179
10-13-78

14. 594

ORNL/TM-6191/V2

MASTER

Monitoring of Prestressed Concrete Pressure Vessels

2. Performance of Selected Concrete Embedment Strain Meters under Normal and Extreme Environmental Conditions

D. J. Naus
C. C. Hurtt

OAK RIDGE NATIONAL LABORATORY
OPERATED BY UNION CARBIDE CORPORATION • FOR THE DEPARTMENT OF ENERGY

DISCLAIMER

This report was prepared as an account of work sponsored by an agency of the United States Government. Neither the United States Government nor any agency Thereof, nor any of their employees, makes any warranty, express or implied, or assumes any legal liability or responsibility for the accuracy, completeness, or usefulness of any information, apparatus, product, or process disclosed, or represents that its use would not infringe privately owned rights. Reference herein to any specific commercial product, process, or service by trade name, trademark, manufacturer, or otherwise does not necessarily constitute or imply its endorsement, recommendation, or favoring by the United States Government or any agency thereof. The views and opinions of authors expressed herein do not necessarily state or reflect those of the United States Government or any agency thereof.

DISCLAIMER

Portions of this document may be illegible in electronic image products. Images are produced from the best available original document.

Printed in the United States of America. Available from
National Technical Information Service
U.S. Department of Commerce
5285 Port Royal Road, Springfield, Virginia 22161
Price: Printed Copy \$6.00; Microfiche \$3.00

This report was prepared as an account of work sponsored by an agency of the United States Government. Neither the United States Government nor any agency thereof, nor any of their employees, contractors, subcontractors, or their employees, makes any warranty, express or implied, nor assumes any legal liability or responsibility for any third party's use or the results of such use of any information, apparatus, product or process disclosed in this report, nor represents that its use by such third party would not infringe privately owned rights.

Contract No. W-7405-eng-26

Engineering Technology Division

HTGR BASE TECHNOLOGY PROGRAM

Prestressed Concrete Nuclear Pressure
Vessel Development (189a 01331)

MONITORING OF PRESTRESSED CONCRETE PRESSURE VESSELS

2. Performance of Selected Concrete Embedment
Strain Meters under Normal and Extreme
Environmental Conditions

D. J. Naus C. C. Hurtt

Date Published: October 1978

NOTICE

This report was prepared as an account of work sponsored by the United States Government. Neither the United States nor the United States Department of Energy, nor any of their employees, nor any of their contractors, subcontractors, or their employees, makes any warranty, express or implied, or assumes any legal liability or responsibility for the accuracy, completeness or usefulness of any information, apparatus, product or process disclosed, or represents that its use would not infringe privately owned rights.

Prepared by the
OAK RIDGE NATIONAL LABORATORY
Oak Ridge, Tennessee 37830
operated by
UNION CARBIDE CORPORATION
for the
DEPARTMENT OF ENERGY

**THIS PAGE
WAS INTENTIONALLY
LEFT BLANK**

CONTENTS

	<u>Page</u>
ACKNOWLEDGMENTS	v
ABSTRACT	1
INTRODUCTION	1
CONCRETE EMBEDMENT STRAIN METERS SELECTED FOR EVALUATION	2
EXPERIMENTAL EVALUATION OF CONCRETE EMBEDMENT STRAIN METERS	3
Performance of Strain Meters Embedded in an Unloaded Sealed Concrete Specimen	3
Performance of Strain Meters Embedded in a Thermally Loaded Sealed Concrete Specimen	8
Performance of Strain Meters Embedded in a Sealed Concrete Specimen Subjected to an Idealized PCPV Environment	10
Performance of Strain Meters Subjected to Extreme Operating Conditions	13
SUMMARY AND CONCLUSIONS	18

**THIS PAGE
WAS INTENTIONALLY
LEFT BLANK**

ACKNOWLEDGMENTS

The planning and execution of this investigation required the assistance and cooperation of numerous people at the Y-12 Plant and in the Solid Mechanics Section of the Engineering Technology Division of Oak Ridge National Laboratory. The authors are indebted to these people for their cooperation and concern for the success of the investigation. A special note of appreciation is due J. P. Callahan, T. M. Cate, H. D. Curtis, and J. E. Smith for substantial contributions during the investigation. Special thanks are also due Mrs. Ragen Foust for typing the manuscript.

MONITORING OF PRESTRESSED CONCRETE PRESSURE VESSELS

2. Performance of Selected Concrete Embedment Strain Meters under Normal and Extreme Environmental Conditions

D. J. Naus C. C. Hurtt

ABSTRACT

Unique types of instrumentation are used in prestressed concrete pressure vessels (PCPVs) to measure strains, stresses, deflections, prestressing forces, moisture content, temperatures, and possibly cracking. Their primary purpose is to monitor these complex structures throughout their 20- to 30-year operating lifetime in order to provide continuing assurance of their reliability and safety. Numerous concrete embedment instrumentation systems are available commercially. Since this instrumentation is important in providing continuing assurance of satisfactory performance of PCPVs, the information provided must be reliable. Therefore, laboratory studies were conducted to evaluate the reliability of these commercially available instrumentation systems.

This report, the second in a series related to instrumentation embedded in concrete, presents performance-reliability data for 13 types of selected concrete embedment strain meters which were subjected to a variety of loading environments, including unloaded, thermally loaded, simulated PCPV, and extreme environments. Although only a limited number of meters of each type were tested in any one test series, the composite results of the investigation indicate that the majority of these meters would not be able to provide reliable data throughout the 20- to 30-year anticipated operating life of a PCPV. Specific conclusions drawn from the study are: (1) Improved corrosion-resistant materials and sealing techniques should be developed for meters that are to be used in PCPV environments. (2) There is a need for the development of meters that are capable of surviving in concretes where temperatures in excess of 66°C are present for extended periods of time. (3) Research should be conducted on other measurement techniques, such as inductance, capacitance, and fluidic.

INTRODUCTION

Unique types of instrumentation are used in prestressed concrete pressure vessels (PCPVs) to measure strains, deflections, stresses, temperatures, prestressing forces, moisture content, and possibly cracking.

Their primary objective is to monitor these complex structures throughout their anticipated operating lifetime (20 to 30 years) in order to provide continuing assurance of their reliability and safety. The data generated by the instrumentation are also used to evaluate the degree of agreement between the original design calculations and the measured responses of the actual structure, and to provide confirmation of the concrete properties employed in the original design.

Numerous concrete-embedment instrumentation systems are available commercially. Since this instrumentation is important in providing continuing assurance of satisfactory performance of PCPVs, it is imperative that the information it provides be reliable. For this reason, laboratory studies were conducted to evaluate the reliability of these commercially available instrumentation systems. The results of these studies are being utilized not only to evaluate current systems, but also to provide data for the development of improved systems where required.

This report, the second of two related to evaluations of commercially available strain meters (also referred to as gages) for concrete embedment,* presents results of an investigation to assess the general performance of concrete embedment strain meters, their performance under simulated PCPV conditions, and their performance under extreme environmental conditions.

CONCRETE EMBEDMENT STRAIN METERS SELECTED FOR EVALUATION

An overview of measurement techniques for concrete embedment strain meters, as well as idealized performance characteristics for PCPV applications and meter design considerations, was presented in the first report of this series and will not be repeated. The selection of strain meters for evaluation in this study was based on the same criteria used in the initial investigation. Because of the large number of types and brands of strain meters available, it would be prohibitive in terms of time and

*D. J. Naus and C. C. Hurtt, *Monitoring of Prestressed Concrete Pressure Vessels. 1. An Overview of Concrete Embedment Strain Instrumentation and Calibration Test Results for Selected Concrete Embedment Strain Meters*, ORNL/TM-6191/V1, Oak Ridge National Laboratory (June 1978).

cost to establish performance-reliability trends for all of them. Thus, since only a representative sample of strain meter types could be obtained for evaluation, the study, at least initially, was restricted to meters readily available in the United States. The meters evaluated, along with general characteristics, are presented in Table 1.

EXPERIMENTAL EVALUATION OF CONCRETE EMBEDMENT STRAIN METERS

The general characteristics of the meters (gage length, strain range, sensitivity, calibration factor, readout requirements, cost factors) and the adequacy of manufacturer-supplied calibration factors were established previously, and the results are contained in the first report of this series. The series of experimental investigations conducted in this phase of the study were designed to evaluate the performance of the meters while subjected to a variety of loading environments, including unloaded, thermally loaded, simulated PCPV, and extreme environments (room- and elevated-temperature alkaline-water baths, and elevated temperatures).

Performance of Strain Meters Embedded in an Unloaded, Sealed Concrete Specimen

The stability of the embedded strain meters was evaluated by using a copper-sealed, cylindrical, reinforced-concrete test specimen 40.6 cm in diameter by 101.5 cm long. Contained within the cylinder and aligned with the cylinder axis were 18 embedment strain meters: three unbonded wire Type A, one unbonded wire Type B, two unbonded wire Type C, two plastic encapsulated Type A, three single wire, two vibrating wire Type A, one vibrating wire Type B, two vibrating wire Type F, and two vibrating wire Type G. Plastic encapsulated Type B and vibrating wire Types C, D, and E meters were not included in the stability test series either because of limited availability of these types or because they were obtained for evaluation after initiation of the test series.

The test specimen fabrication procedure included: wiring the meters into position in the reinforced cage as shown in Fig. 1; applying weldable strain gages (Ailtech MG 125 11H) to the vertical bars of the reinforcement cage at midheight and at 120° intervals; verifying that the strain-

Table 1. Concrete embedment strain gages

Type	Gage length (cm)	Strain range ($\mu\text{m}/\text{m}$)	Temperature range ($^{\circ}\text{C}$)	Sensitivity ($\mu\text{m}/\text{m}$)	Calibration factor	Readout requirements	Meter temperature coefficient ($\mu\text{cm cm}^{-1} ^{\circ}\text{C}^{-1}$)
Electrical resistance							
Plastic encapsulated Type A	1-13	-20,000 to +15,000	-20 to +80	10	2.11	Strain indicator	<i>a</i>
Plastic encapsulated Type B	25	50,000	-100 to +121	5-10	2	Strain indicator	1.8 ^b
Single wire	5-15	$\pm 20,000$	-200 to +315	5-10	2	Strain indicator	10.8
Unbonded wire Type A	10-15	3,900	55	± 5		Bridge circuit	12.1
Unbonded wire Type B	10-25	+500 to -1,000	-30 to +70	± 6		Bridge circuit	14.2
Unbonded wire Type C	5-10	$\pm 5,000$	-20 to +100	5-10	~ 2.5	Strain indicator	<i>a</i>
Vibrating wire							
VWSG Type A	7-14	>1,000	30	0.5	0.96×10^{-3}	Period or frequency meter	11.0 ^c
VWSG Type B	14	>1,000	80	0.5	3.00×10^{-3}	Period or frequency meter	7.5 ^c
VWSG Type C	12.7	4,000	-40 to +66	1.0	<i>d</i>	Period or frequency meter	15.5
VWSG Type D	13	3,000		0.5	2.60×10^{-3}	Period or frequency meter	11.2
VWSG Type E	10	3,000	-40 to +80	0.1	2.01×10^{-3}	Period or frequency meter	13.5
VWSG Type F	8.8	1,000	-10 to +70	1	1.20×10^{-3}	Period or frequency meter	11.0
VWSG Type G	13.3	2,000	-10 to +70 ^e	1	3.00×10^{-3}	Period or frequency meter	-3.6 ^b

^aCorrections for thermal effects obtained from apparent strain vs temperature graphs supplied by meter manufacturer.

^bApparent strain coefficient when meter is embedded in concrete.

^cEstimated values.

^dStrain determined from table supplied with gages which accounts for nonlinearities.

^eMay be specified for temperature range -30 to +200°C.

sensing axis of each meter was aligned with the cylinder axis; placing the reinforcement cage containing the meters in the copper-jacket-lined cardboard mold (Sonotube) shown in Fig. 2; placing the mold containing the reinforcement cage on a vibrating table; filling the mold slowly while it undergoes continual vibration with a representative PCPV mix (gravel/cement ratio = 2.60, sand/cement ratio = 2.02, and water/cement ratio = 0.48); and sealing the upper open surface of the mold with polyethylene sheeting immediately after filling to prevent moisture loss. Control cylinders 15.2 cm in diameter by 30.5 cm long were also cast according to ASTM standard C-192. Approximately 2 days after casting, the cardboard mold and polyethylene sheeting were removed, and the upper surface of the test specimen was permanently sealed with a soldered copper lid* (see Fig. 3). Control cylinders were also demolded, wrapped in plastic, and stored in close proximity to the test specimen. The properties of the concrete used for casting cylinder 1 are summarized in Table 2.

After the cylinder was cured for 68 days, the stability test series was initiated. Three mechanical gage point sets with 20.3-cm gage lengths were attached at 120° intervals to bolt studs which had been precast into the concrete cylinder. Electrical wire resistance meters (plastic encapsulated Type A, single wire, unbonded wire Type C, and weldable) were connected to the Vishay-Ellis signal conditioning and recording system shown in Fig. 4; gage factors (spans) were adjusted taking into account lead wire resistance for each of these meters; and the reading of each meter was zeroed. Initial reference (zero) readings were obtained for the unbonded wire Types A and B meters using a Kyowa CM-4F Universal Indicator (Fig. 5), for the vibrating wire Types A, B, F, and G using a Deakin Model RRL/P/S&T strain (period meter) and temperature measuring instrument (Fig. 6), and for the mechanical gage points using a mechanical gage (Fig. 7). Readings were then obtained from each embedded meter periodically throughout the duration of the test. Temperature measurements were also obtained with each data set for each meter possessing this capability† (unbonded wire Types A, B, and C, and vibrating wire Types A, F, and G).

*A sealed specimen was used to simulate a mass concrete condition.

†Temperature measurements were obtained through resistance changes of a wire or coil within the meter.

Table 2. Properties of concrete mixes
(40.6-cm-diam by 101.5-cm-long cylindrical test specimens)

Cylinder No.	Relative weights, SSD ^a basis				Plastic concrete properties			Hardened concrete properties	
	Cement	Sand	Gravel	Water	Unit weight (kg/m ³)	Slump (cm)	Air content (%)	Elastic modulus (GPa)	Stress at failure (MPa)
1	1.00	2.02	2.60	0.48	2444	6.99	2.3	39.02	42.40
2	1.00	2.02	2.60	0.48	2441	6.99	2.1	38.06	40.00
3	1.00	2.02	2.60	0.48	2435	3.81	2.7	39.02	45.78

^aSaturated, surface dry.

Readings were obtained from each functioning meter throughout the entire 539-day test. Figures 8, 9, and 10 present apparent strain and temperature histories for the bonded wire resistance, unbonded wire resistance, and vibrating wire meters, respectively. Apparent strains were evaluated according to the following relationship:

$$\epsilon_{APP} = \epsilon_{IND} + (\alpha_m - \alpha_c)(T_f - T_i) ,$$

where

ϵ_{APP} = apparent strain,

ϵ_{IND} = indicated strain,

α_m = temperature coefficient of meter* (Table 1),

α_c = temperature coefficient of concrete ($6.66 \times 10^{-6} \text{ cm cm}^{-1} \text{ }^\circ\text{C}^{-1}$),

T_f = temperature when strain reading obtained, $^\circ\text{C}$,

T_i = temperature at test initiation, $^\circ\text{C}$.

No external loadings were applied to the cylinder throughout the test series. Apparent strains were thus the result of autogenous volume changes in the concrete, laboratory thermal fluctuations [$T = (26 \pm 6)^\circ\text{C}$], and systematic drift of the meters.

At the conclusion of the test series, 4 of the 18 embedded strain meters had failed, with failure defined as being either excessive strain (arbitrarily selected as a strain drift rate in excess of $1 \mu\epsilon/3$ days) or the inability to obtain a reading. Meter failures included two plastic encapsulated Type A (excessive strain), one single wire (excessive strain), and one vibrating wire Type F (no reading). Two additional meters, an unbonded wire Type C and a single wire, exhibited excessive strains for approximately 100 days in the first half of the test series, but thereafter their readings returned within acceptable limits. The results from this phase of the study tend to indicate that the stability of the strain meters under controlled conditions (i.e., loaded neither by application of external forces nor by temperature) was generally good. The one notable

*Temperature corrections for the plastic encapsulated Type A and unbonded wire Type C meters were made using values obtained from graphs supplied by the manufacturers.

exception was the plastic encapsulated gage which had a tendency to absorb moisture and thus exhibited excessively large systematic drift errors. However, it should be noted from calibration test results listed in the first report of this series that these meters, when used for short-term tests, provide very good results, and they are among the least expensive of the embedment meter types.

Performance of Strain Meters Embedded in a Thermally Loaded Sealed Concrete Specimen

The effect of thermal loading on the performance of meters embedded in a 40.6-cm-diam by 101.5-cm-long sealed concrete specimen was evaluated in this test series. Six types of meters were available for this phase of the investigation: one plastic encapsulated Type A, one single wire, one unbonded wire Type A, one vibrating wire Type A, one vibrating wire Type F, and one vibrating wire Type G.

The test specimen fabrication procedure was identical to that followed for the first 40.6-cm-diam by 101.5-cm-long sealed concrete specimen. Figure 11 shows the cylinder reinforcement cage prior to placement in the copper-jacket-lined cardboard mold. Also contained within the cylinder were three weldable strain gages (Ailtech MG 125 11H) applied to the vertical reinforcement bars of the cage at midheight and at 120° intervals, and two thermocouples which were cast into the cylinder for the purposes of sensing and controlling temperature throughout the test series. The properties of the concrete used for casting cylinder 2 are summarized in Table 2.

After cylinder 2 was cured for 71 days, a heating blanket was placed around it over its entire length, and insulation was applied to the cylinder sides and top (Fig. 12). Electrical resistance strain meters (plastic encapsulated Type A, single wire, and weldable) were connected to the Vishay-Ellis signal conditioning and recording system, gage factors (spans) adjusted taking into account lead wire resistance, and readings were zeroed. Initial reference (zero) readings were obtained for the unbonded wire and vibrating wire gages. Thermocouples were connected to the recorder-controller system and calibrated against a reference standard, and the test was initiated.

One hundred days after casting (29 days into the testing program) the heating blanket was connected to a Variac controller system, and heatup of the cylinder was initiated. After 11 days of heating, the cylinder temperature reached the desired test temperature of $(65 \pm 4)^{\circ}\text{C}$;^{*} however, during the heatup, there were temperature excursions between 47°C and 74°C . This test temperature was maintained for an additional 189 days (229 days into the test program), at which time there was an equipment malfunction that enabled the cylinder temperature to increase to 100°C , which was in excess of the stated temperature limits of all embedded meters except the single wire and weldable. The temperature of the cylinder was then permitted to return to the test temperature where it was maintained for an additional 53 days (282 days into the test program). Cylinder heating was then terminated, and the cylinder temperature was permitted to slowly return to room temperature, where it was maintained until completion of the test series.

Strain and temperature readings were obtained throughout the entire 539-day duration of this test series. Figure 13 presents apparent strain and temperature histories for each of the meters evaluated in this test series. The only loading applied during the test was thermal; thus, apparent strains were the result of autogenous volume change in the concrete, thermal effects, and systematic drift of the meters.

At the conclusion of this test series, the plastic encapsulated Type A meter, one weldable meter, and vibrating wire Types A, F, and G had failed. The plastic encapsulated gage was indicating excessive strain ($>14,000 \mu\text{cm/cm}$), the weldable meter reading was unstable (rapid drift), and a period reading could not be obtained for the vibrating wire meters. In addition, the single wire meter, 184 days into the test series, started exhibiting more rapid strain increases than the other meters and by the conclusion of the test its apparent strains were approximately twice those of the two functioning meters (unbonded wire Type A and weldable). As

^{*}Table CB-3430-1 of *ASME Boiler and Pressure Vessel Code for Concrete Reactor Vessels and Containments* (ACI Standard 359-74), Section III, Division 2, for normal loading limits the temperature for bulk concrete to 65.6°C , for bulk concrete with nuclear heating to 71.1°C , and for local hot spots to 121.1°C . Bulk concrete temperature limits for abnormal and extreme environments are 93.3°C and 154.4°C , respectively.

would probably be expected, the test results for this phase of the investigation indicate that the meters investigated (except for the unbonded wire Type A and weldable) were unable to survive temperature excursions above their rated limits for even relatively short periods of time (1 to 2 weeks). It should be noted, however, that this temperature excursion was still 21°C less than the ASME code temperature limit for local concrete hot spots under normal loading conditions. Thus, as more data becomes available on the behavior of concrete at elevated temperatures and as the present PCPV concrete temperature limitations (average concrete temperature 66°C) are relaxed, the development of meters for embedment in concrete at elevated temperature will be required; in other words, as Table 1 indicates, the upper temperature limit for most of the meters investigated was only slightly greater than the present PCPV concrete temperature limit. Additional information on the behavior of the strain meters when subjected to temperatures greater than the present bulk concrete temperature (65.6°C) is presented later in the elevated-temperature-effects phase of the test series involving extreme environments.

Performance of Strain Meters Embedded in a Sealed Concrete Specimen Subjected to an Idealized PCPV Environment

The performance of the strain meters subjected to a combination of thermal and compressive loadings such as might be encountered in a PCPV was evaluated in this test series.* A sealed concrete cylinder 40.6 cm in diameter by 101.5 cm long was used as the test specimen. Twelve embedment strain meters (one plastic encapsulated Type A, one single wire, one unbonded wire Type A, one unbonded wire Type B, one unbonded wire Type C, one vibrating wire Type A, one vibrating wire Type B, one vibrating wire Type D, one vibrating wire Type E, two vibrating wire Type F, and one vibrating wire Type G) and one stress meter were evaluated in this test series.

*Costs prohibited the inclusion in the test series of low level ($<10 \times 10^{20}$ nvt) irradiation effects, which would have made the environment more representative of a PCPV.

The fabrication of the test specimen followed the same procedures used for the previous two 40.6-cm-diam by 101.5-cm-long sealed concrete cylinders. Figure 14 shows the cylinder reinforcement cage containing the embedment meters to be evaluated prior to its placement in the copper-jacket-lined cardboard mold. Also contained in the cage were three weldable strain gages (Ailtech MG 125 11H) attached at midheight and at 120° intervals on the vertical reinforcement bars of the cage, and three thermocouples, of which one was used for controlling cylinder temperature and two for recording temperature throughout the test series. The properties of the concrete used for casting cylinder 3 are summarized in Table 2.

Approximately 14 days after casting, a neat cement paste mixture was prepared for capping the upper and lower surfaces of the cylindrical test specimen. The cylinder capping procedure consisted of placing approximately half of the cement paste mixture on the upper loading surface of a 4.72-MN loading ram, placing the cylindrical test specimen on the ram, carefully moving the specimen back and forth until only a thin layer of paste remained to provide continuous contact between the ram and the lower surface of the specimen, placing the remainder of the cement paste mixture on the upper surface of the cylinder, positioning the upper reaction platen on top of the cylinder, moving the platen back and forth until only a thin continuous layer of cement paste remained between the platen and the specimen, and adjusting the upper loading platen to align the holes in the upper and lower platens through which eight 2.86-cm-diam high-strength-steel reaction rods* extend to apply load to the test specimen. Vertical cylinder alignment was maintained throughout the capping procedure. Figure 15 shows the specimen in the test fixture. The capping material was permitted to cure for 2 weeks, after which a heating blanket and insulation were wrapped around the sides of the test specimen. The test specimen prior to initiation of testing is shown in Fig. 16.

Testing was initiated 64 days after the specimen was cast. Electrical resistance strain meters (plastic encapsulated Type A, single wire,

*Every other rod in the test fixture was instrumented and calibrated as a transducer so that actual axial loads applied to the cylinder could be monitored throughout the test series.

weldable, unbonded wire Type C) and the tendon transducers were connected to the Vishay-Ellis signal conditioning and recording system, gage factors (spans) adjusted taking into account lead wire resistance, and readings zeroed. Initial reference (zero) readings were obtained for the unbonded wire meters (Types A and B) and the vibrating wire meters (Types A, B, D, E, F, and G). Thermocouples for sensing and controlling cylinder temperature were connected to a recorder and calibrated against a reference standard. Readings from each of the meters were periodically obtained for the next 29 days during which no external loadings were applied to the specimen.

At a test age of 29 days, thermal loading of the specimen was initiated. During the next 105-day interval (134 days into the test series), the temperature of the cylinder was slowly increased until it reached the test temperature of $(65.6 \pm 5)^{\circ}\text{C}$. This temperature was maintained throughout the compression loading phase of the test series, which was an additional 243 days (test duration of 377 days). Strain and temperature readings were also periodically obtained throughout the heatup phase of the test series.

Superposition of uniaxial compression loading onto the already thermally loaded test specimen was initiated 196 days into the test series. The loading procedure consisted of applying the desired load, maintaining it for several days, and then increasing it to the next level of interest. Stress levels investigated were nominally 2.0, 4.2, 6.6, 9.0, 11.5, 13.7, 17.6, and 21.7 MPa. Durations of loading for each of these levels were 5, 16, 14, 21, 26, 28, 29, and 42 days, respectively. Cylinder loading was monitored using the instrumented tendon rods of the test fixture and a calibrated pressure gage* connected to the pressure line between the pump and loading ram. Load, strain, and temperature readings were obtained periodically during each load level and just prior to and 1 hr after each load increment.

*Pressure readings could be equated to tendon rod transducer values by converting tendon rod loads to an effective pressure and adjusting the pressure gage reading to account for differences in area between the ram and cylindrical test specimen. Maximum deviation during the test between pressure gage and load transducer output was 5.2% for pressures above 1.1 MPa.

As previously noted, strain, temperature, and loading histories were obtained periodically throughout the 377-day duration of this test series. These results are summarized in Figs. 17 and 18 for the wire resistance and vibrating wire meters, respectively. The average result from the three weldable gages is also presented in the figures for comparison. Apparent strains presented were the result of autogenous volume changes in the concrete, thermal effects, external loading, and systematic drift of the meters. Results are not presented for the stress meter because of poor correlation with pressure gage and tendon transducer outputs.*

At the conclusion of this phase of the test series, 5 of the 12 embedment strain meters were considered to have failed. These meters included a plastic encapsulated Type A (excessive strains), an unbonded wire Type B (no resistance ratio reading obtainable), and vibrating wire Types A, D, and E (no period reading obtainable). In addition, the single wire and unbonded wire Type C gages were exhibiting significantly less compressive strains than the other functioning embedded meters. The results for this phase of the investigation indicate that the majority of the meters performed adequately; however, the 377-day duration of this test was considerably shorter than a desired operating life of 30 years. These results tend to indicate a need for development of improved sealing techniques, especially for meters which will be embedded within PCPVs to provide continuing assurance of the safety and reliability of these structures.

Performance of Strain Meters Subjected to Extreme Operating Conditions

The stability of strain meters subjected to environmental conditions more severe than would be encountered during normal operation was evaluated in this test series. Test environments included room-temperature alkaline-

*Differences between the readings of the stress meter and other pressure-sensing devices could be attributed to poor contact between the meter and concrete because of localized concrete bleeding adjacent to the meter. The concrete was cast in one continuous lift; thus, the manufacturer's recommended procedures for installation, which included preparation of the concrete surface adjacent to the meter, could not be followed.

water immersion, elevated-temperature alkaline-water immersion, and elevated temperature. Since these environments are relatively severe, they should provide an accelerated indication of the long-term performance of the meters with respect to moisture penetration and elevated-temperature effects.

Room-temperature alkaline-water immersion test

The effectiveness of the techniques used to prevent the ingress of moisture into concrete embedment strain meters, where it either produces a breakdown of meter resistance to ground or causes corrosion, was investigated in this test series. Each of the 13 types of meters presented in Table 1 was investigated. The test setup, including pertinent meter readout instrumentation, is presented in Fig. 19.

The procedure followed for this phase of the test series included: adding a small amount of unhydrated cement to the water bath to increase the pH of the solution to approximately 10 and thus simulate the pH of concrete; placing samples of each type of meter into the solution; connecting the wire resistance meters (plastic encapsulated Types A and B, unbonded wire Type C, and single wire) and their dummy meters (to compensate for temperature fluctuations) to a switching and balancing box; connecting unbonded wire meters (Types A and B) and vibrating wire meters (Types A through G) to a switching box; zeroing resistance meter readings and obtaining reference (zero) readings for the unbonded wire and vibrating wire meters; and periodically monitoring strain output from each of the meters until either a meter failed or the test series was completed. After a meter failed, with failure defined as the meter indicating excessive strain output* or the inability to obtain a reading, it was generally replaced with a meter of the same type.

The total duration of the room-temperature $[(26 \pm 5)^{\circ}\text{C}]$ alkaline-water immersion test was 590 days. During this time span, a total of 39 meters were evaluated. The types and number of meters of each type tested are listed below; the figure numbers in parentheses identify the figures

*Excessive strain failure by definition is strain drift rate in excess of $3 \mu\epsilon/\text{day}$. This value was arbitrarily selected and may be too lax in some cases and too stringent in others.

in which the corresponding test results for each type of meter are presented. The meters tested were: three plastic encapsulated Type A (Fig. 20), six plastic encapsulated Type B (Figs. 21-22), nine single wire (Figs. 23-27), four unbonded wire Type A (Fig. 28), two unbonded wire Type B (Fig. 29), one unbonded wire Type C (Fig. 30), three vibrating wire Type A (Figs. 31-32), one vibrating wire Type B (Fig. 33), two vibrating wire Type C (Fig. 34), two vibrating wire Type D (Fig. 35), one vibrating wire Type E (Fig. 36), three vibrating wire Type F (Figs. 37-38), and two vibrating wire Type G (Fig. 39). As noted in the figures which present test results for meters that were still being evaluated near the conclusion of the test series, 53 days prior to completion of the test series, the water was removed from the bath and the gages were permitted to air dry. Readings were also obtained from the meters during this drying interval. Table 3 presents a summary of the number of meters of each type tested and the number and type of failures experienced, if any.

Elevated-temperature alkaline-water immersion test

The effectiveness of meter sealing techniques was evaluated in a more severe test using an elevated-temperature water bath. All meters listed in Table 1 were investigated except for the plastic encapsulated Type B meter which was procured after completion of the test series, and the vibrating wire Type B meter which failed so rapidly in the room-temperature bath that it was not tested in the elevated-temperature bath. The test setup utilized for this phase of the investigation is presented in Fig. 40.

The procedure followed for this test series was the same as the one employed for the room-temperature alkaline-water immersion test. The elevated test temperature of approximately 66°C was obtained using an immersion heater. During the test series, temperature fluctuations in the water bath were often quite large and resulted either from difficulty in regulating the temperature or from intermittent failure of the immersion heaters due to the alkaline environment.

The total duration of the test series was 440 days. During this time span, a total of 46 meters were tested. The type and number of meters of each type tested are listed below; the figure numbers in

Table 3. Results of alkaline-water immersion test

Gage type	Room-temperature water bath			Elevated-temperature water bath		
	Number tested	Number and type of failure ^a		Number tested	Number and type of failure ^a	
		a	b		a	b
Unbonded wire						
Type A	4	0	0	8	2	1
Type B	2	0	0	2	0	0
Type C	1	0	0	1	0	0
Polyester encapsulated						
Type A	3	3	0	6	6	0
Type B	6	6	0	0	0	0
Single wire	9	4	0	16	7	0
Vibrating wire						
Type A ^b	3	0	1	3	0	1
Type B ^b	1	0	1	0	0	0
Type C	2	0	0	2	0	c
Type D	2	0	2	1	0	1
Type E	1	1	0	1	0	1
Type F	3	0	0	4	0	1
Type G	2	0	0	3	0	2

^aType of failure: a = excessive strain; b = no reading obtainable. Excessive strain failure by definition is a strain in excess of a 3- $\mu\epsilon$ /day drift rate. This value was arbitrarily selected and may be too lax in some cases and too stringent in others.

^bTested as received; manufacturer recommends additional sealing.

^cErratic readings at temperatures greater than manufacturer's stated upper limit.

parentheses identify the figures in which the corresponding test results for each type of meter are presented.* The meters tested were: six plastic encapsulated Type A (Figs. 41-43), fifteen single wire (Figs. 44-50), eight unbonded wire Type A (Figs. 51-53), two unbonded wire Type B (Fig. 54), one unbonded wire Type C (Fig. 55), three vibrating wire Type A (Fig. 56), two vibrating wire Type C (Fig. 57), one vibrating wire Type D (Fig. 58), one vibrating wire Type E (Fig. 59), four vibrating wire Type F (Figs. 60-62), and three vibrating wire Type G (Figs. 63-64). Temperatures and strains occasionally exceeded the manufacturer's recommended limits; when this occurred, it was noted in the appropriate figures. Seventy-seven days prior to conclusion of this phase of the test series, the temperature of the water bath was permitted to return to room temperature, and this fact is noted in the appropriate figures for meters being evaluated at that time. Twenty-four days later the water was removed from the bath, and the meters still under evaluation were permitted to air dry for an additional 53 days. The meters were periodically monitored throughout this drying phase. The number of meters of each type tested and the number and type of failure experienced, if any, are summarized in Table 3.

Elevated-temperature test

The elevated-temperature ($T > 66^{\circ}\text{C}$) test series was conducted merely as an extension of the test series which evaluated the performance of strain meters subjected to an idealized PCPV environment (Fig. 16). The meters evaluated were those that were still operating at the conclusion of the initial series: one single wire, one unbonded wire Type A, one unbonded wire Type C, one vibrating wire Type B, two vibrating wire Type F, and one vibrating wire Type G.

The testing procedure consisted of maintaining the uniaxial compressive stress of 21.7 MPa on the 40.6-cm-diam by 101.5-cm-long cylinder while incrementally increasing the cylinder temperature above its 66°C

*Corrections were not included in indicated strains for the effect of elevated temperature; that is, indicated strains were a function of thermal strains and systematic drift of the meters.

value. Temperature increments were to nominal temperatures of 70, 75, and 80°C, with the cylinder temperature held at these values for periods of 10, 21, and 70 days, respectively. At the conclusion of the 101-day elevated-temperature test series (478 days total testing for this specimen), the cylinder temperature was permitted to return to room temperature over a 12-day interval. Uniaxial compressive loading of the cylinder was then incrementally reduced, with loads held for several days at each increment. The reduced loading levels were nominally 14.0, 7.0, and 0 MPa, with loads held at each increment for periods of 7, 8, and 26 days, respectively. Readings were obtained periodically throughout the elevated-temperature phase of the test series. Temperature and strain histories are presented in Figs. 17 and 18 for the wire resistance and vibrating wire strain meters, respectively.

During the 101-day duration of the elevated-temperature test series, three additional strain meters had failed and one was registering excessively low strains. Thus, by the conclusion of the test, only three meters were functioning in addition to the weldable strain gages contained on the reinforcement cage. These results substantiate those obtained from a previous test series in which the meters were subjected only to thermal loading. It can therefore be concluded that the majority of strain meters examined in this series of tests are able to survive neither long-term exposures to temperatures near their reported upper limit nor relatively short-term temperature excursions above their upper limit.

SUMMARY AND CONCLUSIONS

This report is the second of two related to evaluations of commercially available strain meters for concrete embedment. The first report contained (1) an overview of meter performance criteria for PCPV applications and techniques for strain measurements in concrete, and (2) an experimental evaluation to assess the reliability of manufacturer-supplied calibration factors. The purpose of the investigation documented in this second report was to establish the trends of performance reliability for selected concrete embedment strain meters over an extended time interval

while the meters were subjected to a variety of loading environments, including unloaded, thermally loaded, simulated PCPV, and extreme environments.

Although only a limited number of meters of each type were evaluated in a particular test series, the composite results of the investigation permit the following general conclusions to be derived:

1. Judging from the performance of the meters examined, it appears that the majority of these meters could not provide reliable data throughout the anticipated 20- to 30-year operating lifetime of a PCPV.
2. The selection of a strain meter should be based on its application; that is, a meter may provide excellent results in short-duration tests, but may exhibit unacceptable systematic drift in extended-time tests.
3. Development of improved corrosion-resistant materials and sealing techniques is needed for meters which are to survive in PCPV environments.
4. Meters need to be developed for long-term use in concretes where temperatures in excess of 66°C are experienced.
5. Research should be conducted on other measurement techniques such as inductance, capacitance, and fluidic.

Fig. 1. Reinforcement cage for cylinder 1.

Fig. 2. Cardboard mold for casting 40.6-cm-diam by 101.5-cm-long test specimens.

Fig. 3. Cylinder 1 test specimen.

Fig. 4. Wire resistance strain gage signal conditioning and recording system.

ORNL PHOTO 6246-78

Fig. 5. Readout instrument for unbonded wire strain meter Types A and B.

Fig. 6. Readout instrument for vibrating wire strain meter.

Fig. 7. Mechanical strain gage with 20.3-cm gage length.

Fig. 8. Cylinder 1 strain meter stability test results for bonded wire resistance strain meters.

Fig. 9. Cylinder 1 strain meter stability test results for unbonded wire resistance strain meters.

Fig. 10. Cylinder 1 strain meter stability test results for vibrating wire meters.

- Fig. 11. Reinforcement cage for cylinder 2.

ORNL PHOTO 6047-77

Fig. 12. Cylinder 2 test specimen.

Fig. 13. Results of cylinder 2 strain meter thermal loading test.

Fig. 14. Reinforcement cage for cylinder 3.

Fig. 15. Cylinder 3 test specimen before application of insulation.

Fig. 16. Cylinder 3 test specimen after application of insulation.

ORNL-DWG 78-3868

Fig. 17. Results of cylinder 3 strain meter test for wire resistance meters in a representative PCPV environment.

Fig. 18. Results of cylinder 3 strain meter test for vibrating wire meters in a representative PCPV environment.

Fig. 19. Setup for the room-temperature alkaline-water bath test.

ORNL-DWG 78-14238

Fig. 20. Results of room-temperature alkaline-water bath test (plastic encapsulated Type A gages 1-3).

ORNL-DWG 78-14239

Fig. 21. Results of room-temperature alkaline-water bath test (plastic encapsulated Type B gages 1-3).

ORNL-DWG 78-14240

Fig. 22. Results of room-temperature alkaline-water bath test (plastic encapsulated Type B gages 4-6).

ORNL-DWG 78-14241

Fig. 23. Results of room-temperature alkaline-water bath test (single wire gages 1 and 2).

ORNL-DWG 78-14242

Fig. 24. Results of room-temperature alkaline-water bath test (single wire gages 3 and 4).

ORNL-DWG 78-14243

Fig. 25. Results of room-temperature alkaline-water bath test (single wire gages 5 and 6).

ORNL-DWG 78-14244

Fig. 26. Results of room-temperature alkaline-water bath test (single wire gage No. 7).

ORNL-DWG 78-14245

Fig. 27. Results of room-temperature alkaline-water bath test (single wire gages 8 and 9).

ORNL-DWG 78-14246

Fig. 28. Results of room-temperature alkaline-water bath test (unbonded wire Type A gages 1-4).

ORNL-DWG 78-14247

Fig. 29. Results of room-temperature alkaline-water bath test (unbonded wire Type B gages 1 and 2).

ORNL-DWG 78-14248

Fig. 30. Results of room-temperature alkaline-water bath test (unbonded wire Type C gage).

ORNL-DWG 78-14249

Fig. 31. Results of room-temperature alkaline-water bath test (vibrating wire Type A gage No. 1).

ORNL-DWG 78-14250

Fig. 32. Results of room-temperature alkaline-water bath test (vibrating wire Type A gages 2 and 3).

ORNL-DWG 78-14251

Fig. 33. Results of room-temperature alkaline-water bath test (vibrating wire Type B gage No. 1).

ORNL-DWG 78-14252

Fig. 34. Results of room-temperature alkaline-water bath test (vibrating wire Type C gages 1 and 2).

ORNL-DWG 78-14253

Fig. 35. Results of room-temperature alkaline-water bath test (vibrating wire Type D gages 1 and 2).

ORNL-DWG 78-14254

Fig. 36. Results of room-temperature alkaline-water bath test (vibrating wire Type E gage).

ORNL-DWG 78-14255

Fig. 37. Results of room-temperature alkaline-water bath test (vibrating wire Type F gage No. 1).

ORNL-DWG 78-14256

Fig. 38. Results of room-temperature alkaline-water bath test (vibrating wire Type F gages 2 and 3).

ORNL-DWG 78-14257

Fig. 39. Results of room-temperature alkaline-water bath test (vibrating wire Type G gages 1 and 2).

Fig. 40. Setup for elevated-temperature alkaline-water bath test.

ORNL-DWG 78-14258

Fig. 41. Results of elevated-temperature alkaline-water bath test (plastic encapsulated Type A gages 1-3).

ORNL-DWG 78-14259

Fig. 42. Results of elevated-temperature alkaline-water bath test (plastic encapsulated Type A gage No. 4).

ORNL-DWG 78-14260

Fig. 43. Results of elevated-temperature alkaline-water bath test (plastic encapsulated Type A gages 5 and 6).

ORNL-DWG 78-14261

Fig. 44. Results of elevated-temperature alkaline-water bath test (single wire gages 1-3).

ORNL-DWG 78-14262

Fig. 45. Results of elevated-temperature alkaline-water bath test (single wire gage No. 4).

ORNL-DWG 78-14263

Fig. 46. Results of elevated-temperature alkaline-water bath test (single wire gages 5 and 6).

ORNL-DWG 78-14264

Fig. 47. Results of elevated-temperature alkaline-water bath test (single wire gage No. 7).

ORNL--DWG 78-14265

Fig. 48. Results of elevated-temperature alkaline-water bath test (single wire gages 8-11).

ORNL-DWG 78-14266

Fig. 49. Results of elevated-temperature alkaline-water bath test (single wire gage No. 12).

ORNL-DWG 78-14267

Fig. 50. Results of elevated-temperature alkaline-water bath test (single wire gages 13-15).

ORNL-DWG 78-14268

Fig. 51. Results of elevated-temperature alkaline-water bath test (unbonded wire Type A gages 1 and 2).

ORNL-DWG 78-14269

Fig. 52. Results of elevated-temperature alkaline-water bath test (unbonded wire Type A gages 3-5).

ORNL-DWG 78-14270

Fig. 53. Results of elevated-temperature alkaline-water bath test (unbonded wire Type A gages 6-8).

ORNL-DWG 78-14271

Fig. 54. Results of elevated-temperature alkaline-water bath test (unbonded wire Type B gages 1 and 2).

ORNL-DWG 78-14272

Fig. 55. Results of elevated-temperature alkaline-water bath test (unbonded wire Type C gage).

ORNL-DWG 78-14273

Fig. 56. Results of elevated-temperature alkaline-water bath test (vibrating wire Type A gages 1-3).

ORNL-DWG 78-14274

Fig. 57. Results of elevated-temperature alkaline-water bath test (vibrating wire Type C gages 1 and 2).

ORNL-DWG 78-14275

Fig. 58. Results of elevated-temperature alkaline-water bath test (vibrating wire Type D gage No. 1).

Fig. 59. Results of elevated-temperature alkaline-water bath test (vibrating wire Type E gage No. 1).

ORNL-DWG 78-14277

Fig. 60. Results of elevated-temperature alkaline-water bath test (vibrating wire Type F gage No. 1).

ORNL-DWG 78-14278

Fig. 61. Results of elevated-temperature alkaline-water bath test (vibrating wire Type F gage No. 2).

ORNL-DWG 78-14279

Fig. 62. Results of elevated-temperature alkaline-water bath test (vibrating wire Type F gages 3 and 4).

ORNL-DWG 78-14280

Fig. 63. Results of elevated-temperature alkaline-water bath test (vibrating wire Type G gages 1 and 2).

ORNL-DWG 78-14281

Fig. 64. Results of elevated-temperature alkaline-water bath test (vibrating wire Type G gage No. 3).

THIS PAGE
WAS INTENTIONALLY
LEFT BLANK

ORNL/TM-6191/V2
Dist. Category UC-77

Internal Distribution

1. S. J. Ball	40. R. E. MacPherson
2. D. E. Bartine	41. A. P. Malinauskas
3. M. E. Bender	43. J. G. Merkle
4-9. J. P. Callahan	44. R. K. Nanstad
10. D. A. Canonico	45-54. D. J. Naus
11. J. A. Clinard	55. K. J. Notz
12. J. A. Conlin	56. C. B. Oland
13. J. H. Coobs	57. H. Postma
14. W. E. Cooper	58. G. C. Robinson
15. J. M. Corum	59. J. P. Sanders
16. J. R. DiStefano	60. M. R. Sheldon
17. W. G. Dodge	61. G. M. Slaughter
18. J. R. Dougan	62. J. E. Smith
19. W. P. Eatherly	63. H. E. Trammell
20. D. N. Fanning	64. M. Tobias
21. Uri Gat	65. D. B. Trauger
22. D. W. Goodpasture	66. J. R. Weir, Jr.
23. A. G. Grindell	67. G. D. Whitman
24. W. L. Greenstreet	68. R. P. Wichner
25. R. C. Gwaltney	69. G. T. Yahr
26. J. F. Harvey	70. ORNL Patent Office
27. R. F. Hibbs	71-72. Central Research Library
28. F. J. Homan	73. Document Reference Section
29-37. P. R. Kasten	74-77. Laboratory Records Department
38. M. Levenson	78. Laboratory Records, ORNL-RC
39. A. L. Lotts	

Consultants and Subcontractors

79. E. G. Burdette, Civil Engineering Department, University of Tennessee, Knoxville, TN 37916 (Subcontract No. 7419, expires Sept. 30, 1978)
80. R. H. Gallagher, Civil Engineering Department, Cornell University, Ithaca, NY 14850 (Subcontract No. 3840, expires March 31, 1978)

External Distribution

- 81-82. Director, Division of Nuclear Research and Applications, DOE, Washington, D.C. 20545
83. Director, Reactor Division, DOE-ORO
- 84-85. Director, Research and Technical Support Division, DOE-ORO
- 86-262. For distribution as shown in TID-4500 Distribution Category UC-77, Gas-Cooled Reactor Technology