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HIGH VOLUME NONDESTRUCTIVE TEST APPLICATIONS

AT THE HANFORD ATOMIC PRODUCTS OPERATION

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Introduction

Industrial applications of nondestructive testing are most economically profitable when they can be applied to large volumes of material under rapid, reliable and routine operation. For maximum benefit, tests must be applied in the field or in a competitive manufacturing process where laboratory conveniences do not exist. The need for inspection techniques with these capabilities has promoted the growth of x-ray, fluorescent penetrant, magnetic particle, and similar methods even though they are intrinsically slow and difficult to automate. The newer electronic methods, such as eddy current and ultrasonic, while being extremely fast and readily adapted to automatic operation, are hampered by their susceptibility to instrument drift and improper calibration, necessity for skilled data interpretation, sensitivity to trivial specimen parameters and other factors. These tests have thus been slow to be applied in those areas where they offer the greatest potential -- the routine inspection of large quantities of material under difficult field conditions.

At the Hanford Operations of the USAEC, major effort has been devoted over the past several years to accelerate transition of these tests from laboratory to field use. This paper describes results in two major areas: The inspection of thin wall tubing, and the automatic inspection of nuclear fuel.

I. THIN WALLED TUBING TESTS

Modern technology consumes tubing with diameters less than one inch and wall thickness less than .050 inch in tremendous quantities. The heat exchanger system of one Hanford nuclear installation uses about a million feet of this material by itself. Typically, the quality of the tubing must be high, necessitating careful nondestructive inspection before installation. During operation, the tubing is normally subjected to rigorous environments. Since efficiency and safety of major installations is often critically dependent upon

the continued integrity of its installed tubing, periodic inspection of this tubing is essential.

Tests are therefore necessary for the inspection of tubing both before and after installation. At Hanford, eddy current tests have been developed for the inspection of installed tubing, and ultrasonic tests are used for the inspection of as-fabricated tubing. Each is discussed below:

1. Eddy Current Test

The eddy current test is particularly useful for inspecting installed tubing having restricted access. It readily scans with an internal probe the inside surface of long tubes where only the ends are accessible. It can also be readily adapted to a scan of the outside surface in instances where this is more convenient. 1.

Its novelty with respect to existing tests lies in the increased information it provides regarding the defects which it detects, and the convenient manner in which this information is displayed. In essence, its principle of operation is based upon two key points: The impedance locus of a coil in motion with respect to a defect is a curve rather than a straight line, and the shape of this locus uniquely describes (to a first approximation) the nature of the defect, i.e., its position with respect to the outer and inner tube surface, its depth, and its size. An important related point is that probe wobble and its associated "lift-off" signal has, with proper instrument adjustment, a unique and readily identifiable characteristic locus.

These concepts are readily demonstrated experimentally. The impedance of a coil approaching a tubing irregularity varies nonlinearly due to the apparent change of wall thickness and the difference in phase of the eddy currents with distance from the coil. It follows that two concentric differentially connected coils, one slightly displaced to the other, will provide an output which varies in magnitude and phase as the two coils pass over an irregularity.

The vectors shown in Fig. 1 demonstrate that these vector signals provide information regarding the nature of the defect. Here the vectors represent the peak output of two differentially connected 130-turn, 0.5 inch diameter coils as the coils move past various irregularities in a $5/8$ inch outside diameter (o.d.) 304 stainless steel tube with 0.054 inch wall. The coils are spaced $1/10$ inch apart and are driven at 200 kc. It is apparent that inner surface flaws are readily distinguishable from outer flaws by the vector position, and that the vectors rotate as the defects increase in depth. It is noted that the probe wobble, or lift of signal, so troublesome to many eddy current tests, has its own characteristic position easily distinguishable from the defect signals.

Useful application of these results requires the data be put in a form readily observed and interpreted by unskilled operators. This is accomplished by displaying the information as Lissajou patterns on a cathode ray tube. In essence, the output signal is separated into quadrature components and separately fed onto the horizontal and vertical plates of a cathode ray tube. The spot is deflected in first one direction and then the other as the two-coil probe passes over an irregularity. Due to curvature of the impedance locus, and the physical displacement of the coils with respect to the irregularity, the spot motion is non-linear. The net result is a "figure 8" whose shape and axis of tilt approximately define defect depth and location. Signals arising from harmless tube conditions such as kinks, bends, etc. degenerate the figure 8 into a straight horizontal line.

Origin of the figure 8 is illustrated in more detail in Fig. 2. The complex impedance locus $f(d)$ of a single coil was plotted with measurements made at .025 inch intervals as the coil moved past a 0.013 inch deep by $1/8$ inch long inner surface notch. $d = 0$ is the coil starting point where the defect makes no measurable effect on the coil, and $d = .175$ represents the coil centered over the notch. Test coil wobble is in this case along arrow A. If now a second identical coil, separated from the first a distance d_1 , is also moved along

FIGURE 1

FIGURE 2

Construction of Figure "8" from Response of Two Differently Connected Coils
to 0.013 inch deep Tubing Defect

the tube it generates a signal $f(d-d_1)$. The differential output in this case is $f(d-d_1)-f(d)$. Point C on the curve of Fig. 2 is derived by letting vector OA represent the negative of the first coil output at $d = 0.150$. Since the output of the second coil is a function of $d-d_1$, its value at this point is $.150-0.075 = 0.075$, assuming the coils are separated by 0.075 inch. In the figure this value is represented by the vector OB. The terminus of vector OC, the sum of OA and OB, locates a point on the figure 8. Other points generated in a similar manner plot the complete figure. Actual oscilloscope traces for representative tubing irregularities are shown in Fig. 3 and 4. Correspondence of pattern shape to defect geometry is obvious. Fig. 5 illustrates the arrangement of the coil inside the tube and response patterns for various defects.

An important application of the technique was made in inspecting ten heat exchangers of the type illustrated in Fig. 6 [2]. Each unit contained two thousand sixty-foot-long tubes. The tubes were "U" shape, with the ends piercing a five-foot diameter, five inch thick carbon steel tube sheet. The probe was blown into each tube end with a few pounds air pressure and manually withdrawn at about 20 ft/min as the scan was made. Some six thousand tubes were tested in a 30-day period on a round-the-clock basis. Serious instances of intergranular corrosion were detected, an example of which is shown in the figure.

In this application, it was desired to identify defects whose depth extended greater than 50 percent of the tube wall. Defect depth was estimated on the basis of the figure 8 display with good precision in view of the difficult conditions under which the test was made. In no case did destructive examination fail to reveal defects predicted by the eddy current test.

2. Ultrasonic Tests

Although ultrasonic methods of inspecting uninstalled thin wall tubing have been in use for years, results in many respects have not been satisfactory. Signal response is often dependent upon defect size and shape rather than being linearly dependent upon severity; uniform day-to-day calibration of test

FIGURE 3A - Probe Wobble

FIGURE 3B - 0.013" I.D. Notch

FIGURE 3C - Shallow I.D. Ring

FIGURE 3

Typical Signal Patterns

FIGURE 4A - 0.023" I.D. Notch

FIGURE 4B - 0.040" Diameter Drill Hole

FIGURE 4C - 0.023" O.D. Notch

FIGURE 4

Typical Signal Patterns

STEAM GENERATOR TUBING TEST EDDY CURRENT TESTER ARRANGEMENT

VECTORSCOPE TEST PATTERNS

- NOTCH .013" DEEP X 1/8" LONG X .004 WIDE ON INNER SURFACE
- NOTCH .023" DEEP X 1/8" LONG X .004 WIDE ON OUTER SURFACE
- NOTCH .013" DEEP X 1/8" LONG X .004 WIDE ON OUTER SURFACE
- HOLE .040" DIA. THROUGH TUBE WALL
- DENT IN TUBE
- TUBE SUPPORT
- EDDY CURRENT TEST PROBE WOBBLE
- INDICATION DUE TO INTERGRANULAR CORROSION

G-102-595

EDDY CURRENT TESTING N-REACTOR STEAM GENERATORS

PROBLEM:

INSPECT TEN GENERATORS
OF THIS DESIGN

ONE HALF OF THE TUBING
IN ONE UNIT

PRIMARY HEAT EXCHANGER

CUTAWAY VIEW

FIELD INSPECTION

NOVEL SIGNAL ANALYSIS:

NATURE OF THE DEFECT AND
BACKGROUND NOISE IDENTIFIED
BY QUADRATURE RECORDING OF
SIGNAL AND BY LISSAJOU
PATTERN DISPLAY

DEFECT CHARACTERIZATION BY SIGNAL ANALYSIS

NOTCH .013" DEEP
1/8" LONG
.004 WIDE ON
INNER SURFACE

DENT
IN
TUBE

HOLE .040" DIA
THROUGH
TUBE WALL

INDICATION
DUE TO
INTERGRANULAR
CORROSION

NOTCH .023" DEEP
1/8" LONG
.004 WIDE ON
OUTER SURFACE

TUBE SUPPORT

MICROSTRUCTURE OF INTER
GRANULAR CORROSION

EDDY CURRENT
TEST PROBE WOBBLE

MULTIPLE
CORROSION

NOTCH .013" DEEP x 1/8" LONG
x .004 WIDE ON OUTER SURFACE

FIGURE 6

equipment is difficult, and satisfactory standardization of separate inspection installations is not possible with existing test methods. Full beneficial use of ultrasonic methods has been hampered by an incomplete understanding of basic propagation mechanisms of stress waves in thin, curved sections. Anomalies exist in data obtained with conventional practices which clearly demonstrate inadequacies of simple theories. Lamb wave concepts are approximately valid for waves propagating in a direction parallel to the longitudinal axis of the tube, but are involved when curvature is taken into account for waves traveling in a circumferential direction. Complexity of the latter case is reflected in the fact that its mathematical solution has not been developed, so far as known.

At Hanford, long range research efforts have developed improved ultrasonic inspection techniques and have provided strengthened understanding of their technical operation. Very briefly, major contribution of this study has been to side step complete solution of the theoretical problem by developing experimental techniques which extend validity of simple shear wave theories to the thin wall case (wall thickness greater than 0.012 inch). Complicated wave motions which resonate the tube wall, distort signal response depending upon defect orientation and shape, and make test results critically dependent upon incident beam angle and ultrasonic frequency, are avoided by use of small, highly focused, transducers whose diameters are less than one half of the wall thickness. Three-sixteenths inch diameter transducers with 0.008 inch focused beam diameters are commonly used. Frequency band widths are made as wide as possible; a 15 Mc center frequency is employed, although this value is not critical $\sqrt{3}$.

Fig. 7 illustrates the key point in the experimental approach. The data demonstrate that under the given experimental conditions, shear waves only propagate in the tube wall in an uncomplicated zig-zag manner entirely analogous to the way shear waves travel in thicker sections. Waves impinge upon the inner and outer tube surfaces at discrete points only. Response amplitude to standard defects increases linearly as the discontinuity approaches the beam entry point. These data were obtained with the incident beam angle purposely

FIGURE 7
 Experimental Arrangement of Ultrasonic Tubing Test

set to exclude the generation of longitudinal waves.

Data defect signal response as a function of defect depth location with respect to inner and outer surface, and incident beam angle are shown in Fig. 8 for axially oriented defects in 0.012 inch thick Zircaloy tubes. Data from defects oriented in a perpendicular direction are essentially identical. It is noted that response increases with defect depth, and that notches located on the inner and outer surface respond with nearly equal amplitude. Sensitivity is capable of detecting notches 0.001 inch deep, and amplitude response is not critically dependent upon incident beam angle. The important conclusion to be drawn from these data is that wide band electronic circuitry, small transducers, and highly focused beams make possible the inspection of thin wall tubing with the same confidence and readily interpreted results as are obtained on thicker sections. This fact guided the development of equipment for routine inspection of fuel sheath tubing. Summarized in Table I are extensive data which define optimum test procedures for tubing of various geometries and materials.

We proceed to a description of the equipment ultimately developed with a review of work done in evaluating transducer performance and the possible importance of transducer variables on the quality of test results achieved [47]. It was observed early that test data anomalies were often traceable to inconsistencies in the transducers themselves. Supposedly identical transducers operating in a given experimental arrangement did not necessarily give equivalent results. A study made to explain these effects has led to the development of a novel method of measuring transducer frequency, efficiency, damping factor, focal length and radiated beam profile. Obviously, each of these parameters affect transducer performance. Unfortunately, however, subtle transducer irregularities affect this performance in a way that is not readily observable from use of the transducers in regular test equipment, yet markedly degrades quality of results obtained. Existence of such irregularities was found to be not uncommon in the commercial transducers examined.

FIGURE 8

TABLE I
GENERAL TUBING TEST DATA

<u>Tube Material</u>	<u>Wall Thickness</u>	<u>Diameter to Thickness Ratio</u>	<u>Minimum Notch Depth and Orientation</u>	<u>Entry Angle</u>	<u>Beam Size</u>	<u>Pitch</u>
Zircaloy	12	31	1 axial	29°	8	6
	12		1 circumferential	29°	8	6
Stainless	12	31	2 axial	22°	8	6
	12		2 circumferential	22°	8	6
Aluminum	12	31	1 axial	22°	8	6
	12		1 circumferential	22°	8	6

Zircaloy	17	35	1 axial	26.8°	8	6
	17		1 circumferential	26.8°	8	6

Zircaloy	25	15	1 axial	26.8°	8	6
	25		1 circumferential	26.8°	8	6
Stainless	25	15	2 axial	18°	8	6
	25		2 circumferential	19.9°	8	6
Aluminum	25	15	1 axial	18°	8	6
	25		1 circumferential	19.9°	8	6

Zircaloy	45	10	2 circumferential	26.8°	20	15
	45		1 axial	24°	20	15
	45		1 circumferential	26.8°	8	6
Stainless	45	10	2 axial	17°	20	15
	45		2 circumferential	19.9°	8	6

Aluminum	45	10	2 axial	17°	20	15
	45		1 circumferential	19.9°	8	6
Aluminum	65	7.7	1 axial	16°	20	15
	65		2 circumferential	19.9°	20	15
Zircaloy	65	7.7	1 axial	21.5°	20	15
	65		1 circumferential	26.8°	8	6
Stainless	65	7.7	2 axial	16°	20	15
	65		1 circumferential	19.9°	8	6
Aluminum	65	7.7	2 axial	16°	20	15
	65		1 circumferential	19.9°	8	6

All dimensions in mils unless otherwise stated.

Fig. 9 illustrates an experimental arrangement especially designed to measure the transducer parameters listed above. As applied to small highly focused units, 0.025 inch ball reflector is translated through the focal point in two perpendicular directions designated X and Y. Motion of the ball in either direction rotates a potentiometer which generates a linearly increasing voltage. Fed onto the horizontal plates of an oscilloscope, this voltage deflects a spot across the face of the scope in one-to-one correspondence with reflector displacement. A broad frequency band electronic system excites the transducer with a sharp voltage spike, receives and amplifies pulse echoes returning from the reflector, and displays them on the vertical plates of the oscilloscope.

Results obtained from a well-made 15 Mc, spherically focused, commercial transducer are shown in Fig. 10. The one exception to the excellent performance of this unit is that its actual frequency is 17 Mc instead of the rated 15 Mc -- an acceptable deviation for this application. The radiated beam profile shown in the lower two wave traces are very important, however. The amplitude of each half cycle of radiated energy is shown as a function of X in the middle photograph, and as a function of Y in the lower photograph. It is noted that the profile is approximately equal in width in both directions. These curves also show that the radiated energy is symmetrical about the midpoint. A damping factor of three (defined as the number of positive half cycles greater in amplitude than the first half cycle) is measured. Transducers with these characteristics readily reproduce data earlier reported in Fig. 8 and provide consistent results in practical application.

The same measurements applied to a supposedly equivalent transducer reveal typical manufacturing imperfections shown in the lower half of Fig. 10. In this case the actual frequency is 17.5 Mc and the damping factor is two. The beam profile width in both the X and Y directions is nearly twice as broad as the former case, revealing reduced sensitivity to small defects. The lower two waveforms are not symmetrical, showing that the focusing lens is improperly

Experimental Arrangement for Measuring Transducer Parameters

FIGURE 9

4.5 mils/cm

Frequency	17 MC
Focal Length	19 μ Sec
Beam Dimensions	
X	8 Mils
Y	8 Mils
Damping Factor	3

Frequency	17.5 MC
Focal Length	34.9 μ Sec
Beam Dimensions	
X	17.1 Mils
Y	16.5 Mils
Damping Factor	2

FIGURE 10

Ultrasonic Transducer Characteristics

aligned on the transducer face. Attempts to use this transducer in practical tube testing equipment would give erratic results. Similar tests applied to an extensive number of units have revealed that regions of improper bonding between crystal and backing member, density variations of the backing, and improper alignment of the focusing lens, are readily apparent. On the basis of these tests, specifications have been developed to insure accurate and reproducible results when applied to routine tubing inspection. These specifications are as follows:

Center Frequency	+ 10% - 0% of specified value (normally 15 Mc)
Damping Factor	3.5 $\pm$.5
Beam Width	.008 $\pm$.001 inches (at 3 db points)
Beam Symmetry	Peak amplitude of each half cycle within 0.004 inches of beam center
Focal Point	19 $\pm$ 1 microsecond

An important outgrowth of this activity has been a general upgrading of the quality of transducers marketed in the United States. At least one leading vendor has adopted the practice of inspecting each unit manufactured with an arrangement equivalent to Fig. 9 as a final step in its manufacture. Transducers made to the specifications prescribed above have thus become available for the first time.

Equipment for inspection of thin walled tubing has been developed and put to routine use [5]. In practice, two transducers are used; one sends a beam circumferentially around the tube, the other is directed down the longitudinal axis of the tube. This insures the detection of defects regardless of their orientation, and eliminates the necessity for repeat tests as is sometimes required. As shown by the sketch in Fig. 11, the arrangement passes the tubes through a 6 by 8 inch "weir" tank which is translated along the tube as the scan is made. Water is continuously filtered and circulated through weir tank. Special bearing design permits free passage of the tube

FIGURE 11

Ultrasonic Tubing Tester

through the tank without appreciable wear to the tube or the bearing.

Tubes rotate at 1800 rpm, pulse repetition rate is 10 kc, and one foot of tubing is inspected per minute. The equipment shown was developed under the United States/Canadian Cooperative Program on Heavy Water Reactors, and is presently applied to the inspection of nuclear fuel sheath tubing in Canada. Similar equipment has been in routine one and two-shift use at Hanford for the past two years inspecting U.S. fuel sheath tubing.

II. AUTOMATIC FUEL TESTING

Hanford's nuclear fuel inspection practices are a good example of the beneficial returns that result from the use of nondestructive methods in routine, automatic production lines. Here the high cost of charging failure-prone fuel into a reactor makes it essential that the quality of each element is non-destructively assured prior to use.

Hanford has had automatic test equipment operating in fuel manufacturing lines for a number of years. While at the time of their development these test techniques were novel and on the forefront of NDT technology -- at this time they are more representative of well accepted practices. For this reason, the following discussion gives main emphasis to the automatic features of the equipment rather than the physics of the tests themselves. More detailed information on the latter subject is available from numerous references [6-9].

Fully automatic ultrasonic and eddy current inspection systems have been developed to insure the integrity of Hanford production fuel elements on a routine, production line, basis. The uranium fuel cores are cylindrical in shape, roughly 1-1/3 inches in diameter by eight inches long, with a 3/8 inch hole down the central axis. The cores are clad in a 0.030 inch aluminum jacket with an aluminum silicon braze alloy which metallurgically bonds the jacket to the core. The fuel elements are closed with aluminum end caps which are Heli-arc welded to the side jacket at one end and a central aluminum spine at the other.

Three separate systems have been developed to inspect the bare uranium core, the cladding, and the closure. In each system, fuel is brought to the test station, submerged in the test tank, separated into acceptable and unacceptable categories on the basis of the nondestructive test performed, and transferred down a continuous production line by automatic conveyor.

Uniform grains of the correct average diameter are assured in the bare fuel cores by a 5 Mc through transmission ultrasonic test. Unacceptable grains which are too large or too small incorrectly attenuate the beam and thereby provide an identifying signal. The bases of the test are shown in the extreme right of Fig. 12. Correspondence of grain size to wave attenuation is graphically illustrated in the right center photograph.

Defects in the weld closure offer potential leakage paths for the reactor coolant to contact the fuel core. Such defects between the core and the extreme ends are detected with an ultrasonic system of high defect resolution capabilities. As illustrated in the upper center diagram, tests are simultaneously applied to both weld closures. Sensitivity is sufficient to detect a hairline crack or 0.020 inch diameter porosity .020 inches below the surface. Electronic memory techniques distinguish continuous from scattered defects.

Combined ultrasonic and eddy current tests insure that cladding braze porosity is within acceptable limits, and that the cladding is free from erosion penetrations of its under surface by the braze alloy. Both tests are simultaneously applied to the inner and outer surface. The inner probe uses a send and receive transducer to generate what are presumed to be Lamb waves in unbonded regions of the cladding. The external bond test uses a conventional 20 Mc pulse-echo technique. Braze porosity or unbond defects as small as .030 inch are reliably detected, and AlSi penetrations reaching within 0.015 inch of the surface are revealed by the eddy current test. The eddy current test operates at 20 kc with each probe consisting of a primary and secondary winding.

In the external eddy current test, a thin film of plastic tape is continuously passed between the test coil and the rotating fuel element. Its purpose is to eliminate wear of the probe and to minimize variation in the spacing of probe and fuel surface. Typical AlSi penetrations with its corresponding detecting signal are shown in the center of Fig. 12. Also shown is an ultrasonic map of typical unbond defects with autoradiograph results of the same element. The under surface of the cladding after destructive removal from the element is also shown.

All systems rotate the fuel cores at about 1000 rpm with a complete scan completed in a few seconds. Fig. 13 shows the automatic test station incorporating ultrasonic and eddy current tests for the fuel cladding. As the external and internal fuel surfaces are inspected simultaneously, each station includes two ultrasonic and two eddy current tests. A close up of an element under test is shown in the lower right of the upper photograph. The lower photograph illustrates the various ultrasonic probes used by the fuel inspection equipment.

Although not applied to such large numbers, nondestructive tests have also been developed for the inspection of irradiated fuel after reactor exposure. For this application, techniques similar to the unirradiated case are employed, except that provision for remotely conducting the test are necessary. At Hanford, tests are applied approximately twenty feet under water. Fig. 14 sketches tests applied to radiated fuel of different design in the upper right. Fuel properties inspected are identified in the sketch. Equipment used to mechanically support the fuel and transducers and provide the necessary scanning motions are shown in the two lower photographs. A fuel element under test is shown in the upper left.

REDUCE REACTOR FUEL FAILURES BY INSPECTING

FIGURE 12
Principle of Operation of Automatic Fuel Testers

AUTOMATIC FUEL TESTERS

Test simultaneously applied to internal and external surfaces-completed in 9 seconds.

Defective elements automatically rejected from process stream.

FIGURE 13

Automatic Fuel Test Station

FIGURE 14

Inspection of Irradiated Fuel

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