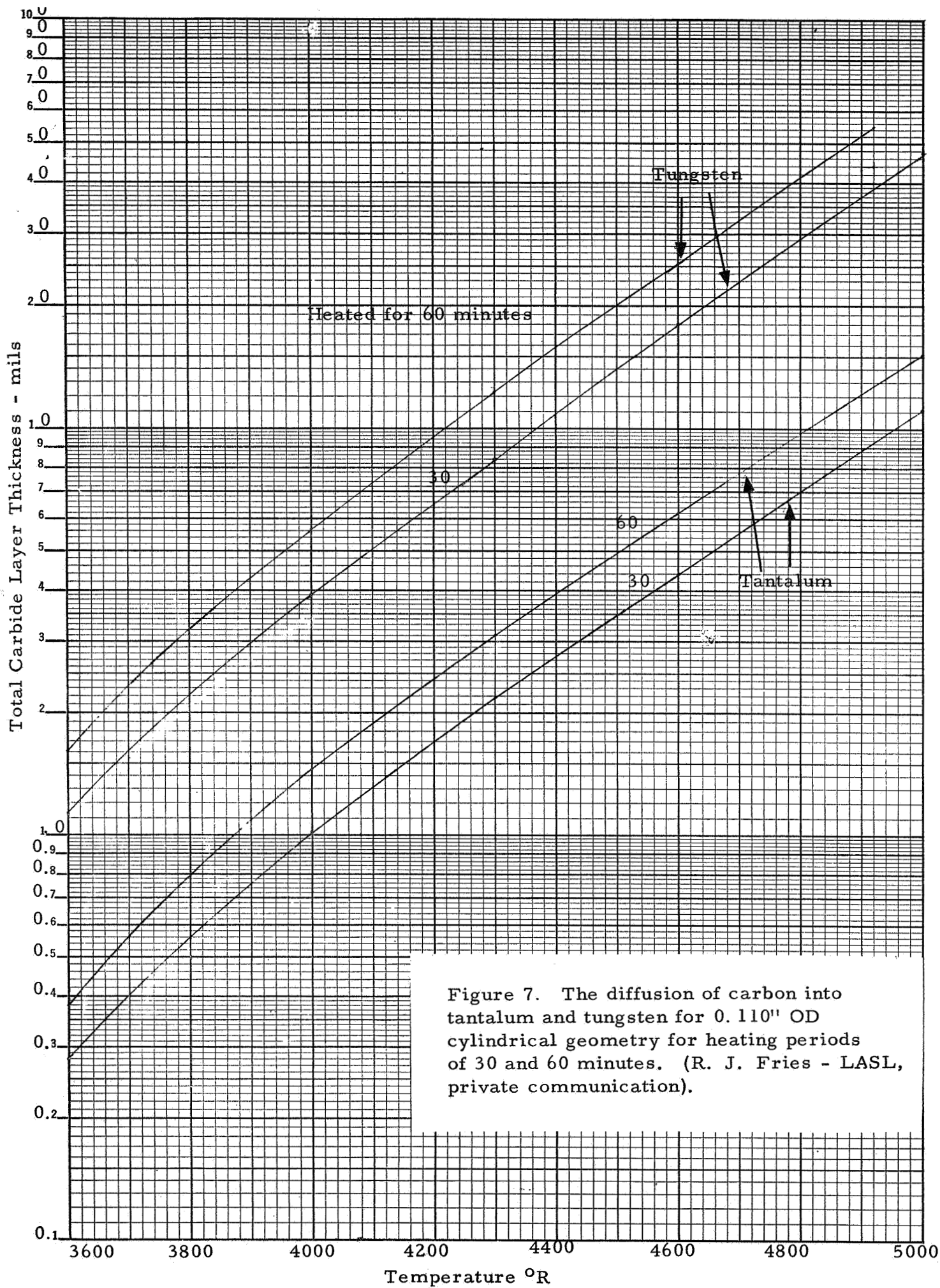
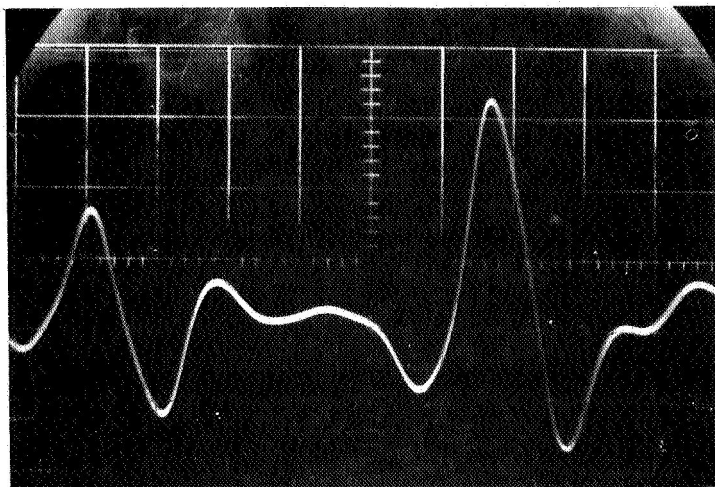


Figure 7. The diffusion of carbon into tantalum and tungsten for 0.110" OD cylindrical geometry for heating periods of 30 and 60 minutes. (R. J. Fries - LASL, private communication).

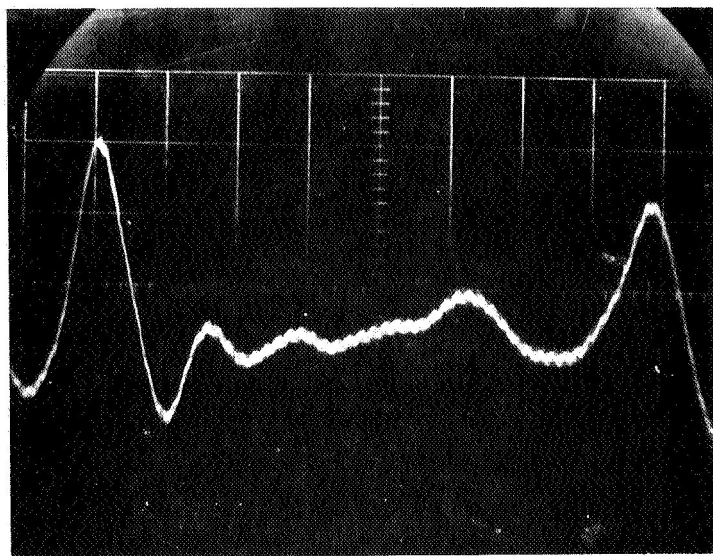


Room Temperature

0.1 v/cm 4 μ sec/cm

↑
Beginning
of Sensor

↑
End of
Sensor



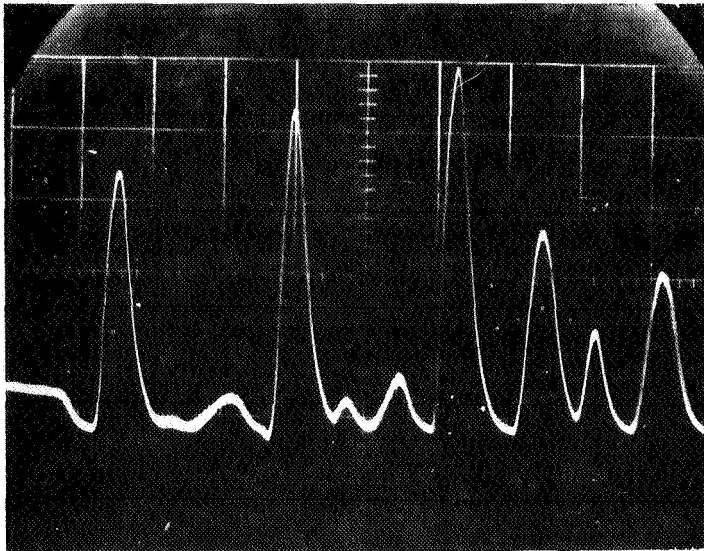
4850°R

0.05 v/cm 4 μ sec/cm

↑
Beginning
of Sensor

↑
End of
Sensor

Figure 8. Oscillograms of echoes in 0.030" diameter x 2" long rhenium sensor in a self-heated tantalum sheath. The sheath was surrounded by graphite felt.

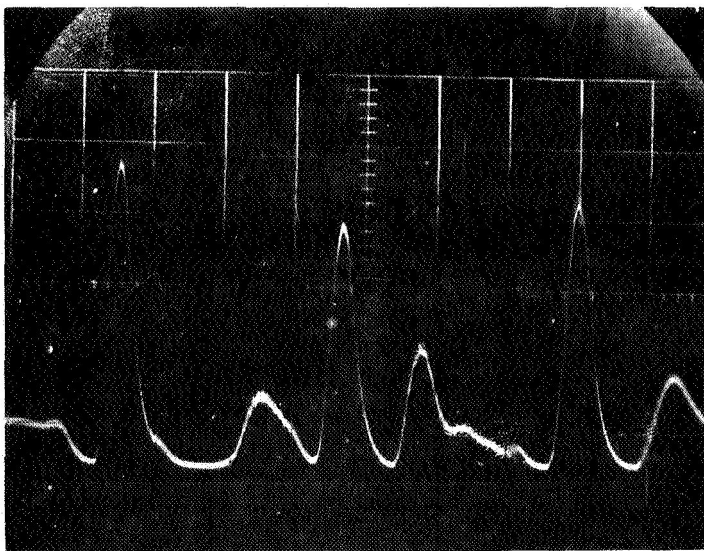


Room Temperature

2 v/cm 10 μ sec/cm

↑
 Beginning
 of Sensor

↑
 End of
 Sensor



5100° R

2 v/cm 10 μ sec/cm

↑
 Beginning
 of Sensor

↑
 End of
 Sensor

Figure 9. Oscillograms of echoes in 0.030" diameter x 2" long rhenium sensor in a self-heated tantalum sheath. The sheath was surrounded by graphite felt and the rhenium was heated to a temperature of 5100°R for 67 minutes.

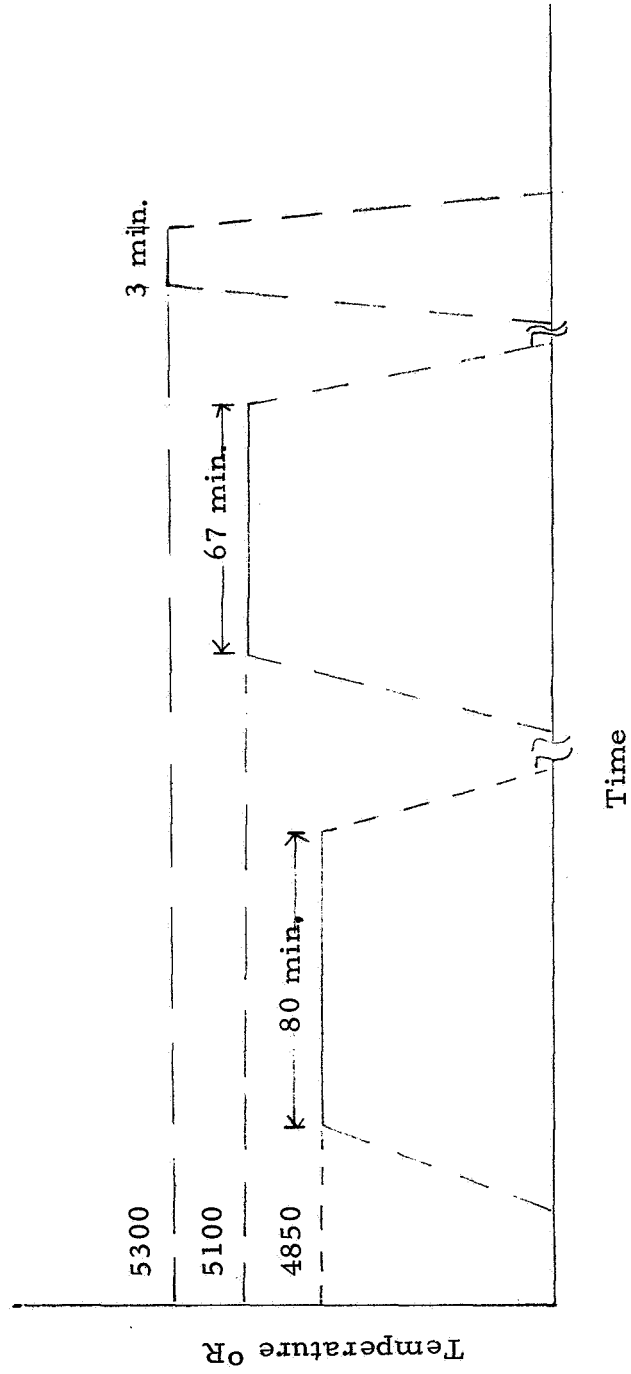
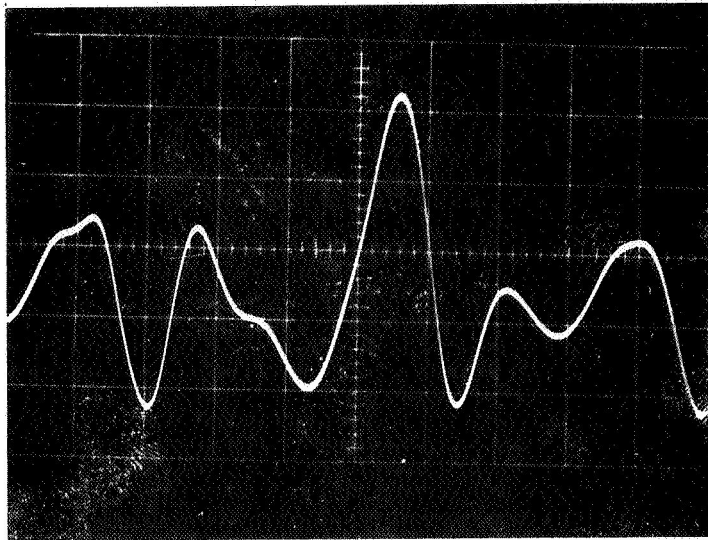


Figure 10. Temperatures greater than 4890°R were measured in a carbon atmosphere for 3 hours with no degradation of the ultrasonic system. The temperature measuring system consisted of 0.030" diameter x 2" long rhenium sensor in a 0.065" OD x 0.012" wall tantalum sheath.

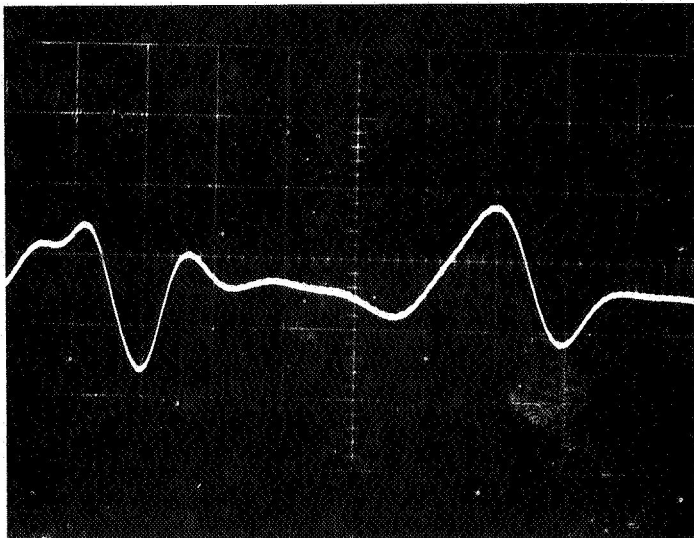


Room Temperature

0.05v/cm 5 μ sec/cm

Beginning
of Sensor

End of
Sensor



4900° R

0.05v/cm 5 μ sec/cm

Beginning
of Sensor

End of
Sensor

Figure 11. Oscillograms of echoes in 0.030" diameter x 2" long rhenium sensor in a self heated W-2% ThO₂ sheath. The sheath was surrounded by graphite felt and the lead-in wire was 0.040" diameter W.

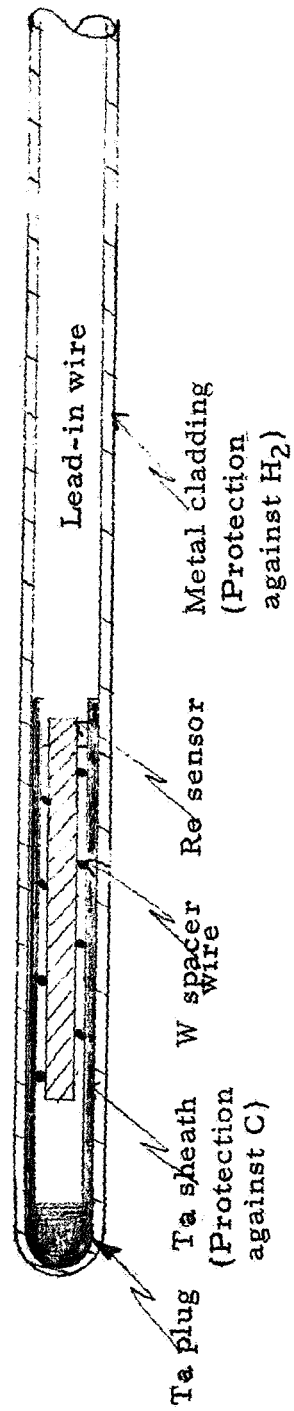


Figure 12. Design of a sheath system intended to
 operate up to 5300°R for one hour in a
 carbon environment.

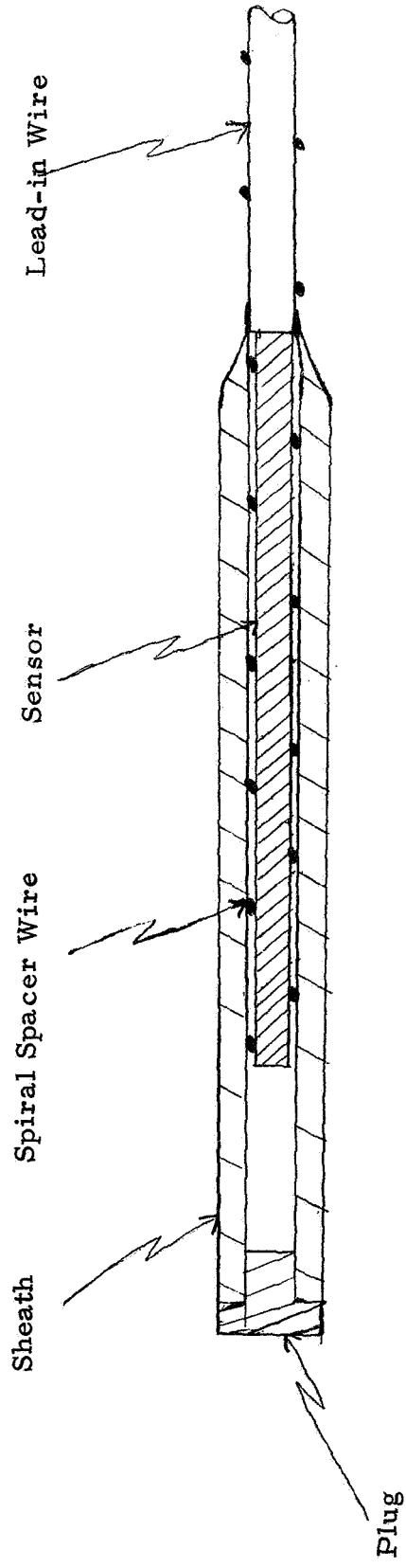
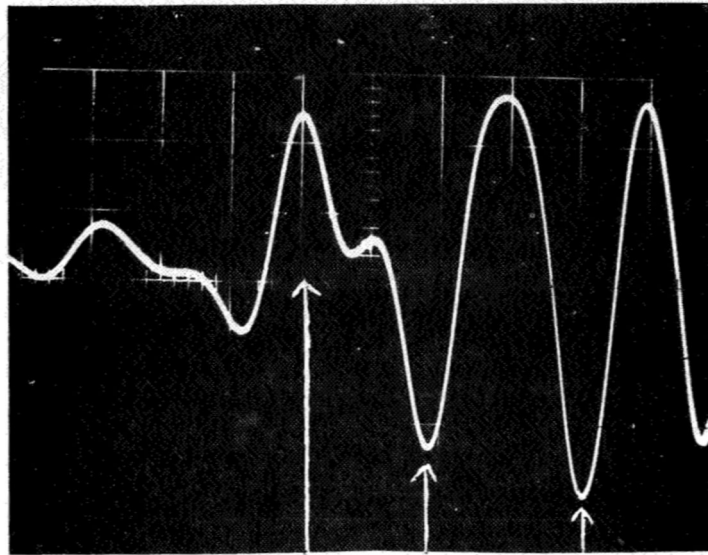


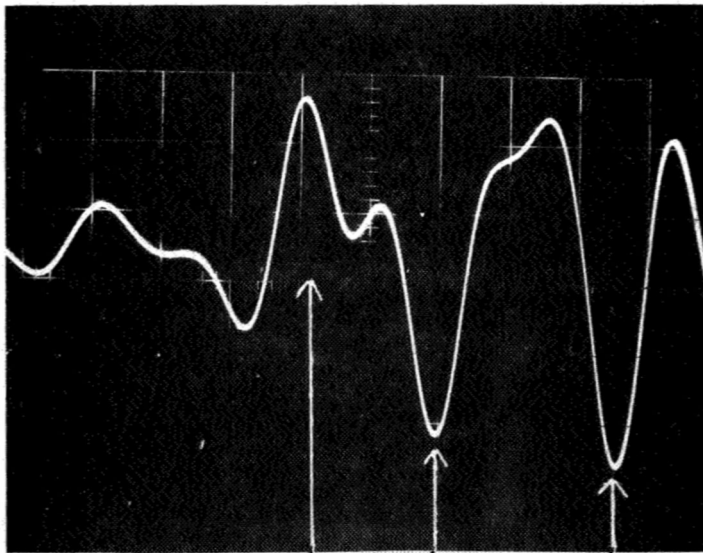
Figure 13. Sheath system consisting of stainless steel tubing and nickel wires. The brazed joints were examined ultrasonically. This showed that the ultrasonic signal could be transmitted through the brazed area with no degradation (see Figure 14).



Braze Echo Sensor Echo End of tube Echo

Room Temperature

1 v/cm 20 μ sec/cm



Braze Echo Sensor Echo End of tube Echo

Last inch of tube heated with torch

1 v/cm 20 μ sec/cm

Figure 14. Oscillograms of echoes in 0.056" dia x 4" long nickel sensor in a 0.096" x 8" long stainless steel tube.

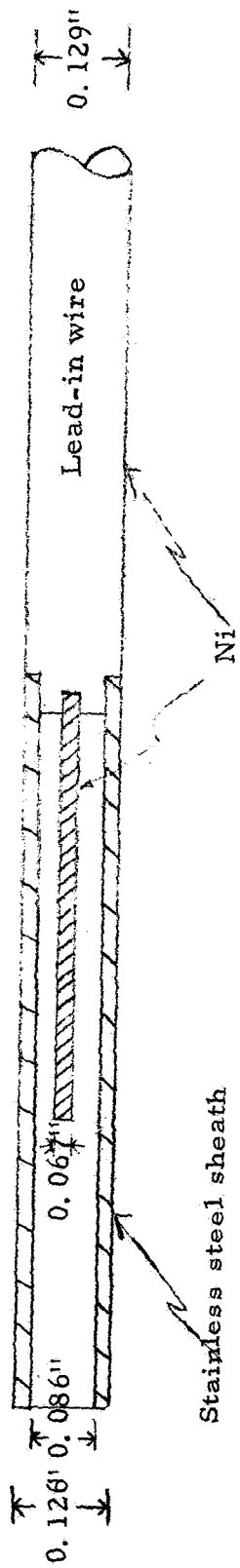
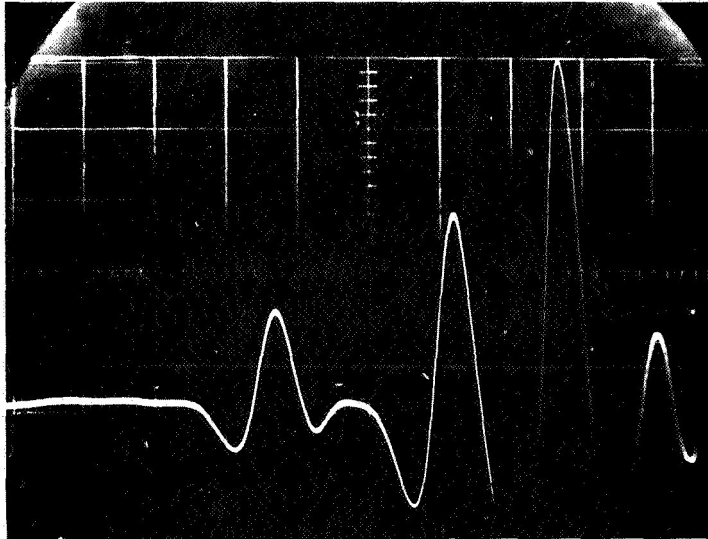
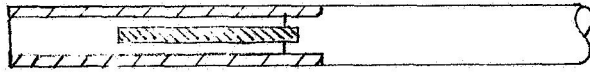


Figure 15. Sheath system consisting of stainless steel tubing and nickel wires. The brazed joints were examined ultrasonically. This showed that the sheath could have the same diameter as the lead-in wire and there was no degradation of the signal (see Figure 16).



Room Temperature

0.2 v/cm 20 μ sec/cm

↑
Braze
Echo

↑
Sensor
Echo

↑
End of Tube
Echo

Figure 16. Oscillogram of echoes in 0.067" diameter x 5' long nickel sensor in a 0.126" diameter x 8' long stainless steel tube.

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MONTREAL, CANADA

October 23 - 25, 1968

ULTRASONIC THERMOMETRY FOR NUCLEAR REACTORS

L. C. Lynnworth,* E. H. Carnevale,* M. S. McDonough,* S. S. Fam*

ABSTRACT

Ultrasonic thermometry, based on the temperature dependence of sound velocity in solids, has been demonstrated under ideal laboratory conditions beyond 6000R. Integrated fluxes (nvt) of 2.6×10^{19} fast and 8.7×10^{19} thermal do not perturb the velocity/temperature relationship. Ta protective sheaths prevented carbon contamination for 1 hr at 5100R, in a program simulating temperature measurements in the graphite/hydrogen atmosphere of a nuclear rocket engine. Tests have also been performed in liquid sodium at 1200R, and separately, inside a 1.6 mm dia Ta tube heated to 5500R, simulating temperatures inside UO_2 -fueled pins of fast breeder reactors.

Introduction: The difficulties in measuring temperature in nuclear reactors stem mainly from severe environmental conditions including nuclear radiation, high temperatures (particularly in the fuel elements), materials compatibility and geometrical restrictions. Until recently, most approaches to nuclear thermometry have been based upon thermocouples. Thin wire ultrasonic systems, however, utilizing the temperature dependence of the speed of sound in solids, offer an alternative to thermocouples.¹⁻³ In principle, ultrasonic thermometers obviate a number of the limitations inherent in thermocouple approaches. So far, ultrasonic data have been obtained in the laboratory beyond 6000R.⁴⁻⁶ By 1970, it is anticipated that ultrasonics will demand the active attention of those responsible for temperature measurement and control, to the extent that potential advantages such as accuracy, stability, reliability, small sensor diameter and low system cost, can, in fact, be demonstrated.

Pulse-Echo System. One type of ultrasonic pulse-echo system is shown in Figs. 1a and 1b. The Pana-Therm electronic instrument automatically measures the round trip time necessary for the ultrasonic wave to traverse the sensor. The response time of the instrument is 0.1 sec. Time resolution is 0.1 μ sec, corresponding to a temperature precision of 1% at 5000R, for a 50 mm (2") sensor. Figure 2 presents the transit time vs temperature for various solids. Given these calibration curves, the transit time/temperature curves for other materials may be readily established by heating them side-by-side

with standard materials, for example, in a tube, as shown in Fig. 3. Such systems are being developed to automatically measure temperatures up to ~5500R in liquid metal fast breeder reactors (LMFBR's) and also to 5300R in a nuclear rocket engine.

Nuclear Rocket Engine. For the hydrogen/graphite/nuclear rocket engine environment, Re sensors have received primary attention.⁴ Bare self-heated Re sensors have been tested up to the melting point (6216R) in carbon-free vacuum, including thermal cycling to 5300R. Rhenium sensors have also survived brief tests in a hydrogen/graphite atmosphere up to ~4765R. Where necessary, protective sheaths, similar to the types developed for thermocouple applications, can be used. For example, Ta sheaths have protected Re sensors from carbon up to 5100R for one hour (Fig. 4). Rhenium wires irradiated to 8.7×10^{19} integrated thermal flux and 2.6×10^{19} integrated fast flux showed no significant radiation effects in the transit time/temperature characteristic. To minimize errors due to gamma heating (> 100 w/g), one approach has been to use very thin sensors, e.g., dia < 0.1 mm, sheath OD < 1 mm.

Fast Breeder Reactor. Another ultrasonic system is being developed to automatically measure coolant, cladding and fuel temperatures in LMFBR's at temperatures up to ~1700, 1800 and ~5500R, respectively.⁵ The feasibility of employing the cladding itself (pat. pending) as a temperature sensor has been demonstrated on an empty fuel pin in the laboratory (Fig. 5). Also, ultrasonic pulses have been transmitted back and forth through 15 m (50 ft) of W lead-in wire, 6 m (20 ft) of which were at ~2500R, and through self-heated W sensors to their melting point, ~6630R. Ultrasonic tests on bare and sheathed W and SS 304 lines immersed up to 6 m (20 ft) in 1200R sodium showed that the attenuating effects due to sodium viscosity and impedance were negligible.

The relative immunity to electrical noise of an ultrasonic line is rather obvious. Not immediately obvious, however, is its immunity to low frequency vibrations. Figure 6 demonstrates that when the sheath, or even the line itself, is vibrated by a doorbell buzzer, there is apparently no S/N degradation. Besides the ultrasonic pulse frequencies being far above the usual mechanical noise frequencies, one may also employ ultrasonic torsional waves to achieve further separation of signal from those noise sources which excite flexural or extensional modes in the line.

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A complete ultrasonic thermometry system including the Pana-Therm 5010, pressure-tight transducer, a sheathed 6 m SS 304 lead-in containing two 50 mm radius bends (for radiation shielding), and a Re sensor 50 mm long centered in a 150 mm long x 1.6 mm dia Ta tube, was operated in our lab with the lead-in at 1700R, and, separately, with the sensor at 5500R. It is planned to install such a system in a high temperature, fast flux facility for further evaluation with respect to fuel meat and cladding thermometry.

Integrated Flux. It is interesting to contemplate whether the above systems might be used to measure nuclear parameters other than temperature - namely, integrated flux. The physical basis for such a measurement lies in the different sensitivities which different materials exhibit for temperature and integrated flux. Copper, for example, exhibits substantial changes in Young's modulus due to irradiation, while Al is relatively insensitive for comparable exposures. Moduli for both metals, however, respond to temperature changes. Figure 7 illustrates a line containing concentric sensors. The Joule-Wiedemann transducer simultaneously launches both extensional and torsional waves. Transducer geometry matches both modes to the lead-in. At the plane where the concentric sensors join the lead-in, dimensions may be chosen so that the torsional wave primarily interrogates the outer Cu tube, while the extensional wave mainly sees the axial Al sensor (pat. pending). Assuming isothermal conditions, the Al sensor would be used to measure the local temperature, and the Cu sensor, the integrated flux. It may also be possible to derive further information on neutron damage via attenuation measurements. We have not yet, however, demonstrated either of these integrated flux or neutron damage measurement possibilities.

Advantages. Regarding thermometry in nuclear systems, ultrasonics offers two principal advantages over thermocouples - a wider choice of sensor materials and geometries. For example, at low temperatures, say, up to ~1000R, Al is of interest as an ultrasonic sensor. To 2000R, SS is a candidate, especially SS parts of the fuel pin itself. Ruthenium and Mo are of interest to ~4000R, while Re, Ta and W appear useful up to the 5000 to 6000R range. As new refractory materials become available, they become candidate sensors, to overcome those limitations which present materials may impose. The choice of sensor geometries, such as wire < 0.1 mm dia, ribbon, tube, etc., and monolithic, one-material, weld-free construction, is also attractive. This measurement depends on density and elastic properties of the sensor, not electrical

properties.* Avoiding the need for a high temperature electrical insulator overcomes another difficulty inherent in thermocouples.

Disadvantages. Ultrasonic thermometry is just now gaining gradual acceptance in industry. Therefore, practical field experience is limited. Lifetime/stability data, and the effects of high flux rates for extended periods, up to $\sim 10^{22}$ nvt, are yet to be determined.

Acknowledgment. The authors gratefully acknowledge the support of NASA and the AEC, and the guidance provided by Dragon Project personnel, especially E. A. Thorne and Prof. J. F. W. Bell, in the above thermometry programs. In addition, valuable cooperation and test facilities have been made available by Westinghouse Astronuclear, Argonne, Los Alamos and Oak Ridge laboratories. At Panametrics, K. A. Fowler, C. Joslin, W. Loizides, D. Patch, B. Spencer and J. Szwanke assisted with the experiments.

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5. S. S. Fam et al., NYO-3906-4 (Sept. 1968).
6. M. S. McDonough et al., NASA CR-72395 (Dec. 1967).

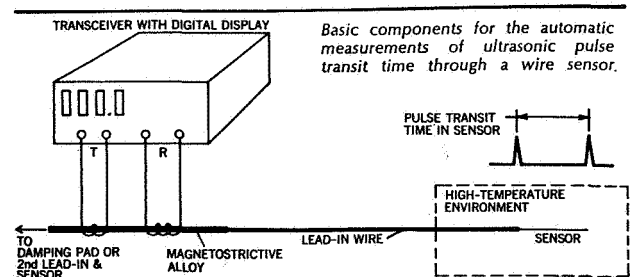


Fig. 1a. Ultrasonic thin wire thermometer.

*The same equipment and techniques described above for measuring temperature can also be applied to measuring physical properties. Young's modulus, shear modulus and Poisson's ratio can be readily determined in thin wire, tube or ribbon. We have tested metals, ceramics, graphites, plastics, paper, wood, glass, etc. in this manner.

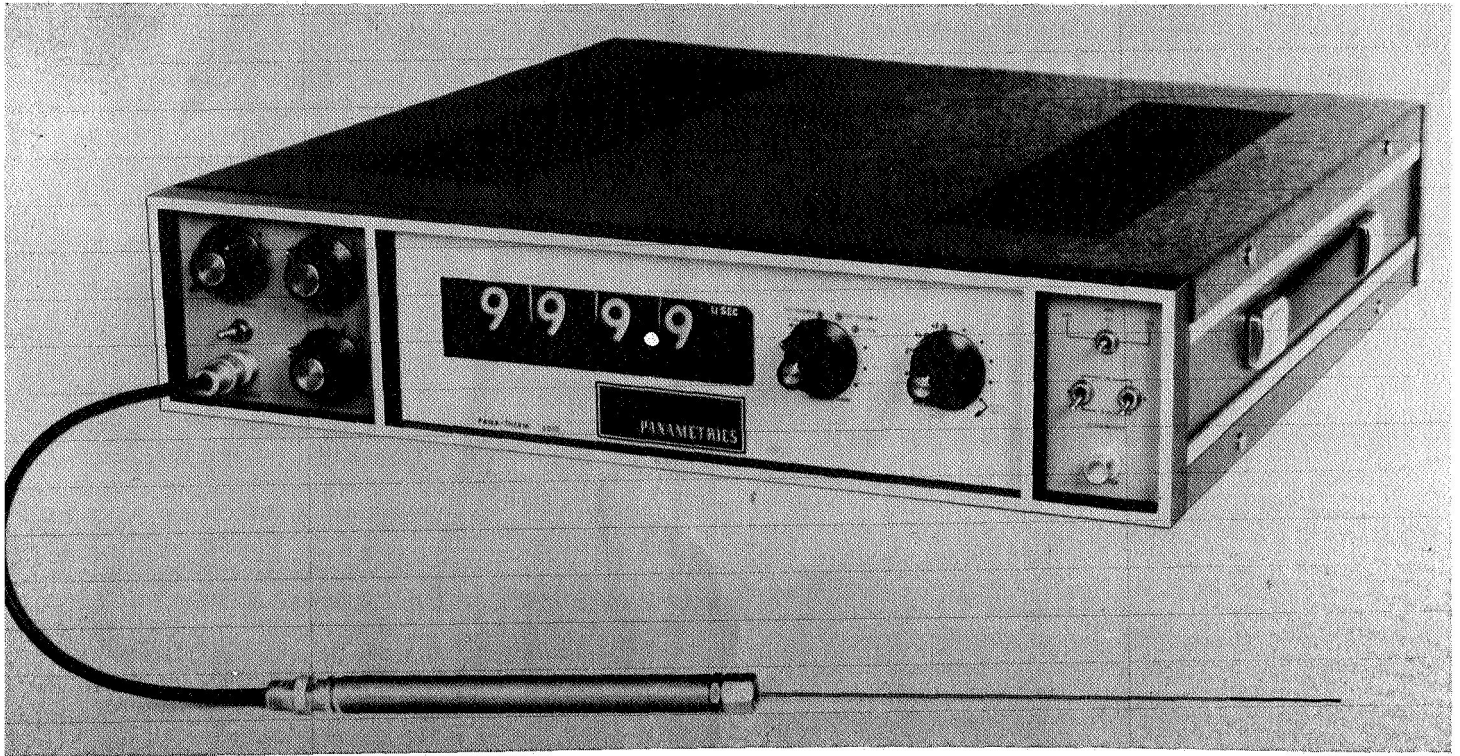


Fig. 1b. Pana-Therm 5010 automatically measures round trip time for pulse to traverse sensor, from which temperature is determined. System consists of (1) transmitter/receiver and readout instrument, (2) transducer, (3) lead-in wire and (4) sensor. Selected echoes are measured between their center-lines to 0.1 μ sec.

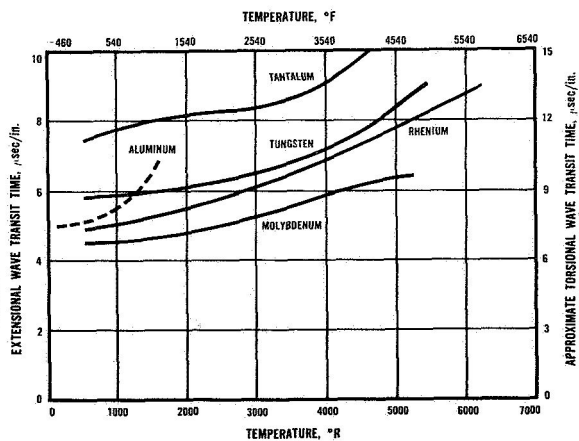


Fig. 2. For extensional waves propagating in solid sensors, the ultrasonic pulse transit time per unit length is equal to the square root of density divided by Young's modulus. Curves show that as temperature increases, the transit time also increases (analogous to emf output of thermocouple). Thus, measurement of transit time in the sensor yields the temperature. For torsional waves, the transit time increases by the factor $\sqrt{2(\sigma+1)}$, where σ = Poisson's ratio. Temperature sensitivity depends on temperature, sensor material and length, wave type, number of reverberations, and time resolution. Self-heating was used to obtain melting point data.

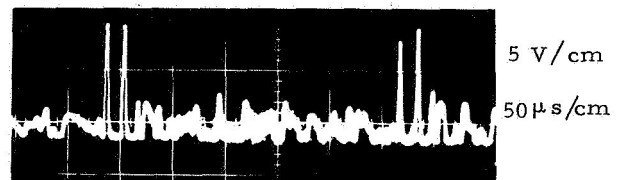
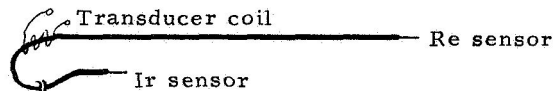
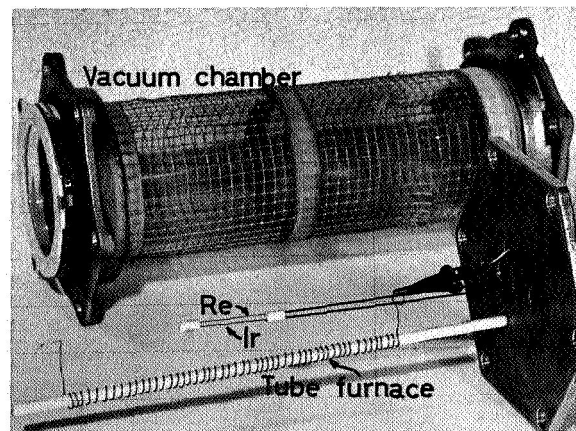


Fig. 3. Simultaneous side-by-side testing of two wires in multibore ceramic tube. Top photo: exploded view shows Ir and Re sensors, wire-wound tube furnace, and Pyrex pipe vacuum chamber. Bottom: oscillogram shows echoes from Ir and Re sensors. Technique may be used to calibrate sensors, or to obtain elastic moduli.

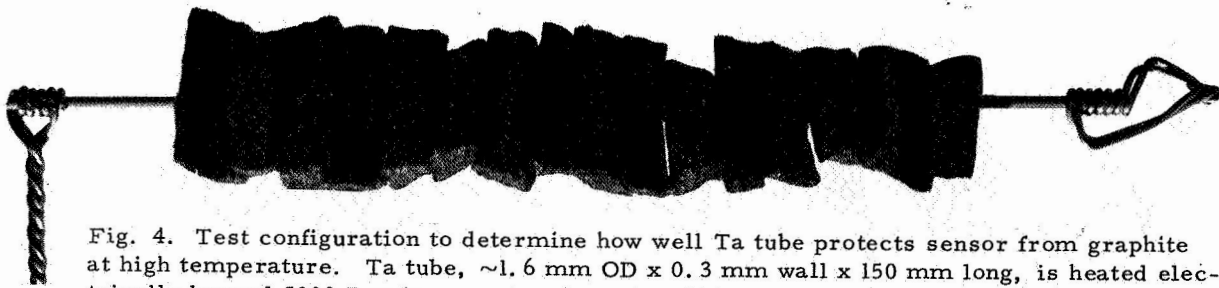


Fig. 4. Test configuration to determine how well Ta tube protects sensor from graphite at high temperature. Ta tube, ~1.6 mm OD x 0.3 mm wall x 150 mm long, is heated electrically beyond 5000 R using currents less than 100 amps.

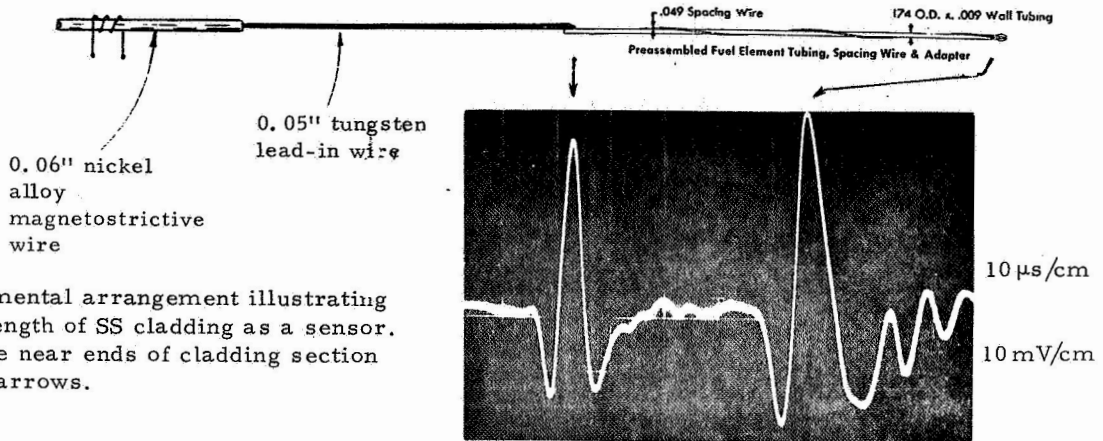


Fig. 5. Experimental arrangement illustrating use of ~10 cm length of SS cladding as a sensor. Echoes originate near ends of cladding section as indicated by arrows.

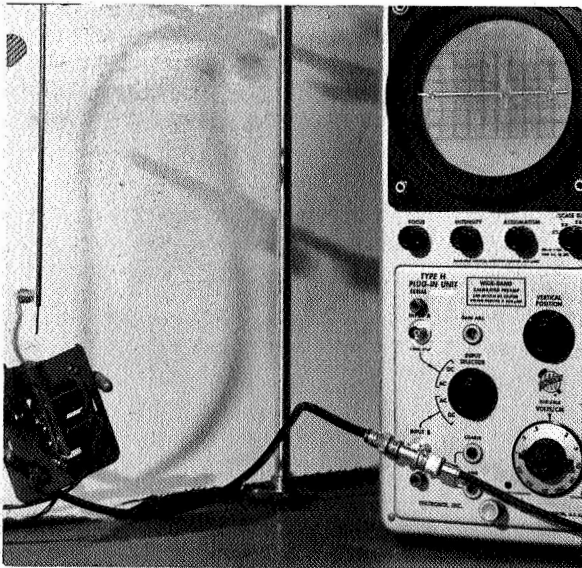


Fig. 6. Ultrasonic signal is "loud and clear" despite doorbell buzzer ringing against sheath, or even against the line itself. Signal/noise ratio remains high for either extensional or torsional waves.

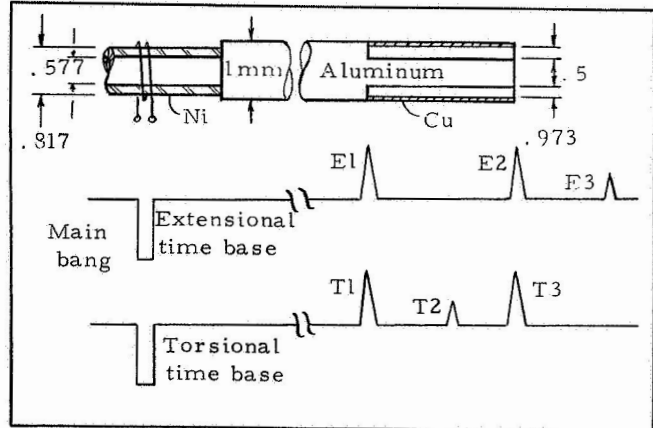


Fig. 7. Coaxial sensors for measuring two environmental parameters, or radial temperature distribution. Above sketch shows Al axial wire to sense temperature, and Cu tube to sense integrated flux. Joule-Wiedemann transducer simultaneously launches extensional and torsional waves in nickel tube. Materials and dimensions are chosen to match both waves to the lead-in. Waveform sketches show extensional echoes E1 and E2 primarily from the Al wire, and E3 from the end of the Cu tube. The two main torsional echoes T1 and T3 are from the Cu tube. The smaller T2 comes from the Al wire. Thus, each mode interrogates a different sensor. Such dual-mode designs exploit the different impedances seen by different waves in the same line.

