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FAST FLUX
TEST FACILITY
PROJECT REPORT

METHODS OF MEASURING
MECHANICAL DISPLACEMENT
AND VIBRATION WITH EMPHASIS
ON FFTF PRIMARY PIPING
AND VESSEL

R. L. Brown, Jr.

August 1968

AEC RESEARCH &
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METHODS
OF MEASURING MECHANICAL DISPLACEMENT
AND VIBRATION WITH EMPHASIS ON FFTF
PRIMARY PIPING AND VESSEL

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August 1968

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METHODS
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R. L. Brown, Jr.

INTRODUCTION

As recently as August 1965 the possibility of catastrophic failure of a reactor pressure vessel was not considered credible in power reactors.⁽¹⁾ Review of the literature indicates that this conclusion was based primarily on three factors: 1) no nuclear pressure vessels had failed, 2) nuclear pressure vessels had been built to standards equal or better than nonnuclear pressure vessels, and, 3) meaningful inspection of nuclear pressure vessels during operation was extremely difficult and expensive. Consideration of the effects of nuclear irradiation on the strength and ductility of pressure vessel materials has recently forced a re-evaluation of this position.⁽²⁾ Several detailed reviews of the effects of irradiation on carbon steel pressure vessels have appeared in the literature,⁽³⁻⁵⁾ and greater interest has been generated in nondestructive methods of assessing the serviceability of pressure vessels during operation.⁽⁶⁾ Many of the factors which apply to surveillance of carbon steel power reactor pressure vessels may also apply to the stainless steel pressure vessels associated with reactors of the liquid metal cooled fast breeder (LMFBR) type such as the Fast Flux Test Facility (FFTF). It is therefore prudent to consider and evaluate various methods of nondestructive surveillance and inspection early in the design phase of the FFTF so that design decisions can reflect realistic inspection goals.

This report is part of a continuing effort to bring together, information on pressure vessel surveillance methods and equipment which may be useful in the in-service inspection of the FFTF. Most of the vessel surveillance methods

used in the past have depended, directly or indirectly, upon detection or measurement of displacement and vibration. Besides the obvious need to measure operationally induced displacement and vibration (for example, to detect such conditions as creep or bowing and to predict potential fatigue or wear) some of the methods described in this report also find extensive use in nondestructive inspection where the displacement or vibration is artificially induced to detect the presence of cracks or other defects (for example ultrasonic testing).

Although primary emphasis in this report has been placed on the measurement of mechanical displacement and vibration, some other areas of vessel surveillance are discussed briefly. Most known methods have been included, for completeness, and estimates of the applicability are made, where appropriate. It is intended that the information included in this report will provide a start toward the design of an effective surveillance system, and that its organization will provide a framework to assist in the orderly assembly of more information as it is obtained.

SUMMARY AND CONCLUSIONS

Consideration of a wide range of displacement and vibration measuring methods indicates that reliability (primarily high temperature and radiation resistance) will be the main criteria which will determine applicability of a given method to the more hostile regions of the FFTF. Frequency response, sensitivity and cost are important factors which will have to be considered. However, it appears that the environmental conditions projected for the FFTF pressure vessel exceed the thermal and radiation exposure specifications of known commercially available instrumentation. Development may therefore be required either to upgrade existing types

or to devise new, more inherently radiation resistant, instrumentation. This is especially true when considering instrumentation intended for permanent installation and continuous operation.

It appears that at least three basic types of high temperature, radiation resistant, transducers (devices for converting mechanical motion to electrical signals) will be required for FFTF surveillance and inspection problems. These are static displacement transducers, low frequency vibration transducers and ultrasonic vibration transducers.

Displacement transducers will probably be necessary to measure static and very slowly changing spacings between components. Present data indicate that resistance strain gages, linear variable differential transformers (LVDT's), capacitive transducers, and remote mechanical micrometers hold the most promise for this type of service; however, it should be noted that all of these methods require that special consideration be given to continuous calibration so that the cumulative effects of temperature and radiation will not introduce excess drift errors. Several companies advertise inductive and capacitive displacement measuring equipment usable at temperatures approaching 1200 °F in radiation environments. Detailed evaluations will have to be conducted to determine their actual capabilities with respect to FFTF requirements.

Low frequency transducers will probably be necessary to detect audio range vibrations which may result in fatigue or wear. Inductive, capacitive, and piezoelectric transducers are all potential candidates for low frequency vibration detection; however, the piezoelectric type is probably the most commonly used. Although inductive and capacitive systems are advertised with probes rated to 1200 °F, present commercial piezoelectric transducers appear to be limited to approximately

650 °F. Recent studies of synthetic ferroelectric crystals (i.e. lithium niobate) indicate that piezoelectric vibration transducers usable to approximately 2200 °F may be possible; however, much development remains to be done.⁽⁷⁾

Ultrasonic transducers may be necessary for active pulse echo applications such as crack detection and displacement measurement, and for passive acoustic emission monitoring. Ultrasonic transducers for use in the FFTF appear to be limited to piezoelectric and electrostatic types. The piezoelectric types are most common and are available commercially up to approximately 650 °F. Most attempts at high temperature applications have involved the use of insulation or cooling rather than high temperature materials. This is due to the fact that most ultrasonic testing has been done in water or oil. Testing in liquid sodium would present unique insulation and cooling problems which might be avoided with high temperature materials. The recent development of new piezoelectric materials has presented the possibility of increasing the high temperature capabilities of ultrasonic transducers. The electrostatic type of ultrasonic transducer has not received much attention; however, it appears to have definite potential for applications at temperatures well above those possible with known piezoelectric materials.

DISCUSSION

AREAS FOR POSSIBLE SURVEILLANCE AND INSPECTION

The development of a comprehensive surveillance system requires that consideration be given to the possible mechanisms through which failure may occur. Displacement and vibration measuring techniques are utilized both for the direct measurement of displacement and vibration, and for the indirect detection of cracks, wear, corrosion and other anomalies.

Material Flaws and Manufactured Defects

It is extremely important that defects be avoided in the key components of the pressure vessel and primary piping. The detection of defects in these components should be made as early in the production process as possible because the difficulty and expense increases as the component progresses from raw material through manufacturing, and installation, to operation. The discovery of cracks, seams, laps, etc. at the factory (with x-rays, penetrants, or ultrasound) is considerably easier and cheaper than trying to detect them remotely in a complicated piping maze with the degrading effects of high temperature, radioactivity and a sodium environment to contend with. It is therefore recommended that extra efforts be expended to ensure the soundness of the materials, welds, etc. before the reactor goes into operation. It should also be recognized that even this will not eliminate the need for subsequent inspection because defects small enough to be acceptable in the fabrication stages may grow or propagate under operating stresses.

Accidental Mechanical Damage During Operation

It is reasonable to assume that mechanical damage may occur to internal components of the reactor during operation due to such factors as vibration, expansion or contraction due to thermal gradients, or irradiation. It is also possible that accidental damage may occur during charging, discharging, or maintenance activities. Methods must be considered for detecting and evaluating the damage.

Optical systems are probably the most commonly used methods of obtaining information about damage in the remote areas of a reactor. Most operating reactors have boroscopes or television equipment which are used to survey and evaluate in detail when other sensors such as pressure, flow, temperature,

or nuclear radiation detectors indicate that a dangerous condition may exist. Some reactor organizations conduct systematic optical scanning of process tubes as a routine part of their preventive maintenance activities. However, this can become time consuming and expensive. Boroscope scanning is usually done with the coolant drained and the tube dry. However, this may not be possible in some sections of the FFTF, so under-sodium scanning systems may have to receive some attention.⁽⁸⁾ No working system is known to be in operation, but development of such equipment, based on acoustical principles, appears to be possible, if justified.

The most highly developed method of monitoring the growth of defects in pressure vessel steel, as they occur, is by acoustic emission detection. In this technique, flaws are detected by sensing the elastic waves produced in the material by the energy released as the metal deforms and/or fractures. One of the basic premises of this technique requires that the metal be in the process of deforming or fracturing to produce the signals as a completely inactive flaw cannot be detected by this method. Acoustic emission provides a tool which is capable of detecting the growth of defects before they are evident to any of the more conventional inspection methods. The location of a defect can also be determined using acoustic emission (by triangulation from three or more sensors), using signal transit time and velocity information.

Ultrasonic flaw detection equipment, many types of which are presently manufactured, may be useful for detecting mechanical damage such as cracks which could increase in size due to operating stresses. The success of this type of flaw detection is highly dependent on such variables as the characteristics of the surface and the sound couplants used. Two important limits in

the use of this technique are the degrading effects of radiation and high temperature on the transducers, and the long scan-time required to test a large area completely.

Mechanical damage might also be detected and perhaps minimized by monitoring the low frequency acoustic vibration which results from such effects as hydraulic turbulence or thermal gradients. Noise and vibration measurement and analysis techniques have been the subject of widespread effort for many years. Many types of transducers are available, and new techniques of data analysis and interpretation are being developed continually. One technique which might be particularly useful would be to build up a library of tape recordings representative of various types of operations. For example, a vibration "signature" could be obtained for a "normal start-up" or a "normal operating period." The "reference signature" recordings could then be compared electronically with new vibration recordings to detect deviations from past performance. This differential system would have the advantage of being insensitive to constant vibrations while responding with high sensitivity to changes in the vibration patterns such as might accompany mechanical damage.

Corrosion

General Corrosion

In general, it should not be necessary to use nondestructive test methods to detect widespread corrosion. Careful attention to known corrosion producing mechanisms during design and construction, the placement and testing of coupons to detect corrosion, and the continuous monitoring of key coolant characteristics should be sufficient to avoid widespread corrosion. In the event that general corrosion progresses in spite of the above mentioned precautions, nondestructive tests may be necessary to determine the extent of damage. For this purpose

eddy current and ultrasonic tests can be used to measure the remaining wall thickness of the vessel or pipe from one side only. Radiation or temperature considerations may complicate this type of testing.

Localized Corrosion

Localized corrosion problems requiring nondestructive detection are more probable than general corrosion problems because coupon and coolant monitoring, which should be effective against general corrosion, may not detect local corrosion. The detection of local corrosion in predictable key areas, such as erosion in pipe bends, can be accomplished with ultrasonic or eddy current techniques. It is extremely important that the complete reactor design be reviewed to pinpoint those areas where localized corrosion may be expected so that access may be provided for testing. It is also possible that semipermanent corrosion sensors can be developed for installation in inaccessible areas.⁽⁹⁾ These sensors would have to be designed to stand up under long exposure to high temperatures and irradiation.

Radiation Damage

The effects of radiation damage in pressure vessel steels, especially the reduction in ductility of carbon steel, have been studied by several investigators.⁽⁵⁾ Preliminary data indicate that a correlation between ultrasonic velocity and neutron fluence can be obtained.⁽¹⁰⁾ This may be useful for measuring the effect of irradiation damage in steels.

MEASUREMENT OF MECHANICAL MOTION

Relative motion between components of a nuclear reactor can be expected due to the expansion and contraction caused by heating, cooling, or irradiation, and the stress or creep caused by pressure or gravity. These movements can cause vibration, distortion, or misalignment which may interfere with operations such as the replacement of fuel, and which may signal the buildup

of other dangerous conditions. It is therefore important to include consideration for mechanical motion measurement equipment in the design of the FFTF.

Review of the available literature indicates that many methods of mechanical motion measurement are possible. Most of the common methods in use are summarized below.

Static Displacement and Low Frequency Vibrations

This section covers methods of detecting or measuring mechanical displacement in the frequency range from 0 to 100 kHz.

Mechanical Methods

Remote Micrometer. In-reactor creep tests have been conducted at Hanford utilizing a specially designed creep capsule which included both an LVDT and a remote micrometer. The remote micrometer consisted of a threaded micropositioner driven through a 2000:1 gear box by a drive shaft which extended out to the face of the reactor. The micropositioner was fastened to one end of the creep specimen, and an electrical contact was fastened to the other end. Measurement of the specimen length was accomplished by counting the number of turns required to establish electrical contact. Creep rates as low as 1×10^{-6} in./hr could be measured over a total range of 0.5 in. (11)

It was originally intended that the LVDT would be used for continuous measurement, and that the remote micrometer would be used only for calibration; however, excessive drift in the LVDT system forced more reliance on the remote micrometer for accurate length data even though its frequency response is severely limited. The present system utilizes an automatic motor driven micropositioner to obtain specimen length measurements at predetermined time intervals. The micropositioner system has been used at temperatures up to

approximately 480 °F. This technique has already been demonstrated in a fairly high temperature nuclear environment and may therefore be useful in making periodic displacement measurements near the core of the FFTF.

Hydraulic Gage. The fact that liquids are practically incompressible offers the possibility of measuring the spacing or displacement between two solid members by measuring the pressure drop in a liquid flowing between them. This principle might be useful for gaging spacings within the reactor core by measuring the pressure of the liquid sodium at appropriate locations.

Air Gage. Air gages operate on a pressure drop principle similar to the hydraulic gage, with allowances made for the compressibility of air. Under laboratory and shop conditions, it is possible to make displacement measurements to approximately ± 0.001 in. on smooth surfaces with commercial air gages. The most attractive aspects of the air gage for FFTF use are the simple, rugged construction of the probes and the high temperature capabilities due to the cooling effect of the airflow. The narrow range over which displacement measurements can be made and the low frequency response for vibration measurements are significant disadvantages, however.

Brittle Coatings. Brittle coatings are sometimes quite useful in obtaining an overall picture of the stress distribution in a complex-shaped part.⁽¹²⁾ There appear to be two possible applications to the FFTF. Conventional brittle coating materials and techniques could be used on models or mockups to obtain information on the design at temperatures up to approximately 700 °F. New materials which could withstand higher projected operating temperatures might be found so that actual stress distribution data could be obtained from the vessel or piping under actual operation (at least on the initial start-up). Long-term high temperature and radiation resistance

should not be significant under these conditions; however, the long-term corrosion potentialities would have to be carefully considered.

DeForest Scratch Gage. The DeForest scratch gage is a self-contained mechanical strain gage and recording system. Each unit, which weighs less than 2 gm, can record deformations from 0.0001 to 0.050 in. over a 2 in. gage length. The information is recorded by the scratching of a spring-loaded arm onto a chrome-plated target.⁽¹³⁾

The DeForest scratch gage may find use in accessible areas of the FFTF where periodic readings could be made. The fact that the gage is made almost entirely of metal, and therefore inherently radiation resistant, suggests that it might be usable within the core region; however, remote (probably optical) readout methods would have to be provided. An alternative approach would be to mount such a gage on a core component which is periodically removed such as fuel assembly or flow duct. The most serious disadvantages appear to be the limited operating time and the low accuracy with which time and frequency are recorded.

Mechanical Recorders. A mechanical linkage can be used to amplify displacements and vibrations which can then be recorded on a motor driven cellulose film. This type of equipment is usually intended for fastening to structural members such as bridge girders.⁽¹³⁾ The temperature and radiation resistance of such equipment is believed to be severely limited by the cellulose film, thereby restricting FFTF use to accessible nonnuclear environments.

Chemical Methods

Several chemical transducers are available such as the Solion, porous disc, and mercury-electrolyte types.⁽¹⁴⁾

However, they appear to have no advantage over the more common electrical types for application to the FFTF. They are limited to temperatures below approximately 150 °F by the boiling of an internal electrolyte.

Electrical Methods

The most common general method of detecting or measuring mechanical displacement or vibration is through the use of a mechanical to electrical transducer. A transducer is a device, placed in the environment to be monitored, which produces an electrical analog voltage bearing information about the mechanical quantities desired. The major types of mechanical to electrical transducers are variable resistance, variable capacitance, variable inductance, piezoelectric and microwave.

Variable Resistance. The most common variable resistance type transducers are the potentiometer, resistance strain gage, and fatigue gage.

Potentiometer Types. The use of resistive potentiometers as the mechanical to electrical conversion element in displacement and vibration transducers is common in low cost applications where the temperature range or the frequency response requirements are not critical. They can be used over a displacement range of 0.1 to 10 in. and at frequencies up to approximately 20 Hz. They are encountered occasionally in pressure transducers. A recent study indicates that ordinary potentiometer type transducers can be expected to operate satisfactorily at fast neutron fluences up to 10^{15} n cm⁻² (E > 2.9 MeV) and gamma exposure up to 10^9 erg g⁻¹ [C] (approximately 1.1×10^7 R) while radiation hardened units can be made to withstand 2×10^{17} n cm⁻² (E > 2.9 MeV) of neutron exposure and 10^{11} ergs g⁻¹ [C] (approximately 1.1×10^9 R) of gamma radiation.⁽¹⁵⁾

Displacement transducers using potentiometers may be useful for measuring such things as expansion, contraction, or tilt in areas where radiation and high temperature are not dominant factors. It is possible to design potentiometer transducers using radiation resistant materials, and compensating techniques to reduce the effects of radiation and temperature. It is doubtful, however, that they will find much use as vibration sensors because of the inherent low frequency response ($\sim 0-30$ Hz) and the limited lifetime due to friction and wear.⁽¹⁴⁾

Resistance Strain Gages. The use of resistance strain gages has been an established practice in industry for many years; however, the problems of accuracy and reliability increase as the temperature of the environment increases.⁽¹⁶⁻¹⁹⁾ Several types are available for use up to approximately 500 to 600 °F; however, they are seldom specifically designed for use in a high radiation environment.⁽²⁰⁾ These gages usually are constructed from Nichrome-V or Karma alloy wires on phenolic or bakelite backing. Foil gages are also widely used at low temperatures.

Above approximately 500 °F organic adhesives and backing materials lose much of their effectiveness, and ceramic materials must be used. Although ceramic cements are widely used, two of the most promising methods of attaching high temperature strain gages are by a flame spray process using aluminum oxide and by the use of weldable metal encased gages. A platinum-tungsten alloy and an iron-chromium-aluminum alloy call "Armour D" are used up to approximately 1000 °F, for steady state measurements, and up to somewhat higher temperatures for dynamic studies.^(21,22)

At the present time the most applicable commercial products appear to be a weldable platinum-tungsten gage made by Micro Dot⁽²³⁾ (which is rated to 950 °F) and a platinum-tungsten gage made by BLH Electronics Inc. which is installed with the Rokide flame process.⁽²⁴⁾ Contacts with sales personnel indicate that Automation Industries (formerly the Budd Co.) plans to market a flame sprayed film gage rated to 1000 °F within the next few months.

Detailed studies of the combined effects of high temperature and high radiation on strain gages in a sodium environment are apparently not yet available; however, several preliminary attempts to assemble this type of information have been reported.⁽²⁵⁻²⁷⁾ Evaluations at high temperature and in sodium have been reported,⁽²⁸⁻³²⁾ and a survey of the effects of radiation has been published recently;⁽¹⁵⁾ however, an extensive search did not reveal any literature concerning the combined effects of all three. Consideration of radiation alone indicates that resistance strain gages can be designed to withstand neutron fluences between 10^{16} and 10^{18} n cm⁻² ($E > 2.9$ MeV) and 10^{10} erg g⁻¹ [C] (approximately 1.15×10^8 R).⁽¹⁵⁾

In summary, resistance strain gages are presently available for continuous static operation at temperatures to approximately 900 °F. Several investigators including the major strain gage manufacturers are working toward increasing the temperature rating to at least 1200 °F.

The radiation resistance of strain gages is not receiving as much attention as the temperature rating. Fortunately, however, changes which increase the temperature rating often increase the radiation tolerance. A serious program of radiation resistant strain gage development is

sorely needed but no reference to such a study has been found. Likewise, the need for an investigation to determine the combined effects of radiation and high temperature on strain gages mounted in a sodium environment is apparently unfilled.

Fatigue Gages. For several years Boeing and Micro-Measurements, Inc., have been developing a gage which can be used to predict fatigue life. In its present form, it is basically a specially designed foil strain gage which exhibits increasing resistance with fatigue. The resistance increase is believed to be caused by cold working and the growth of microcracks. These gages can be installed in critical areas and monitored periodically to determine the remaining fatigue life of the structure.⁽³³⁾ Although this type of gage would appear to have application to FFTF surveillance problems, none of the literature obtained to date indicates the temperature or radiation limitations. The complete lack of temperature data in otherwise complete articles may indicate that the present fatigue gages are only useful around room temperature.

Applicability. The applicability of variable resistance transducers to FFTF surveillance problems is estimated to be good, however difficulties are anticipated in obtaining units with sufficiently high temperature stability and radiation resistance for continuous service in the more hostile areas of the FFTF.

Variable Capacity. Several excellent articles on capacitance-type transducers are available.^(14,34,35,36) There are very little data available on radiation effects; however, transducers with polystyrene dielectric or insulating materials have been estimated to withstand 10^{17} n cm⁻² and 10^{11} ergs g⁻¹ [C] (approximately 1.15×10^9 R).⁽¹⁵⁾

Advantages. Capacitor transducers have the following advantages:

- 1) The capacitor transducers can be made very simple, rugged and reliable. Probes are commercially available to 1400 °F. Although no probes have been found that are claimed to be radiation resistant it is highly probable that they can be made radiation resistant by the substitution of ceramics or glass for any organic dielectrics or insulation. Radiation damage to metal parts should not affect the operation until mechanical distortion sets in. There are no moving parts.
- 2) The capacitor transducer should add very little mass or damping to the vibrating member thereby ensuring low distortion.
- 3) Extreme sensitivity--the resolution is typically less than 10^{-3} in. with equipment available having resolution to 10^{-6} in.
- 4) Wide displacement range (up to 2 in.) presently available.
- 5) Accuracy--commonly ± 2 to $\pm 5\%$.
- 6) Some equipment offers linear output proportional to displacement.
- 7) Wide frequency response--no theoretical limit--dc to 10 or 15 kHz commercially available.

Disadvantages. Capacitor transducers have the following disadvantages:

- 1) Electronic equipment may be more complicated than that used with self-generating transducers such as velocity or piezoelectric types. A dc bias supply or ac carrier system is usually used, also impedance matching circuits are desirable on long cables. These are not serious disadvantages, however.

- 2) The probe and lead wires are voltage sensitive so rapidly varying magnetic fields may induce interference in the system unless adequate shielding is employed. Information on the types of interference to be encountered in a reactor environment should be collected to evaluate this problem in more detail.
- 3) If the system is to be calibrated to readout in terms of absolute displacement or amplitude, the electrical characteristics of the dielectric material must remain constant. This is a fundamental limitation to this method which should be studied more closely. It is probable, however, that usable data on vibration or displacement can be obtained through compensation techniques even if the radiation or temperature changes the dielectric properties.
- 4) It is doubtful that this type of displacement or vibration sensor can be used under sodium because of the high electrical conductivity of sodium which would effectively short out the probe. It is most usable in air or a vacuum.

Applicability. The applicability of capacitor transducers to FFTF surveillance problems is estimated to be good.

Capacitance transducers offer a possible answer to the measurement of displacement and vibration within the high temperature, radioactive areas near the core (not under sodium).

Some commercial manufacturers are:

Reliance Electric Co.
24701 Euclid Ave.
Cleveland, Ohio 44117
Phone: 216-732-7000

Wayne Kerr Corp.
22 Frink St.
Montclair, New Jersey 07042
Phone: 201-746-2438

Also the same instrument is handled by
Mechanical Technology, Inc.
968 Albany-Shaker Road
Latham, New York 12210
Phone: 518-785-2323

Variable Inductance. A large variety of displacement and vibration transducers have been developed using variation of inductance to convert from mechanical motion to an electrical signal. These include self-generating types such as: electrodynamic, electromagnetic, eddy current, magnetostrictive and passive types such as: mutual inductance, differential transformers, and variable reluctance. An excellent survey of these techniques appears in the Shock and Vibration Handbook.⁽³⁷⁾

Advantages. Variable inductance transducers have the following advantages:

- 1) Some types (electromagnetic, mutual inductance, and variable reluctance) can be used to measure displacement and vibration without touching or loading the vibrating member.
- 2) These same types may have a very wide frequency response range.
- 3) Inductive transducers are potentially capable of operating in high temperatures and high radiation. Neutron and gamma exposure as high as 10^{18} n cm⁻² and 10^{11} ergs g⁻¹ [C] (approximately 1.15×10^9 R), respectively, without failure have been reported on radiation hardened components.⁽¹⁵⁾
- 4) A variable reluctance transducer with ceramic potting was operated at 1300 °F.⁽³⁸⁾ Associated Engineering, Ltd., has recently developed an electromagnetic probe

for use at temperatures up to 1100 °F. This item is marketed in the U.S. through Mechanical Technology Inc.

- 5) Both ac carrier systems and self-generating systems are available.
- 6) The electrodynamic transducer can produce a large self-generated voltage therefore reducing the necessary external instrumentation required.
- 7) Much development effort has been directed toward these types of transducers over the years. Many types are available "off the shelf."

Disadvantages. Variable inductance transducers have the following disadvantages:

- 1) High temperature and high radiation capabilities are presently limited by changes in permeability and conductivity of core materials, conductivity of insulating materials, and the effectiveness of sliding or rotating mechanical couplings.
- 2) Some types (electrodynamic) have an upper frequency limit of several thousand hertz.
- 3) Mechanical resonances introduce calibration errors in vibration measurements unless taken into consideration.
- 4) AC-operated carrier modulation type devices should be sensitive to both conductivity and permeability variations in the environment such as might be caused by high temperatures or radiation. DC-operated electromagnetic or permanent magnet displacement transducers should be sensitive to permeability variations only and, therefore, may be more stable in a reactor environment.

Applicability. The applicability of inductive transducers to FFTF surveillance problems is estimated to be good.

Inductive transducers may be used in various displacement and vibration measurements in the fringe areas of the reactor. The degree to which they may be used in the core is not yet known and depends on the actual radiation levels and the degree of radiation hardening which can be obtained. Several interesting commercial units have been found and some of these appear to be usable in environments as high as 1200 °F, 10^8 R gamma and 10^{21} nvt neutrons.

Some commercial manufacturers include:

C-E Electronics 363 West Glenside Ave. Glenside, Pa. 19038 Phone: 215-887-8900	LVDT to 800 °F
Mechanical Technology, Inc. 968 Albany-Shaker Road Latham, New York 12110 Phone: 518-785-2211	1100 °F Probe also Contract with AEC for inductive temperature mea- suring system in sodium
Bently Nevada Corp. Box 157, Airport Road Minden, Nevada 89423 Phone: 702-782-2255	EC Probes to 1300 °F
Daytronics Corp. 2875 Culver Ave. Dayton, Ohio 45429 Phone: 513-298-7542	LVDT's to 800 °F
Kavlico Electronics, Inc. 20869 Plummer Street Chatsworth, Calif. 91311 Phone: 213-882-2400	LVDT's to 1200 °F Gamma to 10^8 R Neutrons to 10^{21} nvt
G. L. Collins Corp. 5875 Obispo Ave. Long Beach, Calif. 90805 Phone: 213-636-8141	LVDT's to 500 °F

Automatic Timing
& Controls, Inc.
King of Prussia
Pa. 19406
Phone: 215-265-0200

Atcotran LVDT's
to 1200 °F

Electro Products
Laboratories, Inc.
6125 W. Howard St.
Chicago, Illinois 60648
Phone: 312-647-8744

Magnetic Pickups
to 800 °F

Piezoelectric. Certain materials, called piezoelectric crystals, can be used to convert mechanical force or motion directly into an electrical signal resulting from a self-generated voltage which appears across this type of material when it is stressed. A large fraction of all the audio frequency vibration transducers or accelerometers and practically all of the ultrasonic transducers now in use are of the piezoelectric type.

Since the turn of the century the piezoelectric transducer field has been dominated by a few materials; namely, quartz, rochelle salt, tourmaline, ammonium dihydrogen phosphate (ADP), and lithium sulphate. Since World War II, several new and interesting materials have been developed, including barium titanate, and a wide range of lead titanate-zirconate (PZT) ceramics. Currently such new materials as lithium gallate, lithium niobate, and bismuth germanate are being investigated. Several comprehensive surveys of piezoelectric materials and their properties are available.⁽³⁹⁻⁴¹⁾

The transducers most commonly used for audio frequency vibration detection are mass loaded which results in an output proportional to acceleration, when used below the resonant frequency.⁽⁴¹⁾ The crystal is mounted with one surface connected to an inertial mass, which provides a position reference, and the other connected to the transducer case. This

type of transducer, commonly called an accelerometer, may have a resonant frequency as high as 100 kHz. Piezoelectric accelerometers and dynamic pressure transducers are produced by many manufacturers. However, the present state-of-the-art appears to be limited to approximately 500 °F for most commonly used materials, with a 650 °F limit for some of the PZT ceramics. Quartz can be used up to approximately 1000 °F; however, its sensitivity is considerably less than the other materials. Some of the new materials have considerable potential for high temperature application (for example, lithium niobate to approximately 2200 °F).

A recent report⁽¹⁵⁾ summarizing the available radiation effects data on piezoelectric transducers indicated that the quartz type had withstood neutron fluences to 10^{18} n cm⁻² without indication of damage, while the PZT type was damaged with less than 10^{16} n cm⁻².

Advantages. Piezoelectric transducers have the following advantages:

- 1) Piezoelectric transducers produce a self-generated voltage. No ac carrier or dc bias systems are necessary.
- 2) Although electrical characteristics such as sensitivity, capacity and frequency response are adversely affected by temperature increases, these characteristics may not seriously hamper the usefulness of piezoelectric transducers for passive acoustic emission monitoring, active pulse echo crack detection, or displacement measurement until sensitivity drops to such an extent that the signals are undetectable. This is because most of the important information to be obtained lies in the pulse rate or the elapsed time between pulses, and amplitude stability is not necessary.

- 3) Several new piezoelectric materials are now available which have potential operating temperatures much higher than 500 °F (i.e., lithium niobate to 2200 °F).
- 4) There is evidence that the effects of high temperature and high nuclear radiation may tend to cancel each other out which will facilitate the development of high temperature, radiation resistant transducers.⁽¹⁵⁾
- 5) Piezoelectric transducers have received considerable attention and development effort by both commercial manufacturers and government labs. They hold considerable promise for development of high temperature radiation hardened units.
- 6) Piezoelectric transducers should be usable in applications requiring immersion in liquid sodium through the use of appropriate cladding.

Disadvantages. Piezoelectric transducers have the following disadvantages:

- 1) Present commercial units appear to be limited to approximately 500 to 650 °F.
- 2) Piezoelectric transducers are not directly applicable to static displacement or very low frequency vibration measurement unless a carrier system or special (low capacity, high resistance) electrometer circuits are used. This is particularly difficult at high temperatures and in the presence of high humidity.
- 3) Piezoelectric transducers are not directly applicable to measuring large displacements. A pulse echo or carrier system must be used.
- 4) A charge amplifier may be required near the transducer to convert the high impedance charge output from the transducer into a low impedance signal to allow more interference-free transmission to a remote readout.

Applicability. The applicability of piezoelectric transducers to FFTF surveillance problems is estimated to be good. Piezoelectric low frequency vibration sensors or accelerometers are one of the likely candidates for use in some of the more hostile areas of the FFTF as well as the fringe areas. Piezoelectric transducers are commercially available from many manufacturers; however, no unit is known at this time to be specifically designed to maximize high temperature and radiation resistance.

Some commercial manufacturers are:

Consolidated Electrodynamics Corp.
Transducer Division
1400 South Shamrock
Monrovia, California

MB Electronics
a Division of Textron Electronics Inc.
781 Whalley Ave.
New Haven, Connecticut 06508

Kistler Instrument Corp.
8989 Sheridan Drive
Clarence, New York 14031
Phone: 716-634-6600

Endevco Corp.
801 So. Arroyo Parkway
Pasadena, California 91109
Phone: 213-795-0271

Microwave. Noncontacting displacement and vibration measurements can be made with microwave techniques.^(14,42)

Advantages. Microwave techniques have the following advantages:

- 1) Displacements from approximately 10 μ in. up to 0.3 in. can be measured at frequencies from zero to approximately 100 kHz with potential application into the MHz range.
- 2) These measurements should not be significantly affected by the temperature of the vibrating surface or the radiation level.

Disadvantages. Microwave techniques have the following disadvantages:

- 1) The equipment is generally quite expensive and complicated.
- 2) The antennae, horns, or waveguides that are used to direct the microwave energy are rather bulky but size reductions may be possible in the future. These components are usually positioned no more than a few inches from the vibrating surface.

Applicability. The applicability of microwave displacement and vibration measuring techniques to the surveillance problems of the FFTF is estimated to be poor. No widespread use of microwave techniques is foreseen, but specialized measuring problems may arise where the independence from temperature and radiation conditions could outweigh the disadvantages.

Some commercial manufacturers are:

Weinschel Engineering
Gaithersburg, Maryland 20760
Phone: 301-948-3434

Microwave Instruments Co.
3111 Second Avenue
Corona Del Mar, California 92625
Phone: 714-673-7688

Optical Methods

Borescopes. Optical borescopes and periscopes are commonly used for surveillance within confined areas such as reactor process tubes. (43,44)

Advantages. Borescopes have the following advantages:

- 1) Detailed images of complex shapes may be obtained.
- 2) Real time observation of complex mechanical motions are possible.

- 3) The probing medium (light) is not affected greatly by temperature or radiation level.
- 4) Permanent records (photographs) may be obtained.
- 5) Both rigid and flexible borescopes may be obtained.
- 6) Borescopes are commercially available as long as 32 ft and as small as 0.1 in. in diameter.

Disadvantages. Borescopes have the following disadvantages:

- 1) The field of view is usually fixed and may be somewhat limited.
- 2) The image may darken as the lenses are irradiated.
- 3) Borescopes are limited to operation in a transparent medium. They are not usable in a sodium environment.
- 4) Cleaning and drying operations are usually necessary to prepare surfaces for borescope inspection.

Applicability. The applicability of optical borescopes to FFTF surveillance problems is excellent. Borescopes are the most commonly used equipment for the periodic surveillance of reactor process tubes.

Closed Circuit Television. Minature, radiation hardened, television cameras have been used to monitor areas of limited accessability such as the inside of reactor process tubes.⁽⁴⁵⁾ Television units have also been used to improve the capabilities of borescope systems.⁽⁴⁴⁾

Advantages. Television systems have the following advantages:

- 1) In general, the quality of the image is not affected by the distance between the object to be viewed and the viewer.
- 2) Television cameras can be made as small as 3 in. in diameter.

- 3) Several people may view the image at the same time and they may be remote from the reactor and out of radiation fields.
- 4) Radiation tolerant cameras are available which are rated to a cumulative dosage of 10^8 R and 10^{12} neutrons cm^{-2} .

Disadvantages. Television systems have the following disadvantages:

- 1) The resolution of a television system is usually less than an optical borescope.
- 2) The television camera tube becomes degraded with exposure to radiation and requires periodic replacement.
- 3) The components in the camera generally limit the the operating temperature to less than 150 °F.
- 4) Television systems are only useful in transparent media. They would not be applicable under sodium.
- 5) Specialized television systems can be quite expensive.

Applicability. The applicability of closed circuit television to FFTF surveillance problems is estimated to be very good. Television offers a practical method of conducting periodic inspection in areas of limited accessibility. This type of inspection may detect minor damage. A remote, closed circuit, television system would also be invaluable for assessing repair work.

Electro-Optical Displacement Follower (Optron). The Optron is a commercial displacement and vibration sensing device which utilizes a light beam as its probing medium.⁽¹⁴⁾

Advantages. The Optron has the following advantages:

- 1) Frequency response from 0 to 10 kHz (possibly 100 kHz)
- 2) No mechanical connection to vibrating object.
- 3) Remote (may be as far away as 200 ft from vibrating part).
- 4) May be used at temperatures up to 5000 °F.
- 5) Unaffected by radiation at vibrating part.

Disadvantages. The Optron has the following disadvantages:

- 1) Expensive, bulky, and complicated.
- 2) Normal working distance approximately 2 to 3 ft.
- 3) Lab equipment, not industrial instrumentation.

Applicability. The applicability of the Optron to FFTF surveillance problems is estimated to be poor, except in special emergency conditions.

Photo Elastic Coatings. Photo elastic coating tests involve the coating of models or actual parts to be tested with a special plastic material which changes color when viewed appropriately with polarized light.⁽⁴⁶⁾ This type of test is used primarily as a design tool to study stress distribution on complex structures.

Advantages. Photo elastic coatings have the following advantages:

- 1) Covers complicated shapes.
- 2) Surveys the whole part or only the trouble spots.
- 3) No external connection or loading of vibrating part.

Disadvantages. Photo elastic coatings have the following disadvantages:

- 1) Temperature limit approximately 250 °F.
- 2) Low frequency response.
- 3) Effects of radiation unknown (probably poor).
- 4) Equipment expensive and cumbersome.
- 5) Lab tool only. Not a production check.

Applicability. The applicability of photo elastic coatings to FFTF surveillance problems is estimated to be poor. However, some use might be made during design.

Tuckerman Gage (American Instrument Co.). The Tuckerman gage utilizes a special fixture which is attached to the specimen and a light beam sensing arrangement.⁽⁴⁷⁾

Advantages. The Tuckerman gage has the following advantages:

- 1) May be used at temperatures up to 1500 °F.
- 2) The readout equipment may be several feet from extensometer mounted on vibrating specimen.

Disadvantages. The Tuckerman gage has the following disadvantages:

- 1) May cut into specimen.
- 2) Low frequency response--basically a static strain gage.

Applicability. The applicability of the Tuckerman gage is estimated to be poor.

Fotonic Sensor (Mechanical Technology, Inc.). The Fotonic sensor utilizes a fiber optic bundle to transmit light to and from the surface to be monitored. Variations in the distance from the surface change the light output.⁽⁴⁸⁾

Advantages. The Fotonic sensor has the following advantages:

- 1) Frequency response from dc to 100 kHz and higher are available.
- 2) Resolution to 10 μ in.
- 3) Noncontacting measurement.
- 4) Electrical or thermal properties of material not pertinent--can test conductors, insulators, or magnets.
- 5) Low cost.

Disadvantages. The Fotonic sensor has the following disadvantages:

- 1) High temperature limited to 300 °F for tip of probe.
- 2) May be affected by radiation (sensitivity reduced)
- 3) Good over small range (2 to 5 mils).

Applicability. The applicability of the Fotonic sensor to FFTF surveillance problems is estimated to be poor. No use is seen inside the pressure vessel, however there may be uses in less hostile areas.

Optical or Laser Interferometers. It is possible to measure small order vibration with a laser interferometer.⁽⁴⁹⁾

Advantages. Interferometers have the following advantages:

- 1) No loading on vibrating member.
- 2) Very small displacements can be measured.
- 3) Wide frequency response range (in theory).

Disadvantages. Interferometers have the following disadvantages:

- 1) Best suited for displacements of less than 30×10^{-6} in.
- 2) Practical frequency range approximately 30 cps to 20 kHz.
- 3) Primarily a lab tool, not a production test.

Applicability. The applicability of interferometers to FFTF surveillance problems is estimated to be poor for in-reactor testing, however they may be excellent for calibration of other transducers.

Stroboscopy. Vibrations of large amplitude and low frequency can be studied optically with the assistance of a short recurrent pulse of light. Stroboscopes are available with pulse duration from 0.5 to 8.0 μ sec and a variable repetition rate up to 2.5 kHz. This type of equipment may be useful for study of

specific vibration problems in accessible areas of the FFTF, but no application is foreseen to the core or to continuously operating inspection systems.

Nuclear Methods. While it is theoretically possible to measure displacement and low frequency vibration with nuclear counting techniques, the usefulness of such methods in a reactor environment has not been established. The chief advantage would appear to be the absence of temperature effects on the radiation rate or on the absorption in the medium between the source and the detector. The detector gain would of course be subject to temperature effects. Although no references on the subject have been found, it appears probable that alpha, beta, gamma, neutron or X-rays, could be used depending on the characteristics desired. The major disadvantages appear to be: 1) the lack of resolution to small displacement, 2) the limit to high frequency response resulting from the statistical nature of the detector output and the subsequent electrical integration, 3) the expense and complication of the necessary equipment, 4) the danger inherent in the radiation source, and, 5) the possible interference from other sources of radiation in the area.

High Frequency Vibrations

This section is concerned with methods of generating and measuring ultrasonic vibrations from approximately 100 kHz to 20 MHz. Ultrasonic acoustic waves may be usefully employed to detect existing defects, measure static and dynamic displacements, or to detect and locate defects as they occur.

A pulse echo type ultrasonic crack detection system operates much like a miniature acoustic radar set. A pulse of ultrasonic acoustic energy is generated in the material to be tested, and sensitive receivers listen for echos from defects,

cracks, unbonded areas, or other anomalies. Similar equipment could probably be used to measure displacements in liquid metals such as sodium. The information obtained includes both the amplitude of the echo and its time of arrival. From these, defect size and location may be estimated.

Passive ultrasonic listening devices may be used to detect the acoustic emission which radiates from a defect when metal deforms or fractures. This may also be done with low frequency vibration sensors. However, it is generally agreed that wide-band width is desirable in this application. When several transducers are used, it is possible to calculate the location of the defect from the transit time and velocity information.

Ultrasonic vibrations have been generated and detected at frequencies much higher than 20 MHz (many references are available in the GHz region). However, the technology does not appear ready for practical nondestructive testing applications.

Although several methods have been used to generate and detect ultrasound, piezoelectric transducers presently dominate the field with the electrostatic type showing promise for high temperature applications. A brief description of each of the major methods of generating and detecting ultrasound follows.

Piezoelectric Method

Piezoelectric ultrasonic transducers are constructed with much the same materials and techniques that have been discussed under low frequency measurements. A quick review of that section is advisable. The high temperature serviceability and radiation resistance of piezoelectric ultrasonic transducers is believed to be roughly comparable with that of low frequency accelerometers. The only factors known which might cause differences are the materials selected and the additional effect of gamma heating on the inertial mass within an accelerometer.

Many of the small changes which elevated temperatures and extensive radiation can be expected to cause in piezoelectric transducers are not expected to seriously degrade their usefulness. This is because most of the significant information obtained from ultrasonic transducers is available in pulse rate or the time between pulses. Both of these parameters are time based measurements, and amplitude changes do not seriously affect their accuracy until the sensitivity drops below the noise level. Pulse amplitude is only used in estimates of defect size and some form of standard is always necessary. Some development will be necessary to determine the best way to provide this standardization if defect sizes are to be measured.

A potentially serious problem may be involved in maintaining a reliable acoustic coupling between an ultrasonic transducer and a pressure vessel or pipe under long-term operating conditions. This type of contact is commonly made through a liquid couplant, but few liquids can be used in the projected environment. The possibility exists that sodium could be used as the couplant at elevated temperatures. However, trouble can be expected near the freezing point where cracks and shrinkage normally occur. A tight spring loaded mechanical contact or some form of flame sprayed bond may prove useful. However, the problem will have to be studied carefully if ultrasonic transducers are to be coupled to the pressure vessel or primary piping.

Acoustic emission detection is the only technique known which is capable of detecting defects or cracks as they form or grow. This technique may therefore become a surveillance technique in the FFTF. Although several basic unknowns have yet to be resolved, it is reasonable to predict that if such a system is used it will require the development of high temperature, radiation-resistant, ultrasonic transducers with a significant lifetime.

Fortunately, it appears that the same type of transducer can be used for at least three types of service: acoustic emission monitoring, pulse-echo crack detection, and pulse-echo displacement and vibration measurement under sodium. It is also highly possible that this type of transducer will find additional uses such as monitoring coolant properties or possibly as a direct fuel failure detector (mounted on or near the fuel). These potentials only make the development of a high temperature, radiation resistant, ultrasonic transducer more desirable. Recent development of several new piezoelectric materials with potential high temperature capabilities have increased the possibility that such a transducer can be developed. Lithium niobate, for example, retains its piezoelectricity up to approximately 2200 °F.

Some commercial manufacturers are:

Clevite Corp.
Piezoelectric Division
232 Forbes Road
Bedford, Ohio 44014
Phone: 216-232-8600

Automation Industries Inc.
Research Division
P.O. Box 950
Industrial Park
Boulder, Colorado 80302
Phone: 303-443-6011

Parametrics Inc.
221 Crescent Street
Waltham, Massachusetts 02154

Electrostatic Method

The electrostatic transducer is considered one of the most attractive candidates for the development of ultrasonic transducers usable in the 3000 to 4000 °F range. An electrostatic transducer is composed of two or more thin layer-shaped electrodes separated by thin dielectric insulators.

Although practical experience is limited to a few experimental prototypes,⁽⁵⁰⁾ it appears that the layers could be made very thin and almost any shape desired. A wide range of high temperature radiation resistant metals and ceramic dielectrics are available to choose from. Electrostatic transducers might be cemented or flame sprayed in place on pressure vessels or pipes. However, the development of a high temperature fastening method appears to be one of the significant problem areas.

Magnetostrictive Method

While the piezoelectric ultrasonic transducer has effectively dominated the field, the magnetostrictive transducer historically must be rated second in terms of numbers produced. However, it is losing popularity as better low frequency piezoelectric materials are developed. Several materials (including nickel) change length when subjected to a magnetic field. Magnetostrictive ultrasonic transducers consist of a coil of wire wound around nickel rods. They have been limited to low frequencies and were used in applications such as sonic cleaning and SONAR where large amounts of acoustic power were desired. At this time there is no indication that magnetostrictive transducers will be needed in the FFTF surveillance program.

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