7.
-13-82
JWS

(1)

Dr. 902

I-5888

PNL-4480

UC-25

Do Not
Microfilm Cover

MASTER

Equipment for Nondestructive Evaluation of the Strength of the Fort St. Vrain Core- Support Blocks

W. E. Morgan
J. M. Prince
G. J. Posakony

September 1982

Prepared for the U.S. Department of Energy
under Contract DE-AC06-76RLO 1830

Pacific Northwest Laboratory
Operated for the U.S. Department of Energy
by Battelle Memorial Institute

PNL-4480

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.

PACIFIC NORTHWEST LABORATORY
operated by
BATTELLE
for the
UNITED STATES DEPARTMENT OF ENERGY
under Contract DE-AC06-76RLO 1830

Printed in the United States of America
Available from
National Technical Information Service
United States Department of Commerce
5285 Port Royal Road
Springfield, Virginia 22151

NTIS Price Codes
Microfiche A01

Printed Copy

Pages	Price Codes
001-025	A02
026-050	A03
051-075	A04
076-100	A05
101-125	A06
126-150	A07
151-175	A08
176-200	A09
201-225	A010
226-250	A011
251-275	A012
276-300	A013

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.

PNL--4480

DE83 000926

EQUIPMENT FOR NONDESTRUCTIVE EVALUATION
OF THE STRENGTH OF THE FORT ST. VRAIN
CORE-SUPPORT BLOCKS

W. C. Morgan
J. M. Prince
G. J. Posakony

September 1982

Prepared for
the U.S. Department of Energy
under Contract DE-AC06-76RLO 1830

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.

Pacific Northwest Laboratory
Richland, Washington 99352

SUMMARY

A novel sweep-frequency eddy current instrument has been constructed for measuring density-depth profiles in oxidized graphite. Development work on additional parts of the instrumentation package, that was to be tested in the Fort St. Vrain High Temperature Gas-Cooled Reactor, has been temporarily halted. This report documents the work which has been accomplished to date and presents the current status of the equipment development effort.

CONTENTS

SUMMARY	iii
INTRODUCTION	1
CONCLUSIONS	3
BASIS FOR DESIGN	4
GENERAL DESIGN CONSIDERATIONS	5
EDDY-CURRENT MEASUREMENTS	8
ULTRASONIC BACKSCATTER ANALYSIS	11
INSTRUMENTATION PACKAGE	16
STATUS OF DEVELOPMENT WORK	17
EDDY CURRENT INSTRUMENTATION	18
Sweep Frequency Eddy-Current Test System	18
System Control and Data Logger	18
Storage Oscilloscope Monitor	18
Sweep Frequency Eddy-Current Processor	20
BACKSCATTERING INSTRUMENTATION	23
CONCEPTUAL DESIGN OF THE INSPECTION SYSTEM	23
ACKNOWLEDGMENTS	26
REFERENCES	27
APPENDIX: CIRCUIT DIAGRAMS OF THE EDDY CURRENT INSTRUMENTATION	A.1

FIGURES

1.	Sectional View of the FSVR Reactor Building	6
2.	Sectional View of Core Support and Reflector Blocks	7
3.	Conductance as a Function of Density	9
4.	Compressive Strength as a Function of Density	10
5.	Attenuation as a Function of Frequency and Density	13
6.	Test Configuration and Display	14
7.	Backscattered Energy as a Function of Frequency and Density	15
8.	Sweep Frequency Eddy Current Test System	19
9.	Sweep Frequency Eddy Current Processor	20
10.	Block Diagram of the Data Processor	21
11.	Block Diagram of Ultrasonic Backscatter System	24
12.	Conceptual Design of the Inspection System	25
A.1	Circuit Board Positions	A.1
A.2	Slot 1, Front Panel and IO Board	A.2
A.3	Front Panel Interface Circuits	A.3
A.4	Slot 2, Micro-Processor Controller Board	A.4
A.5	Micro-Processor Controller Circuits, Sheet 1	A.5
A.6	Micro-Processor Controller Circuits, Sheet 2	A.6
A.7	Micro-Processor Controller Circuits, Sheet 3	A.7
A.8	Micro-Processor Controller Circuits, Sheet 4	A.8
A.9	Slot 4, Eddy Current Signal Processor Board	A.9
A.10	IF Bandpass Filtering and Gain Control Circuit, Sheet 1	A.10
A.11	IF Bandpass Filtering and Gain Control Circuit, Sheet 2	A.11

A.12	Scope Multiplexer Circuit	.	.	.	.	.	.	.	A.12
A.13	Sample Pulse Generator Circuit	.	.	.	.	.	.	.	A.13
A.14	Slot 5, Frequency Source and Converter Board	.	.	.	.	.	.	.	A.14
A.15	Digitally Controlled VCO Circuit	.	.	.	.	.	.	.	A.15
A.16	0-Degree and 90-Degree Mixer Circuit	.	.	.	.	.	.	.	A.16
A.17	Frequency Drive Divider Circuit	.	.	.	.	.	.	.	A.17
A.18	IF Divider and Frequency to Voltage Converter Circuit, Sheet 1	.	.	.	.	.	.	.	A.18
A.19	IF Divider and Frequency to Voltage Converter Circuit, Sheet 2	.	.	.	.	.	.	.	A.19
A.20	Slot 6, Wave Shaper and Probe Drive Boards	.	.	.	.	.	.	.	A.20
A.21	Square-Wave to Triangle-Wave Converter Circuit	.	.	.	.	.	.	.	A.21
A.22	Triangle-Wave to Sine-Wave Converter Circuit	.	.	.	.	.	.	.	A.22
A.23	Variable Gain Probe Driver Amplifier Circuit	.	.	.	.	.	.	.	A.23

EQUIPMENT FOR NONDESTRUCTIVE EVALUATION OF THE STRENGTH OF THE FORT ST. VRAIN CORE-SUPPORT BLOCKS

INTRODUCTION

Tingey et al. (1982) have discussed the reasons for in-service monitoring, and the rationale for the choice of nondestructive evaluation methods for monitoring the changes in strength of the graphite core-support blocks in the Fort St. Vrain High-Temperature Gas-Cooled Reactor (FSVR). Development and evaluation of the nondestructive testing (NDT) techniques for in-situ measurements on the core-support components of High-Temperature Gas-Cooled Reactors (HTGR) are proceeding under a program funded by the Nuclear Regulatory Commission (NRC). The FSVR (Walker and Johnston 1969; Dallberg et al. 1969) is the only operating HTGR and, there is concern that, because the graphite used for the FSVR core-support blocks and posts was not nuclear purified, there is a potential for significant oxidation (and loss of strength) during its operating lifetime. Furthermore, PGX^(a) graphite, which was used for the FSVR core-support blocks,^(b) is extremely heterogeneous in terms of its unoxidized density and strength (Morgan et al. 1982), and in terms of its oxidation rate (Morgan et al. 1982; Eto and Growcock, 1981). For example: Morgan et al. (1982) have observed that the physical properties of individual large (76 mm diameter x 152 mm long) samples may deviate from the mean values, of all samples cut from the same segment of a PGX log, by 3% in density and 22% in compressive strength; further, Eto and Growcock (1981) have reported differences of 50X in chemical reactivity of PGX samples.

It is important to note that no one is suggesting that the oxidation, which has occurred to date, in any way jeopardizes the current safety of the FSVR. The above facts clearly indicate, however, that in-service monitoring will be required long before the FSVR reaches its "design operating life".

(a) Union Carbide Corporation, New York, NY 10017.

(b) "Fort St. Vrain Nuclear Generating Station", Public Service of Colorado, Docket 50267.

It is also important to note that no samples were obtained from the PGX logs used for the FSVR core-support blocks; therefore, no base-line test data exist and there are no archived samples from which the data can be obtained. Although FSVR has been in operation since July 1976, practically all of its operation has been at low power; thus, those portions of the upper surface of the core-support blocks that are in direct contact with the bottom-reflector elements should have suffered very little oxidation. Measurements obtained on these semi-protected areas could still be considered to be quasi-base-line data. However, FSVR is expected to soon begin extended operation at 100% of full power; such operation will rapidly erode the credibility of assuming that subsequent measurements represent quasi-base-line data. Thus, unless data are obtained very soon on the FSVR core-support blocks, in-situ, interpretation of future measurements will be an extremely tedious and arduous task.

The situation can be briefly summarized as follows:

1. The NRC has recognized the need for in-service monitoring of strength changes in HTGR graphite core-support components; therefore, the NRC is funding development of non-destructive techniques so that base-line data can be acquired prior to the initial operation of future HTGRs.
2. The DOE has recognized the need to obtain "base-line" (quasi-base-line) data on the FSVR; therefore, the DOE funded this program to develop the equipment and obtain the needed "base-line" data.
3. Negotiations with the Public Service Company of Colorado (owner of FSVR) have broken down; therefore, this equipment development effort is being "moth-balled" until such time that it appears that the equipment will be needed.

This report, summarizes the status of the equipment development work at the end of FY-1982, and outlines the approach which we had planned to take in order to obtain base-line data during the next refueling outage at FSVR (scheduled for October 1983).

CONCLUSIONS

- Sweep-frequency eddy-current instrumentation has been assembled as a breadboard package, complete with the computerized unit for system control and data collection. The complete package is transportable, it can be directly interfaced with existing data processing equipment, and it is capable of providing an indication of graphite strength-versus-depth to a distance of about 3 to 5 mm below the surface of the block.
- Additional operating experience is expected to be gained by use of the completed eddy-current instrument package in obtaining data from an NRC-funded graphite-oxidation experiment in the CFTL at ORNL, scheduled to begin in FY-1983.
- Conceptual design of the ultrasonic backscattering instrumentation has been completed; however, construction of the instrumentation awaits resumption of funding.
- Conceptual design of the mechanical package, which would contain the probes and associated in-reactor equipment for control and data transmission, was cancelled at a very early stage; however, the preliminary conceptual package was designed to virtually negate any possibility that its use could adversely effect operation of the FSVR.
- The orderly shut-down of this equipment development program has allowed a maximum return from the work accomplished to date, and will permit a rapid revitalization of the development program when it becomes practicable to do so.

BASIS FOR DESIGN

Development of the basic technology for in-service monitoring of strength changes in HTGR core-support components is being funded by the NRC. During the initial phase of the work (Morgan and Becker 1977, 1979), the primary emphasis was placed on development of a correlation between strength and ultrasonic velocity of the longitudinal and shear waves transmitted through prototypic core-support post graphites. During testing of the various prototypic post graphites, Morgan and Becker determined that the density profile for most graphites would be required in order to fully correlate the changes in strength with changes in ultrasonic velocity. Eddy-current technology was chosen to provide the required density profile near the surface of the component; because, it was assumed that extrapolation of the near-surface profile would suffice to provide information on the oxidation (density changes) at greater depths from the surface.^(b)

It was at this stage of the development effort that we began to apply the techniques to PGX graphite, which was apparently the only contender^(a) for use as core-support blocks in advanced HTGRs. DOE became interested in obtaining measurements of the PGX core-support blocks in FSVR, for the following reasons:

1. Failure testing of a 3/4-scale model of the FSVR core-support block and post assembly (Luci 1970) had shown that the block represented the "weakest link" in the core-support assembly.
2. The oxidation rate of PGX graphite had been shown (Romano and Chow 1977; Growcock et al. 1978) to be two, or more, orders of magnitude greater than the rates of other graphites used in FSVR.

(a) It is most probable, however, that the blocks will be of a specially purified grade of PGX, not the standard grade used in the FSVR.

(b) Note: Later information (Morgan and Thomas 1982) showed that this assumption is not valid under all conditions; thus, the ultrasonic backscattering technique is being developed to provide the density profile at greater depths.

3. The PGX graphite used in FSVR was not nuclear purified and, as such, the impurity content and localized oxidation rates are highly variable (Growcock et al. 1978).
4. Samples from the PGX blocks in FSVR had not been tested or archived, so there is no way to obtain base-line data on properties of these blocks.

Several changes in approach were required during development of the techniques to be used in obtaining "quasi-base-line" data from the FSVR core-support blocks; these changes were necessitated by the following findings (Morgan, Davis and Thomas 1982):

1. Ultrasonic velocity techniques are not feasible for monitoring strength changes in oxidized PGX graphite due to the rapid attenuation of the signal; and,
2. Near-surface oxidation profiles cannot be, a priori, extrapolated to greater depth from the surface due to the potential for occurrence of the "Inverse Oxidation Phenomenon" (Morgan and Thomas 1982).

Therefore, ultrasonic backscattering analysis was added to the NRC-funded technology development program, and was incorporated in the DOE program for obtaining "quasi-base-line" NDE data on the core-support blocks in FSVR.

GENERAL DESIGN CONSIDERATIONS

General layout of that portion of the FSVR which is of interest to the design, testing, and operation of the NDE equipment package is shown in Figure 1. Access to the core-support blocks (CSB) is through the refueling penetrations in the head of the prestressed concrete reactor vessel (PCRV), after removal of a control rod drive unit, plus at least one full column of fuel and reflector elements. Except for the bottom reflector elements, all of the above components are normally removed by the fuel-handling machine (FHM) during the refueling outage and transferred to the appropriate storage facility. Figure 2 shows a cut-away view of a CSB and the bottom reflector elements; the upper face of the CSB is located 44.5 ft below the floor of the reactor building. One of the constraints on design is that the FHM be used

FIGURE 1. Sectional View of the FSVR Reactor Building

to position the NDE equipment package on the CSB. A second constraint is that use of the FHM should not extend the normal refueling outage time. Representatives of PSC did not consider it feasible to install additional electrical cables in the FHM; therefore, a third constraint on design is that the existing cables be shared with the TV camera and the lighting system presently installed on the pick-up head of the FHM.

FIGURE 2. Sectional View of Core Support and Reflector Blocks

The fourth, but most important, design consideration is that the continued safe operation of the FSVR not be imperiled in any way by introduction of the NDE equipment package.

EDDY-CURRENT MEASUREMENTS

Eddy-current inspection is based on measurement of electrical conductance of a material by electromagnetic induction. An oscillating current, induced in a test coil, produces a magnetic field around the coil. If the coil is brought near an electrically conductive body, the magnetic field induces electrical currents (eddy currents) in the body, which in turn produce a secondary magnetic field. This secondary magnetic field then alters the response of the test coil.

Under test conditions, the signal from the test coil is balanced against the signal from a second coil in an electronic bridge circuit. Bringing the test coil close to the conductive body unbalances the bridge circuit, and the resultant signal from the bridge can be resolved in terms of two voltages (V_x and V_y) which are related to the changes in resistance (R) and reactance (X) of the test coil. The changes (ΔR and ΔX) are, in turn, related to the change in electrical conductance of the material under the test coil. By using different frequencies, the eddy currents are induced to different depths into the material; thus, the conductance can be determined as a function of depth.

Under the NRC-funded technique development program, a computer program called ZFIT was assembled to calculate conductance as a function of the measured eddy-current voltage signals (V_x and V_z). ZFIT includes an algorithm and incorporates the theory developed by Dodd (Dodd et al. 1973; Dodd and Deeds 1975; Deeds, Dodd and Scott 1979) to calculate the conductance profile as a function of depth into the material.

Also under the NRC program, a correlation was established between the conductance and density of oxidized PGX graphite, as shown in Figure 3. A similar correlation was established between the compressive strength and density, as shown in Figure 4. Equating the two relationships yields a direct relationship for compressive strength as a function of conductance for uniformly oxidized

FIGURE 3. Conductance as a Function of Density

FIGURE 4. Compressive Strength as a Function of Density

PGX graphite (Morgan et al. 1982). Combining the correlation between compressive strength and conductance with the conductivity versus depth output from ZFIT will yield the strength versus depth profile near the surface of the FSVR core-support blocks.

A novel design concept for the eddy current instrument is that, instead of using a few discrete frequencies to establish the conductivity versus depth profile, the frequency is swept between 10 kHz and 10 MHz; this permits the acquisition of data at up to 12,000 frequencies (12,000 increments of depth) to provide information for a much more detailed analysis than could be done using data obtained at a few discrete frequencies. Maximum penetration is, however, limited to about 7 mm from the surface.

ULTRASONIC BACKSCATTER ANALYSIS

The energy of an ultrasonic wave, propagated into a material, is scattered at discontinuities such as voids and grain boundaries. By directing the transmitted signal along a given path in the material and measuring the amplitude of the signal scattered by discontinuities at various depths, one can obtain a measure of the void density (and, hence, the density of the material) as a function of depth.

To establish the effectiveness of the backscatter technique in graphite materials, two parameters must be studied, namely: 1) the attenuation coefficient of the material as a function of oxidation and as a function frequency, and b) the energy backscattered as a function of grain size and as a function of frequency. The theory indicates that scattering from grain boundaries is dependent on the third power of the grain diameter and the fourth power of the test frequency (Krautkramer 1969). This relationship holds for metals with various grain sizes but for acoustically lossy materials, such as graphite, the attenuation coefficient has still a further influence on the backscattered energy.

Under the NRC program, we established the attenuation coefficients as a function of oxidation and frequency. We also developed a single transducer test procedure for backscatter tests to replace the dual transducer configuration previously used. This latter development enhances the test as it reduces

the number of transducers required to perform the test; moreover, it reduces the uncertainties associated with coupling the ultrasonic energy from the transducer into the graphite and back. Initial signal processing procedures in which echos from internal structures were digitized and analyzed in the frequency domain were abandoned. It was found that higher reproducibility could be achieved by making measurements at selected discrete frequencies.

Figure 5 shows the experimental data obtained for a series of thru-transmission attenuation measurements. Test data were taken at 500 kHz, 780 kHz and 970 kHz. These test data clearly show the difference in attenuation between specimens that have different degrees of oxidation. These data show that attenuation is a real concern and that the use of test frequencies higher than about 800 kHz is probably impractical. It is interesting to note that prior ultrasonic velocity measurements (Morgan and Becker 1979) used a frequency of 800 kHz.

Limiting the upper test frequency to 800 kHz presents some interesting problems. It is desirable to use a frequency as high as possible to get as much backscattered energy as practical. While greater penetration can be achieved at lower frequencies, the ratio of the grain diameter to wavelength is lower, thus, less energy will be reflected or scattered from the grains. A series of experiments were performed to determine the amount of backscattered energy that could be recorded for different degrees of oxidation at different test frequencies. The test configuration is shown in Figure 6. The transducer was aimed so that the energy entered the graphite at a fixed angle to the surface. This technique eliminates the large front-surface echo that occurs when the sound energy enters straight (normal) into the part but does not reduce the response of the backscatter signals because the scattered energy is essentially nonspecular.

An adjustable time gate is used to select the depth of the signals to be displayed. Because the front surface echo no longer generates a "blind spot" near the surface, the entire volume of the material can be examined from very near the surface (e.g., 2 to 3 mm) to many centimeters into the material.

FIGURE 5. Attenuation as a Function of Frequency and Density

6a. Test Setup

6b. Oscilloscope Display

FIGURE 6. Test Configuration and Display

Test frequencies of 500 kHz, 750 kHz, 900 kHz, and 1.5 MHz were chosen for the backscatter experiment, as shown in Figure 7. This pattern of responses should be expected. The response at the lower frequencies is low because the grain size is small with respect to the test frequency. The response at the upper frequency is low because the attenuation of the ultrasonic energy is high. The response appears to peak at ~750 kHz which, as noted above in regard to the attenuation tests, is a compromise between the grain size and attenuation responses. Although some anomalies are noted in Figure 7, the separation between the responses at different degrees of oxidation is quite apparent. PGX is quite inhomogeneous and, at least part, of the anomalies may be due to differences other than average density in the samples. From these test data it would appear practical to establish an algorithm, which use data obtained at three or more frequencies, to calculate the density versus depth profile in oxidized PGX graphite (Morgan, Prince and Lessor 1982). Combining this profile with the correlation of compressive strength versus density for oxidized PGX will yield the strength versus density profile to a considerable depth into the FSVR core-support blocks.

FIGURE 7. Backscattered Energy as a Function of Frequency and Density

INSTRUMENTATION PACKAGE

Considering that the fuel element handling machine (FHM) would be used to place the instrument package in position on the core support block, and that existing electrical cables in the FHM would be used to transmit any commands and data, we deemed it prudent to configure the instrumentation package to the same exterior dimensions as a fuel element, and to use the same mode of attachment to the fuel pick-up head as is used when transferring fuel elements or upper reflector blocks. Thus, the only external part of the package which would appear to be "non-standard" would be the short electrical cables connecting the package to the existing cables and instrumentation on the FHM.

In order to ensure that meaningful data was obtained during the measurements, we decided to digitize the analog signals from both the eddy current and backscattering equipment, and transmit the digitized signals over an existing coaxial cable in the FHM. To ensure that reliable data were being obtained, the digitized signal would be partially processed on-line, and stored for later detailed analysis. This detailed analysis would be done on the large computer system which hosts the algorithm ZFIT.

It was envisioned that the eddy current and backscattering probes be movable within the area covered by the fuel-block shaped container; thus, they could be positioned to make measurements at several positions on the upper surface of the core-support block (CSB). Part of the upper surface of the CSB is directly exposed to the hot gases exiting from the central fuel (control) column (see Figure 2); the remainder of the CSB surface is partially protected from the gas, due to direct contact, by the under-surface of permanent reflector blocks. Those areas on the CSB surface which are partially protected from exposure to the coolant gases should, at the present time, have suffered very little oxidation and could still be considered to represent quasi-baseline material. In contrast, areas that are exposed to the hot coolant gases should have oxidation profiles that are fairly typical of those at all other CSB surfaces, including the surfaces of the coolant channels through the CSB.

STATUS OF DEVELOPMENT WORK

The decision to postpone further design and development work on this project was made when it appeared highly improbable that an agreement could be reached in time to permit testing of this equipment in FSVR during the refueling outage scheduled for October, 1983. At that time, design of the eddy current equipment, and much of the breadboarding of the components, was already complete. Conceptual design of the ultrasonic backscattering equipment was complete, but detailed design of the circuitry had only just begun. Conceptual design of the equipment package was also a long way from being complete.

In order to obtain a maximum return from the work which had been completed, and to permit the equipment development program to be rapidly and economically resumed when the need arises, it was agreed that we would:

- 1) Immediately halt all work on the equipment package and on design of the ultrasonic backscattering equipment.
- 2) Complete the assembly of the sweep-frequency eddy current instrumentation as a completely workable and transportable system.
- 3) Provide detailed documentation on the status of the development work.

The first two objectives have been completed; this report is in fulfillment of the last objective and includes in the Appendix the complete circuitry diagrams for the novel sweep-frequency eddy current instrumentation developed under this program.

In addition, we plan to test (under the NRC technique development program) the eddy current system in conjunction with a (NRC funded) graphite oxidation and testing program at ORNL, beginning in FY-1983. The program at ORNL involves oxidation of improved core-support graphites in a high-pressure gas loop, the CFTL, under conditions approaching those expected in an advanced HTGR. Thus, both programs should benefit from the cooperative efforts of the two laboratories.

EDDY CURRENT INSTRUMENTATION

Sweep Frequency Eddy-Current Test System

The sweep frequency eddy-current test system, shown in Figure 8, is configured to provide experimental data for generation to the density profile of graphite. Utilizing test frequencies from 10 kHz to 10 MHz, the graphite density profile can be plotted at depths from 7 to 0.5 mm from the surface, respectively.

This system is designed to generate the necessary data for the development of our ZFIT program and to provide a breadboard model for the EC components in an HTGR graphite core support block NDT inspection system.

System Controller and Data Logger

In this configuration the system is controlled from the HP 9826, which sends the appropriate commands to the eddy-current processor and collects and logs onto flexible disc storage the resultant eddy-current-based data. The eddy-current data consists of two 16-bit words for each test frequency. With the potential of 12,000 test frequencies available in the sweep frequency processor the data taken for each profile sequence could be as much as 24,000 words or 48,000 bytes (1 byte = 8 bits).

The HP 9826 is configured with a RAM-based Pascal language system and a GPIO interface. This configuration provides for data transfers in excess of 60 Kbytes/sec and preliminary data analysis and display on the 178-mm CRT display located on the HP 9826. This computer system has 576 Kbytes of RAM to buffer eddy-current data to be logged onto flexible disc. The dual flexible disc drive unit is an HP 9895A which provides for upto 2.36 million bytes of mass storage. For detailed analysis with our ZFIT algorithm the logged data is transferred to the large computer system which hosts the algorithm.

Storage Oscilloscope Monitor

The test data generated by the eddy-current processor can be observed on a storage oscilloscope. The storage feature allows several calibration profiles to be put on the scope along with the test sample profile for visual test monitoring and analysis. To facilitate profile analysis the data are

FIGURE 8. Sweep Frequency Eddy Current Test System

presented with amplitude in the vertical axis and frequency (depth) in the horizontal axis. This concept provides real-time monitoring and analysis as the profile test sequence is being performed.

Sweep-Frequency Eddy-Current Processor

The sweep-frequency eddy-current (EC) processor, shown in Figure 9, generates the EC data from which density is deduced. This EC tester is a Z80 microprocessor-based eddy-current processor that can operate at frequencies from 10 kHz to 10 MHz. It has microprocessor controlled functions and test sequences that are set up and initiated from the front panel keyboard and can be run from an external controller. Manual controls are also provided to operate the EC-signal processor for system calibration as required.

The block diagram of the sweep frequency EC processor is shown in Figure 10 where each block coincides to a circuit board in the processor. The detailed schematics of these boards are shown in the Appendix.

FIGURE 9. Sweep Frequency Eddy Current Processor

FIGURE 10. Block Diagram of the Data Processor

EC Processor Controller

The function of this board is to control the automated features and test sequences and provide for manual (keyboard) or computer (HP 9826) initiation and monitoring. It performs these functions over its external data base (XDB) and with program-generated control strobes. The controller is built around the Z80 microprocessor with 8 Kbytes of EPROM and 4 Kbytes of RAM. It has an arithmetic processor unit (APU) for internal EC data processing capabilities and 16 analog signal lines multiplexed into an A/D converter for digitizing the EC data.

Front Panel Interface

This board provides the drivers and receivers for the front panel functions. All of the LED displays and indicators are driven from this board. Also the solid-state speaker is driven with the tone that is generated by the controller board.

Frequency Source and Converter

Two functions are provided on this board: 1) the system test frequencies (10 kHz to 10 MHz) are generated, 2) the probe preamplifier signal is converted to the 10-kHz IF to simplify the signal processing circuitry for such a wide operating frequency spectrum. The test frequencies originate in the digitally controlled VCO which operates over a 4- to 40-MHz range. This is divided down in selectable ranges to provide the total operating test frequency range of 10 kHz to 10 MHz. The conversion of the preamplifier signal is accomplished by first detecting the 0 and 90° Fourier components of the signal at the test frequency. The next step is to recombine the components utilizing 0 and 90° switching and summing at the intermediate frequency (IF) of 10 kHz.

Wave Shaper and Probe Drive

On this board the square wave drive signal is shaped into a sine wave, amplified and buffered to provide a 50- Ω output for probe drive. The square wave is shaped into a sine wave in two steps: 1) square wave to triangle wave, and 2) triangle wave to sine wave. The sine wave is then put through a variable gain amplifier which can either be digitally or manually set for a drive signal amplitude of from zero to over 3 V rms.

Eddy Current Signal Processor

This board filters and processes the IF signal developed from the pre-amplifier signal on the frequency source and converter board. The processing consists of variable gain control (digital or manual) and eddy-current data detection in both cartesian and polar coordinates. The rotation of the eddy-current data is performed digitally or manually through the sample pulse generator circuitry. The eddy-current data along with selected test signals are multiplexed and presented at the Channel 1 and Channel 2 outputs where they can be observed utilizing an oscilloscope or stripchart recorder.

BACKSCATTERING INSTRUMENTATION

Figure 11 shows a block diagram of the ultrasonic backscatter system. It was envisioned that the ultrasonic backscattering test equipment, discussed in the section entitled Ultrasonic Backscatter Analysis, be adapted to the requirements imposed by the in-service testing program; however, this phase of the work was initiated later than the eddy current work, and it had not progressed to the point where specific circuitry design could be documented.

CONCEPTUAL DESIGN OF THE INSPECTION SYSTEM

The conceptual design shown in Figure 12 utilizes hardware and software designs developed in the breadboard phase of this program along with additional interfacing hardware. The same system control and data-logging equipment would be used while the inspection electronics would be integrated into a package for attachment onto the fuel handler. Test commands and data will be transferred over a serial-data link connecting the eddy-current (EC) and ultrasonic (UT) inspection electronics with the system control and data-logging equipment. The interface electronics on both ends will contain the appropriate circuitry to establish a reliable data link utilizing the fuel-handler cabling. At Fort St. Vrain this will require some switching at both ends so that the cabling can be shared with the camera system located on the fuel handler.

FIGURE 11. Block Diagram of Ultrasonic Backscatter System

FIGURE 12. Conceptual Design of the Inspection System

ACKNOWLEDGMENTS

The development of the techniques described herein has largely been accomplished under sponsorship of the Office of Nuclear Regulatory Research, U.S. Nuclear Regulatory Commission. The construction of the equipment and testing in the Fort St. Vrain Reactor is supported by Gas-Cooled Reactor Program and Division, U.S. Department of Energy.

The authors hereby acknowledge the able assistance of P. L. Tomeraasen in assembly and testing of the eddy current instrumentation; they also acknowledge the technical support received from D. K. Lemon, R. W. Hill and L. L. Kopf in the performance of the work and in generating the data described under the ultrasonic measurement section of the report.

REFERENCES

- Dahlberg, R. C., R. R. Turner and W. V. Goeddel. 1969. "Core Design Characteristics," Nucl. Eng. Intern. 14:1073.
- Deeds, W. E., C. V. Dodd and G. W. Scott. 1979. Computer-Aided Design of Multifrequency Eddy-Current Tests for Layered Conductors with Multiple Property Variations. ORNL/TM-6858.
- Dodd, C. V., C. C. Cheng, W. A. Simpson, D. A. Deeds, and J. H. Smith. 1973. The Analysis of Reflection-Type Coils for Eddy-Current Testing. ORNL-TM-4107.
- Dodd, C. V., and W. E. Deeds. 1975. Calculations of Magnetic Fields from Time-Varying Currents in the Presence of Conductors. ORNL-TM-4958.
- Eto, M., and F. B. Growcock. 1981. Effect of Oxidizing Environment on the Strength and Oxidation Kinetics of HTGR Graphites, NUREG/CR-2480.
- Growcock, F. B., D. Chandra, J. Heiser, and J. Skalyo, Jr. 1978. "Graphite Oxidation by Moisture," Proc. Second U.S. Japan Seminar on HTGR Safety Technology, CONF-781144, Vol. 1, p. 241.
- Krautkramer, J. and H. Krautkramer. 1969. Ultrasonic Testing of Materials. Springer-Verlag, New York.
- Luci, R. K. 1970. Summary of Core Support Graphite and Carbon Research and Development Test Programs for the Ft. St. Vrain Reactor Plant, GA-9641.
- Morgan, W. C., J. M. Prince, R. W. Hill, D. L. Lessor, and M. T. Thomas. 1982. "Graphite Nondestructive Testing (NDT) Research," Reactor Safety Research Programs Quarterly Report, January-March 1982 (S. K. Edler, Ed.), NUREG/CR-2716, Vol. 1, p. 1.
- Morgan, W. C., J. M. Prince and D. L. Lessor. 1982. "Graphite Nondestructive Testing (NDT) Research," Reactor Safety Research Programs Quarterly Report, April-June 1982 (S. K. Edler, Ed.), NUREG/CR-2716, Vol. 2, p. 1.
- Morgan, W. C., T. J. Davis and M. T. Thomas. 1982. Feasibility of Monitoring the Strength of HTGR Core Support Graphite--Part III, NUREG/CR-2929.
- Morgan, W. C., and F. L. Becker. 1977. Feasibility of Monitoring the Strength of HTGR Core Support Graphite--Part I BNWL-2239.
- Morgan, W. C., and F. L. Becker. 1979. Feasibility of Monitoring the Strength of HTGR Core Support Graphite--Part II. NUREG/CR-0995.
- Morgan, W. C., and M. T. Thomas. 1982. "The Inverse Oxidation Phenomenon," Carbon 20:71.

- Romano, A. J., and J. G. Y. Chow. 1977. "The Effect of Steam Oxidation on the Tensile Strength of HTGR Structural Graphites," Proc. Topical Meeting on Thermal Reactor Safety, CONF-770708, Vol. 1, p. 518.
- Tingey, G. L., G. J. Posakony, W. C. Morgan, J. M. Prince, R. W. Hill, and D. L. Lessor. 1982. Nondestructive Evaluation of the Oxidation and Strength of the Fort Saint Vrain HTGR Support Block. PNL-4203.
- Walker, R. E., and T. A. Johnston. 1969. "Fort St. Vrain Nuclear Power Station," Nucl. Eng. Intern. 14:1069.

APPENDIX: CIRCUIT DIAGRAMS
FOR THE EDDY CURRENT INSTRUMENTATION

FIGURE A.1. Circuit Board Positions

FIGURE A.2. Slot 1, Front Panel and IO Board

A.3

FIGURE A.3. Front Panel Interface Circuits

A.4

FIGURE A.4. Slot 2, Micro-Processor Controller Board

FIGURE A.5. Micro-Processor Controller Circuits, Sheet 1

FIGURE A.6. Micro-Processor Controller Circuits, Sheet 2

FIGURE A.7. Micro-Processor Controller Circuits, Sheet 3

FIGURE A.8. Micro-Processor Controller Circuits, Sheet 4

FIGURE A.9. Slot 4, Eddy Current Signal Processor Board

A.10

FIGURE A.10. IF Bandpass Filtering and Gain Control Circuit, Sheet 1

A.11

FIGURE A.11. IF Bandpass Filtering and Gain Control Circuit, Sheet 2

FIGURE A.12. Scope Multiplexer Circuit

FIGURE A.14. Slot 5, Frequency Source and Converter Board

FIGURE A.15. Digitally Controlled VCO Circuit

A.16

FIGURE A.16. 0-Degree and 90-Degree Mixer Circuit

FIGURE A.17. Frequency Drive Divider Circuit

A.18

FIGURE A.18. IF Divider and Frequency to Voltage Converter Circuit, Sheet 1

FIGURE A.19. IF Divider and Frequency to Voltage Converter Circuit, Sheet 2

A.20

FIGURE A.20. Slot 6, Wave Shaper and Probe Drive Board

FIGURE A.21. Square-Wave to Triangle-Wave Converter Circuit

FIGURE A.22. Triangle-Wave to Sine-Wave Converter Circuit

FIGURE A.23. Variable Gain Probe Driver Amplifier Circuit

DISTRIBUTION

No. of
Copies

No. of
Copies

OFFSITE

A. A. Churm
DOE Patent Division
9800 S. Cass Avenue
Argonne, IL 60439

F. E. Dearing
Department of Energy
Oak Ridge, TN 37830

- 3 J. E. Fox
Nuclear Research and Applications
Department of Energy
Washington, DC 20545

W. L. VonFlue
San Francisco Operations Office
Department of Energy
1333 Broadway
Oakland, CA 94612

- 27 DOE Technical Information Center

R. A. Meyer
Aerospace Corporation
P.O. Box 92957
Los Angeles, CA 90009

G. W. Morelli
Airco Carbon
800 Theresia Ste.
St. Marys, PA 15857

C. Hastings
Army Materials and Mechanics
Research Center
Watertown, MA 02172

M. Eto
Brookhaven National Laboratory
Upton, NY 11973

C. A. Sastre
Brookhaven National Laboratory
Upton, NY 11973

Electric Power Research Institute
3412 Hillview Ave.
P.O. Box 10412
Palo Alto, CA 94303

H. L. Gotschall
Gas Cooled Reactor Associates
3344 N. Torrey Pines Ct., STE-300
La Jolla, CA 92037

F. E. Swart
Gas Cooled Reactor Associates
3344 N. Torrey Pines Ct., STE-300
La Jolla, CA 92037

T. D. Gulden
General Atomic Company
P.O. Box 81608
San Diego, CA 92138

A. J. Neylan
General Atomic Company
P.O. Box 81608
San Diego, CA 92138

W. A. Simon
General Atomic Company
P.O. Box 81608
San Diego, CA 92138

No. of
Copies

R. D. Burnette
General Atomic Company
P.O. Box 81608
San Diego, CA 92138

A. A. Cline
Great Lakes Carbon Corp.
Niagara Falls, NY 14302

I. W. Gazda
Great Lakes Carbon Corp.
Niagara Falls, NY 14302

M. Stevenson
Los Alamos Scientific Laboratory
P.O. Box 1663
Los Alamos, NM 87544

M. A. Kinna
Department of Navy
Washington, DC 20555

R. A. Clark
Nuclear Regulatory Commission
Washington, DC 20555

2 R. B. Foulds
Nuclear Regulatory Commission
Washington, DC 20555

G. Kuzmycz
Nuclear Regulatory Commission
Washington, DC 20555

P. M. Williams
Nuclear Regulatory Commission
Washington, DC 20555

S. J. Ball
Oak Ridge National Laboratory
P.O. Box X
Oak Ridge, TN 37830

W. P. Eatherly
Oak Ridge National Laboratory
P.O. Box X
Oak Ridge, TN 37830

No. of
Copies

A. P. Malinauskas
Oak Ridge National Laboratory
P.O. Box X
Oak Ridge, TN 37830

R. P. Wichner
Oak Ridge National Laboratory
P.O. Box X
Oak Ridge, TN 37830

P. A. Thrower
Department of Materials Science
Pennsylvania State University
University Park, PA 16802

C. P. Murphree
POCO Graphite, Incorporated
P.O. Box 2121
Decatur, TX 76234

J. L. Helm
Proto-Power Management Corporation
591 Toquonnock Road
Groton, CT 06430

2 L. Brey
Fort St. Vrain Nuclear Generating
Station
Public Service of Colorado
406 Coffman
Longmont, CO 80501

J. Reesy
Fort St. Vrain Nuclear Generating
Station
Public Service of Colorado
406 Coffman
Longmont, CO 80501

R. R. Paxton
Pure Carbon Company
P.O. Box 386
St. Marys, PA 15857

D. W. Ballard
Sandia Laboratories
Albuquerque, NM 87115

No. of
Copies

H. S. Starrett
Southern Research Institute
Birmingham, AL 35205

W. A. Nystrom
Carbon Division
Stackpole Carbon Company
St. Marys, PA 15857

J. C. Bowman
Parma Technical Center
Union Carbide Corporation
Parma, OH 44130

A. E. Goldman
Union Carbide Corporation
P.O. Box 6116
Cleveland, OH 44101

D. B. Fischback
Dept. of Mining
Metallurgy and Ceramic Engineering
University of Washington
Seattle, WA 98195

H. Burte
Wright Patterson AFB
Dayton, OH 45433

No. of
Copies

ONSITE

2 DOE Richland Operations Office

H. E. Ransom
I. M. A. Garcia

2 United Nuclear Industries, Inc.

D. H. Curtiss
J. P. Schmidt

27 Pacific Northwest Laboratory

L. R. Bunnell
W. J. Gray
C. R. Hann
P. E. Hart
A. J. Haverfield
D. L. Lessor
W. C. Morgan (10)
G. J. Posakony (2)
J. M. Prince (2)
A. M. Sutey
G. L. Tingey
Technical Information Files (3)
Publishing Coordination Y0(2)