NONDESTRUCTIVE TESTING FOR MULTIPLE CONDITIONS IN TUBE AND PIPE

By DONALD N BUGDEN, VICE PRESIDENT
MAGNETIC ANALYSIS CORPORATION

A number of years ago, I presented a paper on the issues to consider in choosing the most appropriate NDT methods for a particular manufacturing facility. Since then, we have seen many changes and new developments making the task even more complicated. In addition to constantly evolving new techniques, there is the realization that portions of the systems now available to make up an automatic inspection line for final product can be strategically placed upstream, providing process control to minimize rejects at the final inspection. The choice and placement of NDT equipment is now based on the growing understanding that each of the NDT methods still most common to tube manufacturing has its own set of advantages and disadvantages. This leads to the use of final inspection stations that incorporate various types of ultrasonic and electromagnetic equipment and the addition of process control NDT apparatus in line on production machines.

Fortunately, this ever-expanding myriad of options has become manageable with the adaptation of NDT equipment to the power of digital electronics, computers, and programmable controllers. The major conclusion drawn from the material presented here is that incorporating more modern NDT equipment in the tube making process, if designed to match the needs of the tube buyer and identify with the unique possibilities of each operation to experience defects, will decrease the percentage of false rejects sustained by an inadequate or inappropriate NDT operation. Compromising on the initial investment usually results in ongoing excessive operational costs.

The correct, computerized NDT equipment provides, among other things:

- Fewer false rejects and higher yield
- Simplified operator interface with complex tasks and results.
- Faster changeover times
- Error free setups and reporting
- Results oversight through networking automation of the physical operations
- Reliability of equipment and less downtime.

The systems considered here are based upon ultrasonic techniques or one of the electromagnetic techniques that encompass eddy current or flux leakage methodology.

As in the past, some of the issues that must be considered in selecting an NDT system are:

- The end use of the tubing
- Grade or alloy chosen
- Seamless or welded
- Cold finished or not
- Mandatory nondestructive test specifications
- Documentation

Supplements to Flaw Detection:

- Grade mix protection

- Demagnetizing
- Dimensional measurement
- Proof testing
- Mechanical sampling

The major needs of the tube manufacturer derived from the tube buyer can be listed in the following way:

- Compete in quality and price
- Avoid customer complaints
- Reduce liability exposure
- Meet industry and customer specifications
- Maintain maximum yield
- Limit testing cost
- Limit downtime
- Satisfy diverse clientele

Tables 1 and 2 may be a useful general overview of the tube manufacturing processes and types of defects of interest to the reader.

TABLE 1 - FACTORS TO CONSIDER IN SELECTING NDT TECHNIQUE FOR YOUR APPLICATION

END USE	MANUFACTURING PROCESS	**POSITION and MECHANICAL CONDITIONS**	NDT MEASUREMENT TASK	**NDT EVALUATION TASK**	**APPLICABLE PROCEDURES**	**COSTS**
Fluid Transmission Heat Exchanger Pressure Hydraulic Gas & Oil **Mechanical** Force Transmission Cylinder Tubing Hot Forming Stock Cold Forming Stock Machining Stock **Structural** **Ornamental** **Furniture** **Medical**	**Welded** Longitudinal or Spiral, Electrical Resistance Weld, Induction Weld, High or Low Frequency AC or DC Continuous Weld, Tungsten Inert Gas, Electron Beam, Laser Beam, Bead Condition: None, Scarf, Hammer, Roll In Line Annealing Butt Welding **Seamless** Continuous Casting or Ingot Piercing Extrusion **Finishing Operations** Hot stretch Reduce Pilger Mill Rotary, Roll, Stretch, Straightened, Pickled & Shotblast, Sinking, Plug Drawn, Drawn Over Mandrel, End Chamfer, Upset End, Threading, Heat Treating & Annealing	Diameter & Wall thickness, Shape, Straightness, Roundness, Surface condition, End Condition, Cleanliness, Temperature, Metallurgy	**Flaw Detection** Minimum detectable size Geometry/ Orientation: Short or Continuous, OD, ID, Midwall, Longitudinal, Transverse, Oblique Natural Defects: Weld Skips, Incomplete Weld, Hook Cracks, Lamination, Inclusions, Metal Separation, Mechanical Cracks, Open welds, Butt Welds, Weld Bead Variance, Weepers, Pastey weld **Dimensional Measurement** Wall thickness, Outside Diameter, Inside Diameter, Wall Variations, Ovality, Straightness	Defect Marking Reject Sorting Documentation: Calibration & Setup, Defect Count by type, Defect location by type, Defect Severity by type SPC Trends	ASTM MIL DIN API	**Operating Costs** Yield Level of Automation Personnel Skill Level & Certification Changeover Time, Utility Costs, Maintenance & Calibration, Maximum Throughput Speeds, Location of Test or Tests, Purchase or Lease, Service Contracts **Investment Costs** Choice of Method or Methods, Tooling Costs, Peripherals, Adaptability, Future Flexibility, Location of Test or Tests, Purchase or Lease

TABLE 2 - FACTORS TO CONSIDER IN DIFFERENT TEST TECHNOLOGIES

TEST METHOD					
EDDY CURRENT (1)	TYPICAL APPLICATION	DEFECT CAPABILITY	TYPICAL LOCATION	TYPICAL THROUGHPUT SPEED LIMIT	RELATIVE COST See Table Note (5)
Full Body Encircling Differential Coil	Ferrous & nonferrous Cold Finished Welded & Seamless (.050” D x .004” Wall) to 7.5” D x .400” Wall	**Excellent** for Short, small defects, Pinholes, Weld skip, Slivers, Transverse, Metal Separation or Cracks. **Poor** for long defects, Incomplete ID Welds, Lamination, Stringers, Laps, Seams, Longitudinal cracks	Operator tended, Off-Line with automated conveyor In-line on Weld Mills, Straight and Cut Straights	Easily accommodates normal mill requirements up to 1000 FPM Low speed on TIG welding Heavy Wall requires special adaptation	Moderate
Ancillary Encircling Absolute Coil	Same as Above	Some capability on Gross, Long Defects such as open weld	Same as Above	Same as above	Low
Weld zone Segmented Differential Coil	Ferrous & Nonferrous as welded 1” diameter x .035” Wall to 20” dia x .400” Wall)	Excellent for Short Defects, except very small weepers	Weld Mill Usually non tended with automated defect recording, marking & test result reporting	Same as Above	
Ancillary Segmented Absolute coil	Same as Above	Continuous Open Weld	Weld Mill		Low
Grade Sorting	Boiler Tube, Mechanical tube (up to 7.5” dia)	Will sort, but not identify grades or heat treat variances	In tandem with NDT flaw system	No Limit	Low

FRINGE FLUX	TYPICAL APPLICATION	DEFECT CAPABILITY	TYPICAL LOCATION	TYPICAL THROUGHPUT SPEED	RELATIVE COST See Table Note (5)
Full Body (2) Rotating Head	Ferrous Hot Rolled Seamless Welded Cold Finished (2 5/8" Dia x .100" Wall to 20" Dia x .600" Wall) Extensive Use on O.C.T.G.	Better than EC for ID Defects on Heavier Wall Thickness, Short and Long Defects Good OD Detection of Longitudinal Defects OD – 5% of Wall Thickness in Depth ID – 12% of Wall Thickness in Depth	Operator Tended, Off-Line with Automated Conveyor	Up to 600 FPM Very Dependent upon diameter and length	Moderate to High, Depending on Product Size
Full Body (3) Longitudinal Magnetization (Segmented Sensor Array)	Same as Above	Transverse Defects	In-Line with Above	Same as Above	Moderate to High, depending on product size
Weld Zone Transverse Magnetization	Ferrous as Welded Field Inspection	Short Defects, Not as good as UT, but does not require couplant	Weld Mill	Same as Above	Moderate
Electromagnetic Acoustical Transducer	Usually Ferrous	Wall Thickness Does not require couplant	Off-Line	Depends upon required coverage	High

ULTRASONIC (4)	**TYPICAL APPLICATION**	**DEFECT CAPABILITY**	**TYPICAL LOCATION**	**TYPICAL THROUGHPUT SPEED**	**RELATIVE COST See Table Note (5)**
Full Body Rotating Head	Ferrous & Nonferrous Seamless and Welded Hot or Cold Finished Light to Very Heavy Wall Thickness ¼” to 5” 2” to 7” 2” to 10”	Longitudinal and Transverse Defects, Short or Continuous Better than EC or FF on ID Stringers, Inclusions, Incomplete Weld, Hook Cracks Tapered Defects Response very dependent upon defect orientation in relation to transducer orientation	Operator tended, Off-Line with automated conveyor	Depends upon length of notch specified	Depends upon size of product, number of measurements, and system location and level of automation and throughput speed required Moderate to High High to very very high
Full Body Rotating Tube	¼” to 5” 2: to 7” 2” to 20”	Same as Above	Off-Line with specialized conveyor system for spinning the tube	Very dependent upon diameter and length of product. As a rule, slower than rotating head systems	Moderate to High High Very High
Weld Zone	1” and above Any wall thickness	Same as Above	Longitudinal and Spiral Weld Mills	Dependent upon wall thickness, but able to keep up with welding speeds	Moderate to high

Dimensional UT		Wall Thickness OD and/or ID Wall Variation Ovality Weld Bead Monitoring	Auxiliary to Flaw UT	Same as Above	Low to High depending upon number of measurements
MECHANICAL TESTING	**TYPICAL APPLICATION**	**DEFECT CAPABILITY**	**TYPICAL LOCATION**	**TYPICAL THROUGHPUT SPEED**	**RELATIVE COST (see Table Note 5)**
	As welded in all sizes	Pastey weld, Visual Weld Defects	Tube Mill	No restrictions	Very low
PROOF TESTING	**TYPICAL APPLICATION**	**DEFECT CAPABILITY**	**TYPICAL LOCATION**	**TYPICAL THROUGHPUT SPEED**	**RELATIVE COST (see Table Note 5)**
Hydrostatic Air under water Leak testing	Welded and seamless heat exchanger tubing	Pastey weld Very small weepers	Final inspection	Normal Producing speeds	Very High Labor intensive

Notes:

(1) Typical calibration specifies small, drilled hole and/or transverse outside diameter notch.

(2) Typical calibration specifies 1/16” or 1/8” diameter drilled hole and/or 1” or 2” long longitudinal outside diameter and inside diameter notches, 12% of wall thickness in depth

(3) Typical calibration specifies 1” or 2” long transverse outside diameter and inside diameter notches, 12% of wall thickness in depth

(4) Typical Calibration specifies .030” to 1” long longitudinal and transverse notches, 3% to 12% of the tube wall in depth. For some API specifications, oblique notches at two 45 degree orientations are added to longitudinal and transverse notches.

(5) Relative cost: Low – Less than $50,000; Moderate - $50,000 to $200,000; High - $200,000 to $500,000; Very High – above $500,000.

Tables I and 2 were originally included in a paper presented by Donald N. Bugden, VP – Marketing, Magnetic Analysis Corporation at the International Tube Association Better Tube Technology Conference in Monterrey, Mexico, in October 1992.

The obvious questions that encompass the details in Table 1 and 2 are:

- What kinds of defects are harmful?
- What kinds of defects can occur?
- Where in the process do defects occur?
- How are the defects oriented?
- What is the maximum acceptable size of defect?
- Are there any supplementary tests?
(hydrostatic, air under water, helium leak, magnetic particle, dye penetrant, mechanical sampling)

REVIEWING THE BASICS

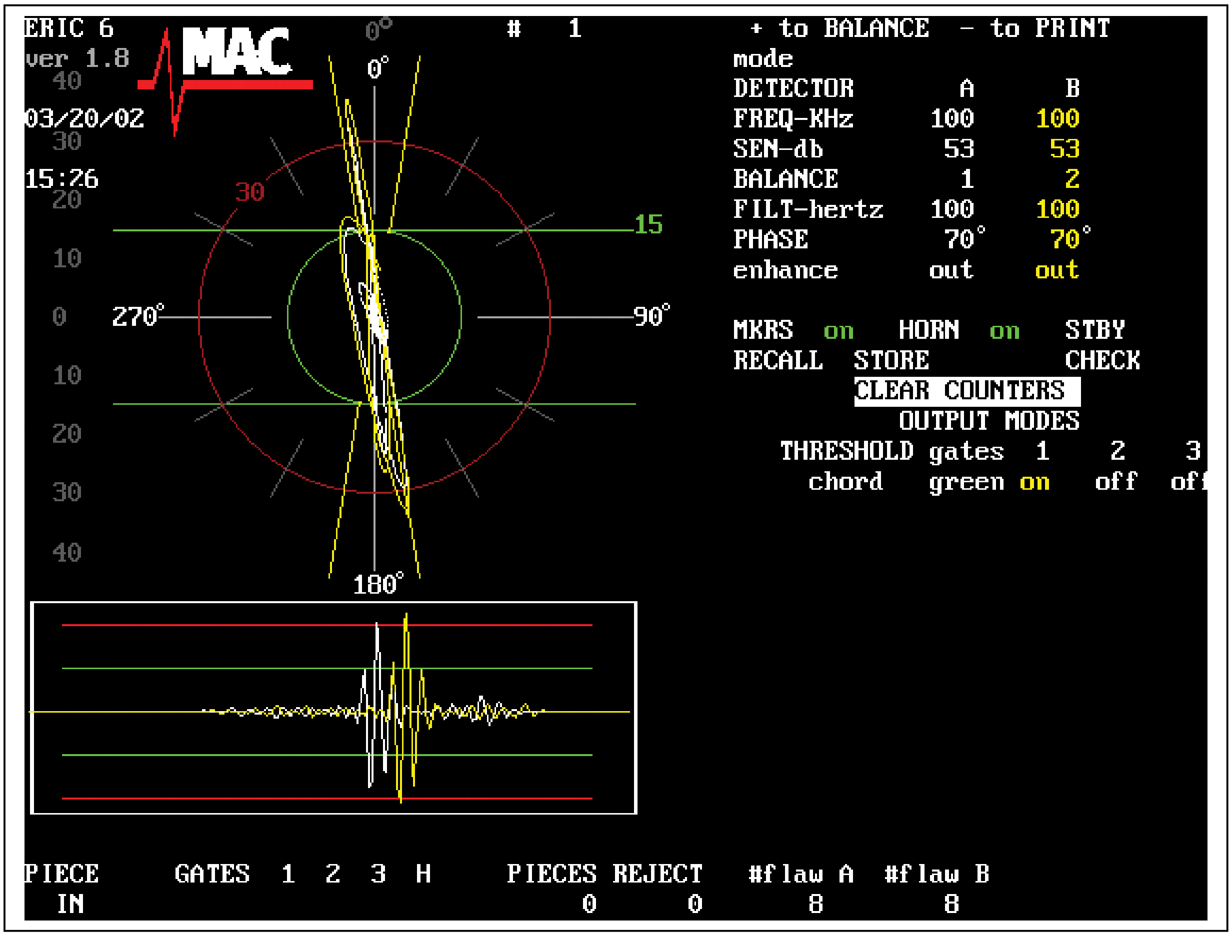
Without going into great detail, it may be useful to review some of the basic phenomena of the three methods, and the techniques incorporated that make them effective, realizing that, as each one is optimized, it becomes increasingly limited in its scope. This explains the growing trend towards incorporating more than one method, as well as a variety of techniques, in applying the methods. The main goal of this effort is to ship a tube that will withstand further transformation, such as bending or hydroforming or, when used directly, eventually perform a designated task over its predicted life. Fortunately, documents such as ASTM recommended practices provide a consensus of what apparatus and methods are most likely to detect defects that may cause premature failures. These practices also provide excellent explanations of the basic methodology and techniques. (1)

SEPARATING THE REALLY BAD FROM THE GOOD

In order to simplify the discussion it is useful to point out some of the many basic requirements and responses that are common to all NDT techniques, but first it may be helpful to review the principles of the three methods detailed in the informational sheets we have handed out. (2)

We have already pointed out that the obvious main purpose is to detect flaws in metal tubing that may lead to premature failure. The other side of the coin is to accomplish this task without sacrificing an inordinately high percentage of rejects, caused by material changes that are indigenous to the tube making process, but not detrimental to the tube's end use. Examples might be minor variations in dimensions or chemical composition that are within tolerance. All of these NDT methods are based upon sensing change from an original setting established by exposing the system to a sample that is determined by other means to be free of detrimental flaws. Often, based upon the experiences of the tube industry, written standards such as those of the ASTM, (1) specify setting the instrument to respond to an artificial defect such as a notch or hole machined into another sample. These, to some extent, correlate with industry consensus as to the type of defects likely to occur. Each method, in its own way, will produce a signal indicating the artificial defect or eventually a real defect that, hopefully, will be different from the variations in system output produced by acceptable product variations. In the simplest case, the signal for the defect is greater than the ever present background signal of good product, and the separation can be made on the basis of amplitude differences, given an adequate signal to noise ratio. The development of NDT instruments that are really computers has vastly improved the starting point for obtaining adequate signal to noise ratios by nearly eliminating background instrument noise associated with analog devices

Also common to the three methods is the need to inspect the tube completely along its length and through its cross-section, although, to varying degrees for each method, the signal from defects diminish as they occur deeper in the tube wall. Because of this, obtaining adequate signal to noise from ID defects which will prevent rejecting good tubes may not be achievable, but it is possible to separate and equalize eddy current or ultrasonic signals based upon small time differences between signals produced by defects at different depths, and gating them at different threshold levels to produce defect alarms. In the case of eddy currents, the time differential is called phase and can be seen in Figure 1, including phase gates. The figure also shows an electronic strip chart for a length of product that tracks the location in time or length and shows the signal to noise ratio of a defect.



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                                     MKRS  on    HORN  on    STBY
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                                             CLEAR COUNTERS
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                                          chord   green  on    off   of

PIECE     GATES  1  2  3  H     PIECES REJECT   #flaw A   #flaw B
 IN                                  0      0         8         8
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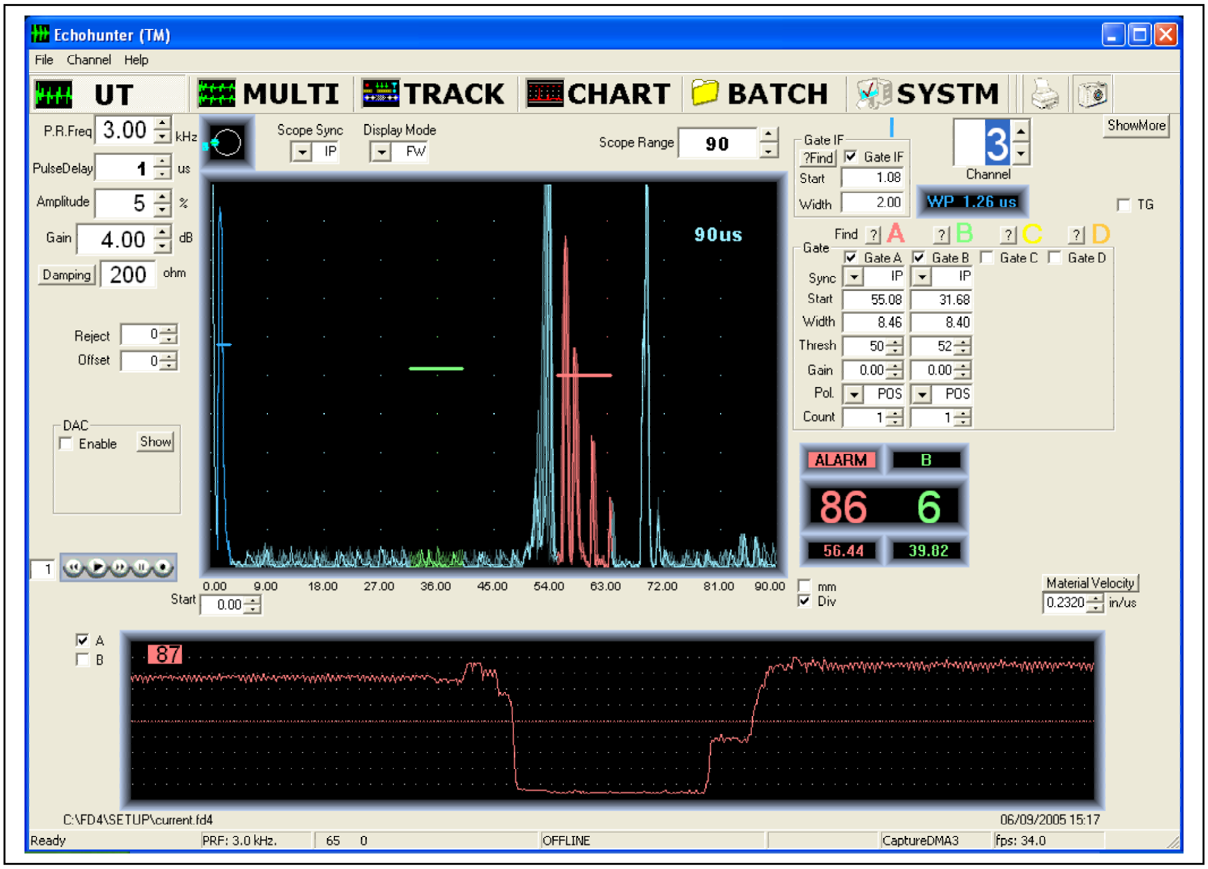
FIGURE 1

Test settings are at upper right, polar presentation at left clearly displays thresholds and two test signals from a 0.020" drilled hole in a ½" stainless steel tube. Linear presentation of the test signals is shown below – Channel A is yellow, B is white.

Figure 2 shows the A-Scan of an ultrasonically detected defect along with the electronic strip chart. Multiple threshold gates can be used to separate signals caused at different depths, sometimes employing distance amplitude techniques, (DAC) to enhance low level signals from deep in the wall. In the A-Scan, the base line is scaled in real time.



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PulseDelay 1 us
Amplitude 5 %
Gain 4.00 dB
Damping 200 ohm
Reject 0
Offset 0
DAC ☐ Enable Show
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Display Mode FW
Scope Range 90
Gate IF ?Find ☑ Gate IF
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Width 2.00
Channel 3
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Start 0.00
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Gate	☑ Gate A	☑ Gate B	☐ Gate C	☐ Gate D
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Thresh	50	52		
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Count	1	1		

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Ready PRF: 3.0 kHz. 65 0 OFFLINE CaptureDMA3 fps: 34.0

FIGURE 2
The A-Scan screen, shown above, displays detection of an OD surface notch 0.3mm deep using shear waves that also detect ID defects. The horizontal bars indicate gate thresholds. The strip chart display in the lower portion of the screen shows the peak amplitude of the signal within the gate.

In the case of electromagnetic methods, defect signals can be enhanced by using signal filtering that separates short defects from slower changing normal variations such as chemistry and dimensional changes. A further device often employed in eddy current systems is the use of differential test coils that compare short increments along the tube length. They produce very good signal to noise ratios in response to the short defects, but are severely limited in effectiveness on long, continuous defects. In contrast, an ultrasonic transducer is used in an absolute steady state configuration and will respond to a defect uniformly, whether standing over it statically, or passing over it dynamically within certain speed limitations. In the final analysis, effectively detecting long and short defects in tubing often requires applying both methods.

In those circumstances where it is necessary to detect long, shallow defects on the O.D. of tubes and discriminate accurately between acceptable and unacceptable conditions, based upon small depth differences, rotating eddy current systems are sometimes included. Although this technique does not detect subsurface or I.D. defects, the capability just described and its response to surface defects of varying orientation provides an additional NDT tool. A prominent use of rotating (spinning) probe and encircling coil combinations is for small diameter, light wall copper refrigeration tubing on coil to coil level winders.

A basic distinction needing to be made is that the flux leakage method works only on ferromagnetic tubing. The eddy current method works on any tubing made of a conductive material which includes all metals. Ironically, the eddy current method only works well on ferromagnetic tubes if the variables in magnetic properties are removed or substantially reduced. The ultrasonic method will work on any material that will conduct high frequency ultrasound waves which includes all metals and some plastics. An important distinction between the electromagnetic methods, as described in the handouts, is that eddy currents detect changes caused in an A.C. field to detect a flaw, while the flux leakage method detects changes in a DC field to detect flaws.

MATCHING THE NDT TO THE PRODUCTION PROCESSES

Certain characteristics of the compared methods tend to give them an inherent ranking when making a basic selection. From a convenience standpoint, conventional ultrasonic systems are generally considered the least desirable since the sound must be coupled from the transducer to the tube through a dense medium, usually plain or treated water. There is an alternative that uses electromagnetic acoustic transducer (EMAT) techniques where energy is coupled from the transducer to the tube surface and back electromagnetically but converts to ultrasound in the tube wall. This technique is not thoroughly discussed here but details are available in ASTM # E-1816 and ASTM E 1774 (1). So far, the technique is not widely used for tube inspection, but it is certainly important to stay abreast of developments as EMAT will probably gain broader use.

In addition to the coupling concerns, there are many complications and expenses in building ultrasonic apparatus which will, at production speeds, detect short defects, and defects with a wide variety of orientations. However, the ability to find defects with small cross-section in heavy wall products mandates the use of ultrasound.

Encircling or segmented coil eddy current systems that easily keep up with production speeds and couple through air but have relatively limited depth penetration are the simpler choice to implement and are sufficient for many applications.

Except on non-ferrous or heavy wall (above 15mm) ferrous tubing, flux leakage techniques are widely used, especially for oil country goods to conform to many API specifications.

In order to satisfy the more stringent demands of customers, it is sometimes practical to separate the product mix in order to take maximum advantage of the capabilities of each method while accommodating their limitations. This would involve diverting heavy wall products requiring calibration on shallow ID defects to an alternative, often slower ultrasonic test line from an electromagnetic line which runs smaller tubes. Although this adds equipment and operations, trying to meet UT standards with eddy current or flux leakage will, in some cases, increase the risk of missing unacceptable defects while, at the same time, sacrificing good product.

Because of its dependence on sound reflections to indicate the possible presence of defects, which differ from calibration notches as shown in Figure 3, U.T. testing requirements commonly specify multi-direction testing for longitudinal defects (clockwise and counterclockwise) (Figure 4) and transverse defects (upstream and downstream) (Figure 5) as well as normal beam testing for in-wall inclusions and thickness measurement (Figure 6).

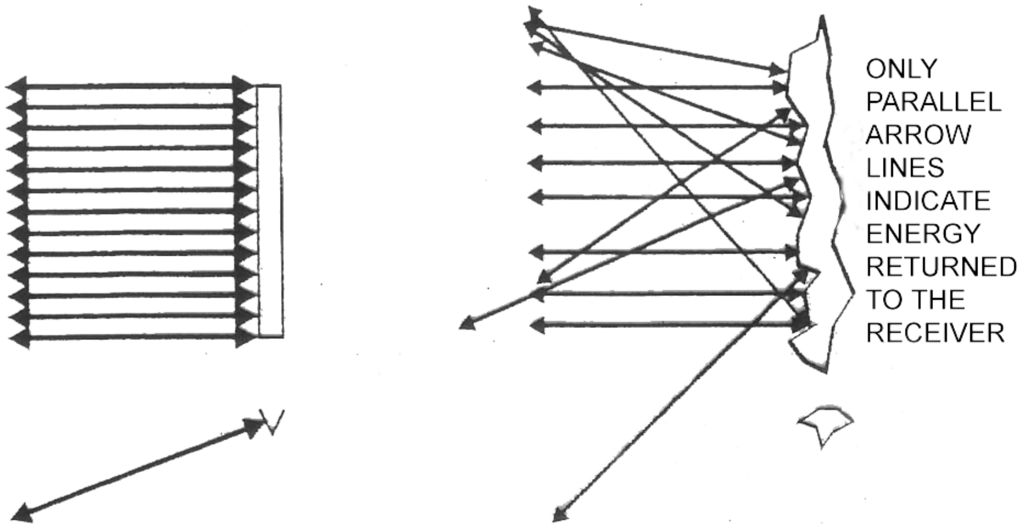
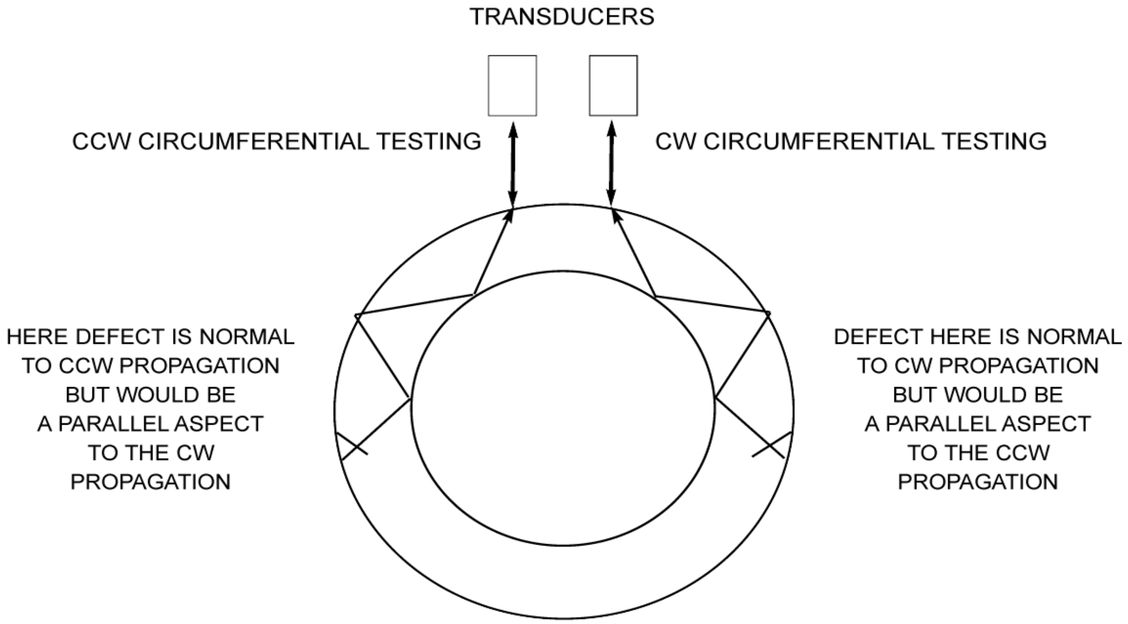


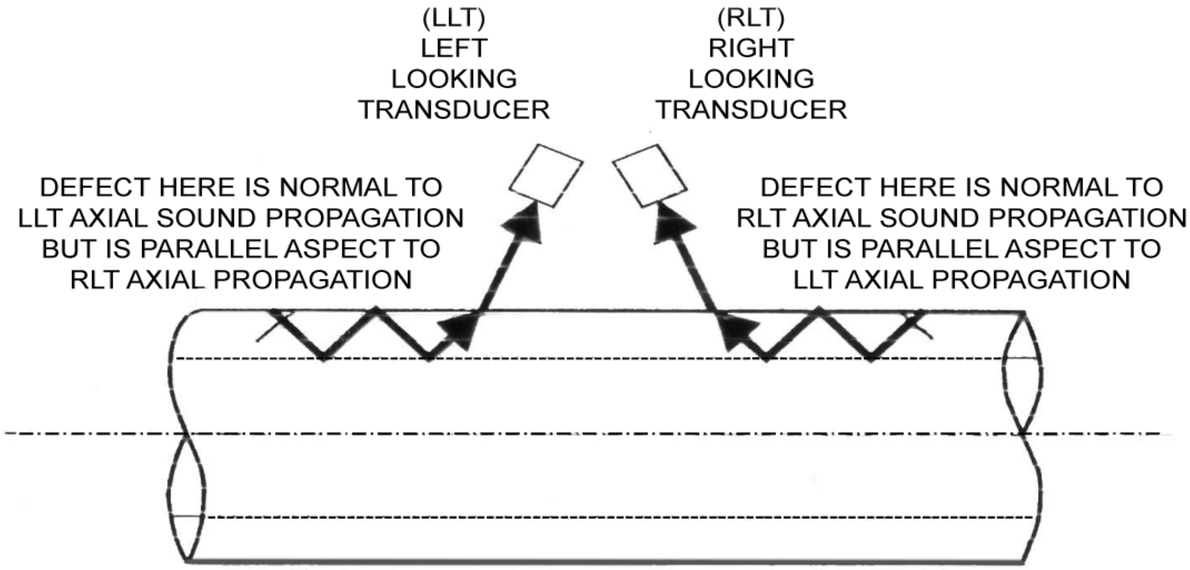
DIAGRAM COMPARING THE RETURN SIGNAL ENERGY FROM A NOTCH AS OPPOSED TO A LARGER SIZE NATURAL DEFECT WITH AN IRREGULAR SURFACE AREA

FIGURE 3



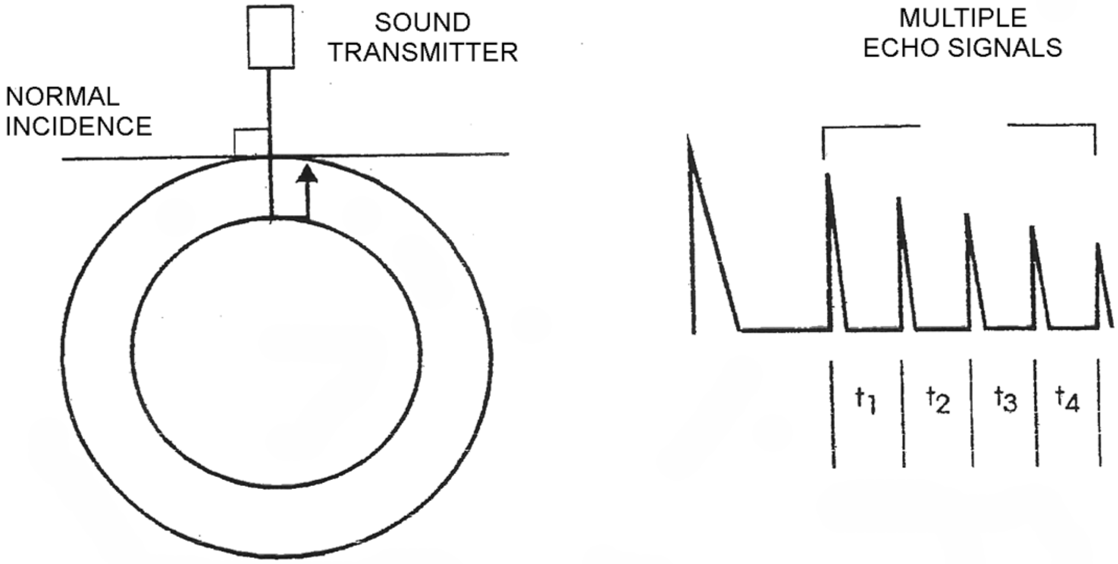
TWO DIRECTION CIRCUMFERENTIAL TESTING

FIGURE 4



**TWO DIRECTION AXIAL TESTING
FOR TRANSVERSE DEFECTS**

FIGURE 5



WALL THICKNESS IS DIRECTLY PROPORTIONAL TO THE TIMES (t1, t2, t3, t4)
BETWEEN THE MULTIPLE SIGNALS

**NORMAL BEAM TESTING FOR IN-WALL
INCLUSIONS AND THICKNESS MEASUREMENT**

FIGURE 6

These tests can be provided in a typical rotating transducer head as shown if Figure 7. A detail of the transducer arrangements is shown in Figure 8.

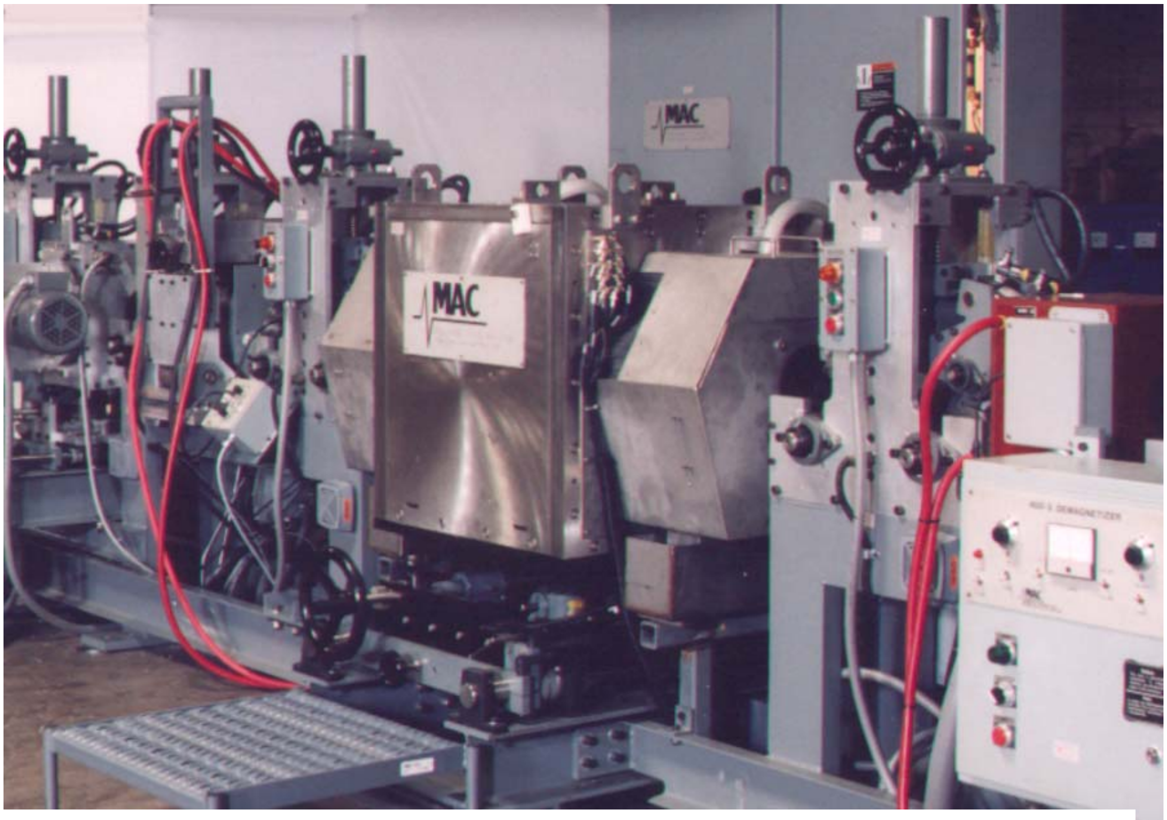


FIGURE 7
Echomac® Rotary Ultrasonic Series UT 510 10 Channel System

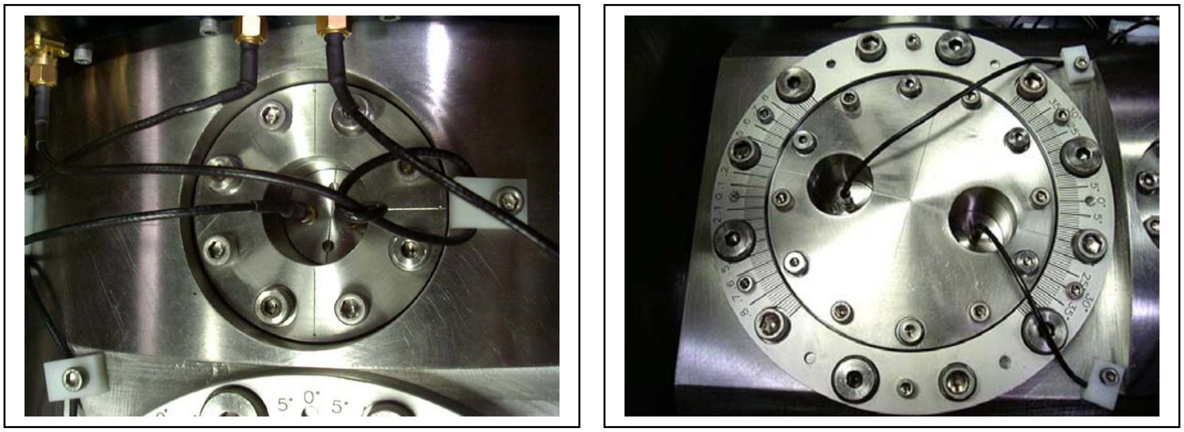


FIGURE 8
Longitudinal mode transducer is shown at left, Shear Wave mode transducer holder with simple offset mechanism is shown at right.

ONE EXAMPLE OF AUTOMATION

Perhaps the best way to illustrate a system that combines ultrasonic and eddy current methods is to look at components of an actual system used to inspect drawn over mandrel steel cylinder tubing with a diameter range of 19 mm to 95 mm. (Exhibit I). The system includes an encircling eddy current coil with D. C. saturation, a demagnetizer to remove the residual magnetism introduced by the DC saturation and a rotating transducer ultrasonic system. These components are mounted on a bench that uses pneumatically actuated top rolls to drive the tubing, which is supported by bottom V-rolls, through the test stations. The tubing is brought into and away from the test bench by V-roll conveyors. Photocells sense the ends of each tube, and encoders track its progress through the system so as to provide end suppression, defect marking and sorting of rejected from accepted tubes, all automatically, under the control of a programmable controller.

Both the ultrasonic system and the eddy current system utilize electronics built into a computer that stores setups for fast changeover and can display and archive test results locally or through a network.

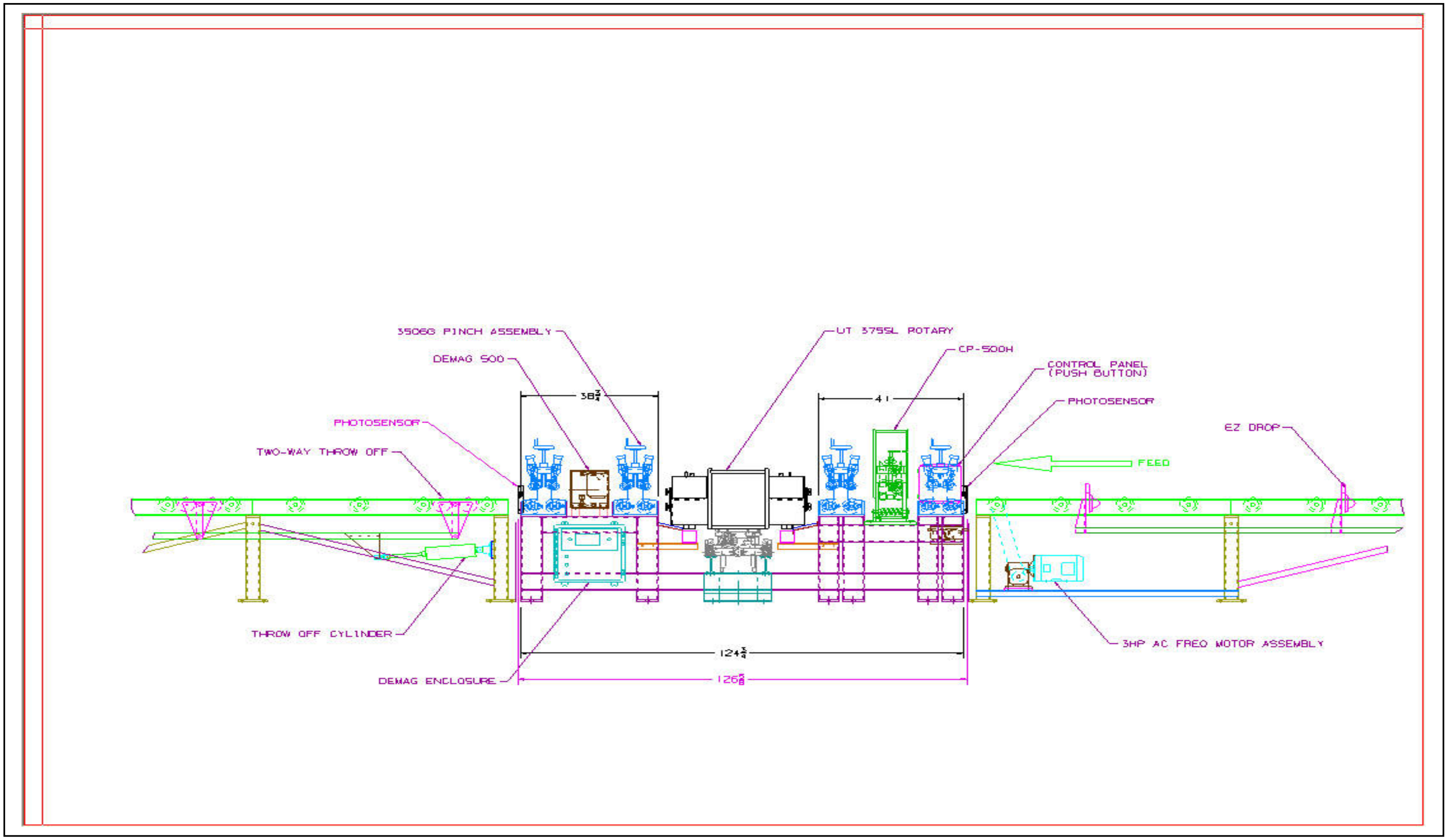
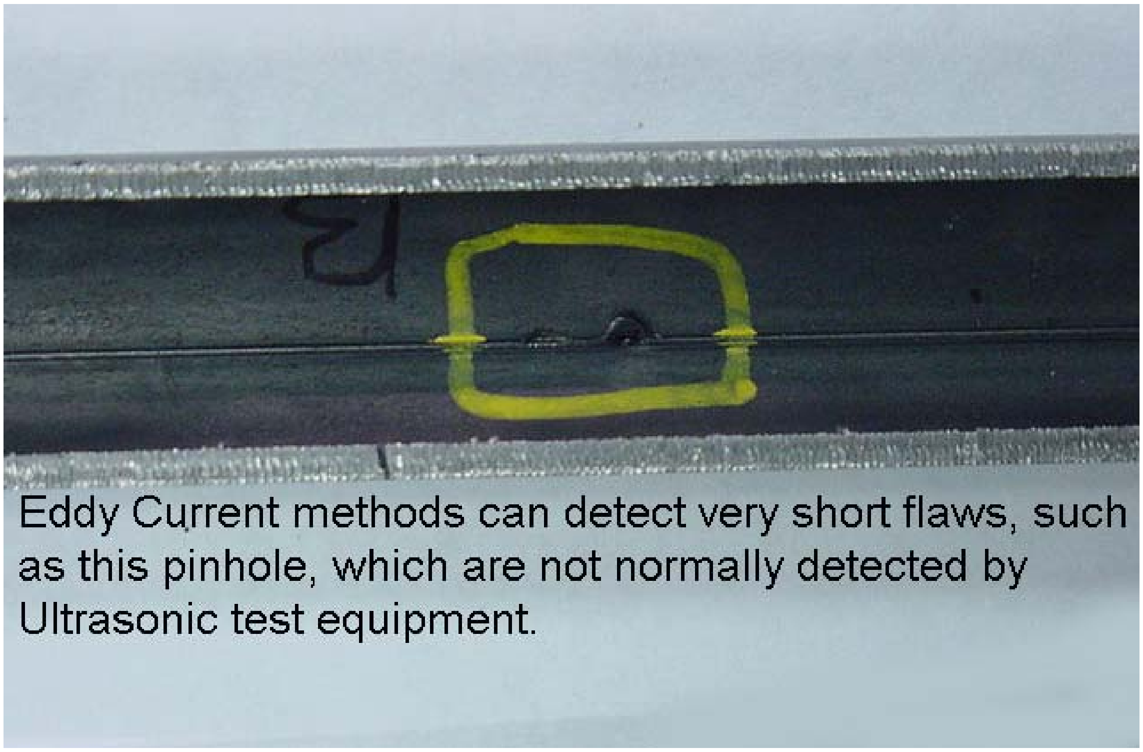


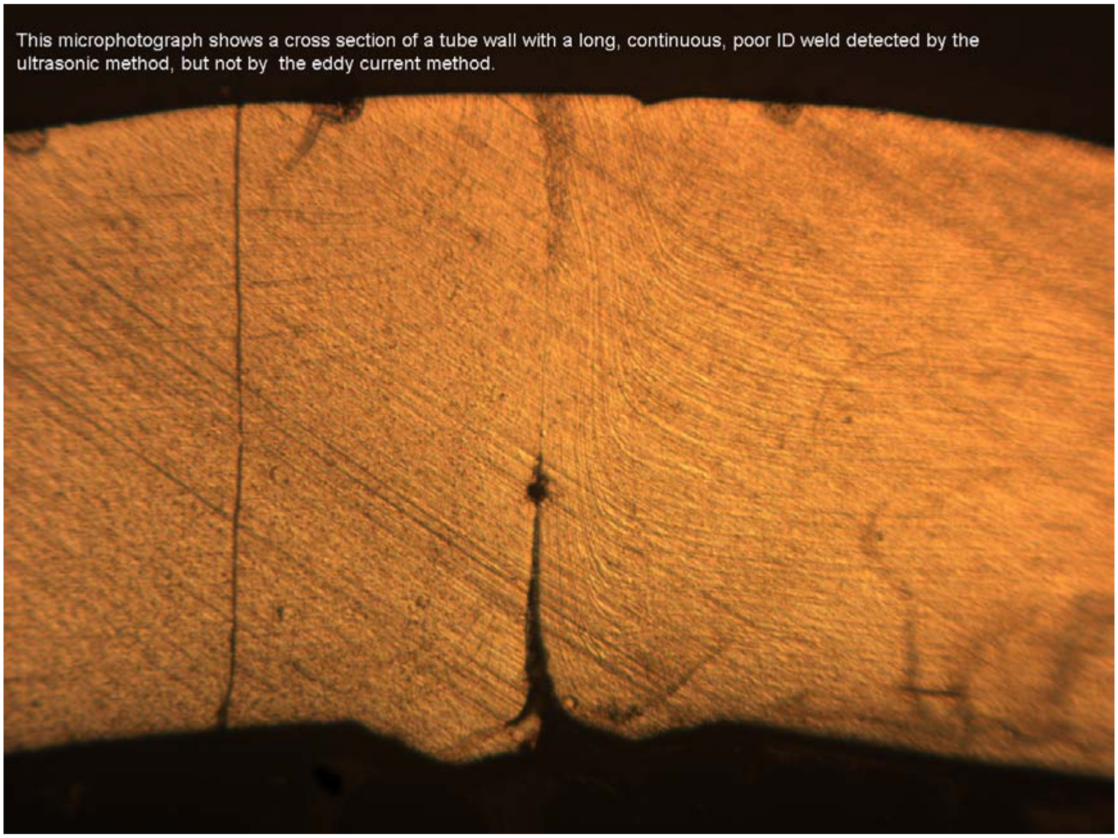
EXHIBIT 1
Drawing of a combined Eddy Current and Rotary Ultrasonic test bench with automated conveyors

This brings us to the question of why is all this necessary? As it happens, the drawn over mandrel tubes in this case, as is somewhat typical, are drawn from welded hollows. (Figures 9, 10, and 11) tell their own story. The situation is similar when tubes are made from extruded hollows containing stringer type inclusions or pierced steel hollows with oblique defects. For the variety of reasons presented, the eddy current method is most effective in finding very small short defects, but not long continuous defects, on the inner wall and to some extent mid-wall. Conversely, the ultrasonic method is effective in detecting long continuous defects on the I.D., such as incomplete weld, but can miss defects in an unexpected orientation or short defects with small reflective areas such as pinholes.



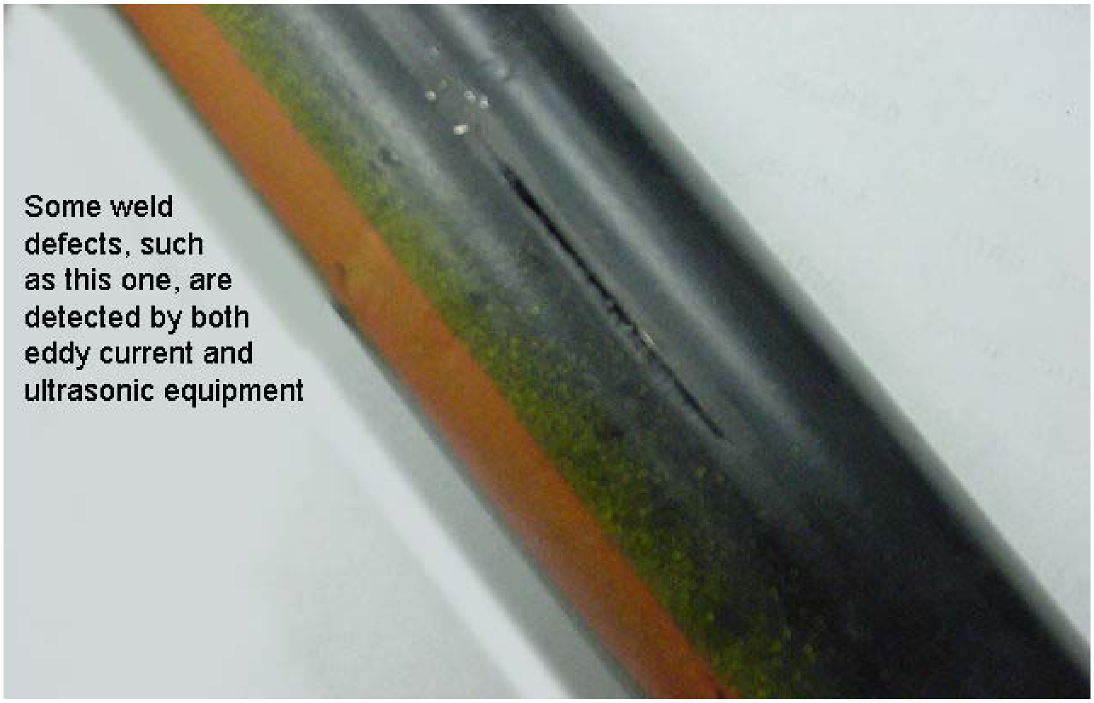
Eddy Current methods can detect very short flaws, such as this pinhole, which are not normally detected by Ultrasonic test equipment.

FIGURE 9
Short flaw detected by eddy current



This microphotograph shows a cross section of a tube wall with a long, continuous, poor ID weld detected by the ultrasonic method, but not by the eddy current method.

FIGURE 10 – Long, continuous, poor ID weld detected by UT



Some weld defects, such as this one, are detected by both eddy current and ultrasonic equipment

FIGURE 11 – weld defect detected by UT and ET

The system shown satisfies an important requirement pertaining to the use of eddy currents to inspect ferro-magnetic tubing - the need to apply a DC field with the AC field. The DC field, commonly called a saturation field, if powerful enough, renders the magnetic tube as almost non-magnetic while it is within the DC field. A schematic of a differential coil system surrounded by a DC saturation coil is shown in Figure 12. The saturation field allows deeper penetration of the eddy currents into the tube wall and eliminates background noise caused by magnetic variations along the tube. The actual apparatus is shown in Figure 13. Usually a demagnetizer must be provided to reduce the residual magnetism to within acceptable levels.

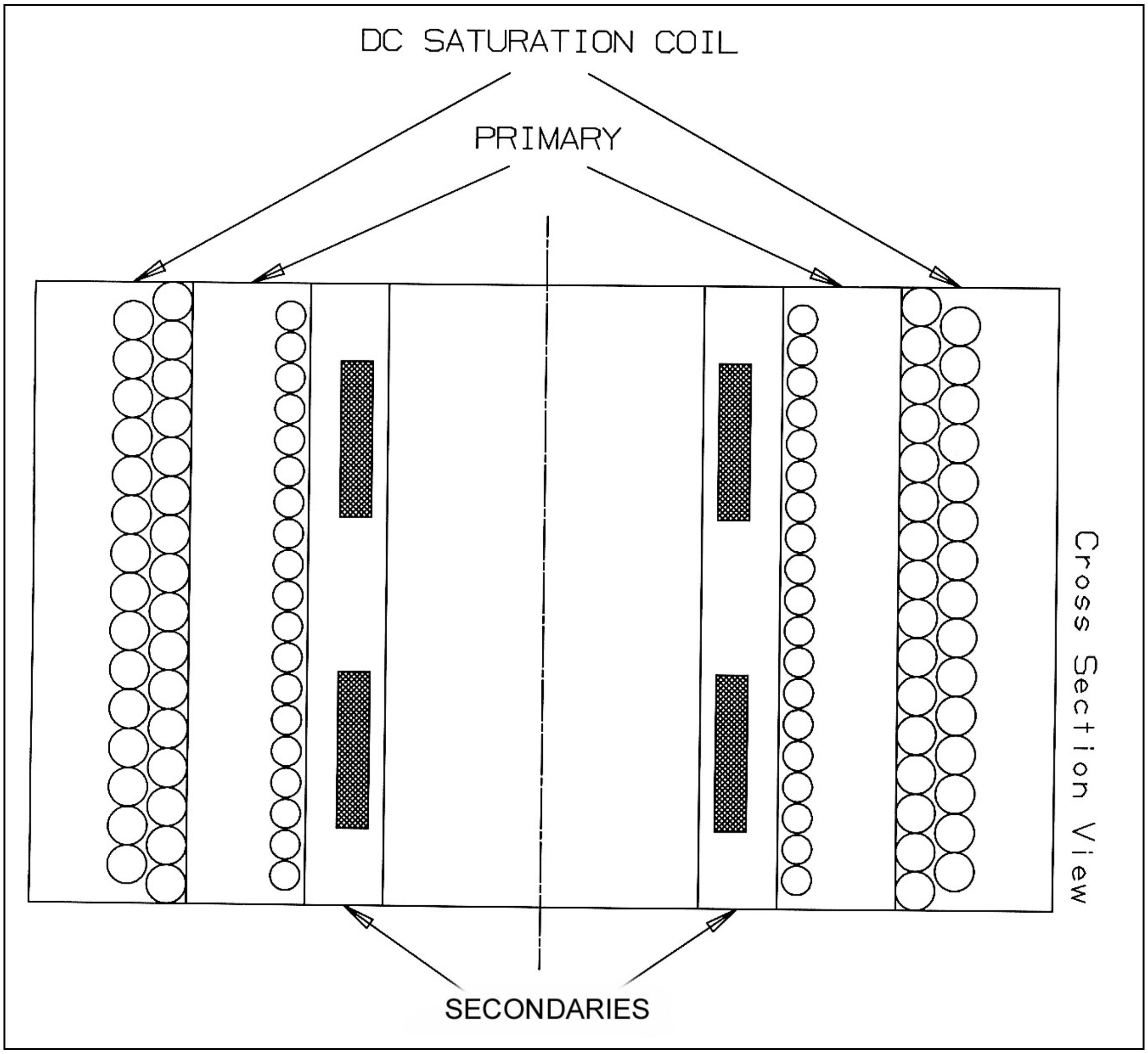
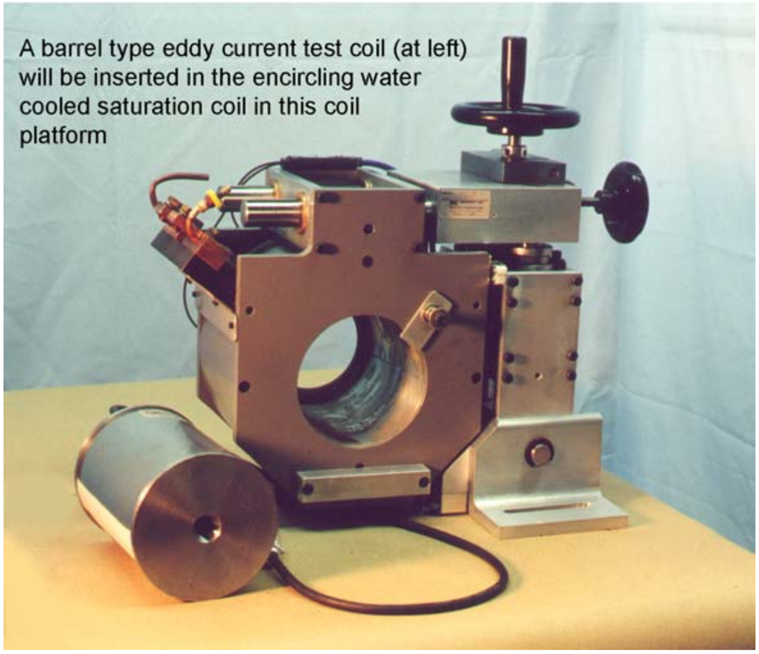


FIGURE 12



A barrel type eddy current test coil (at left) will be inserted in the encircling water cooled saturation coil in this coil platform

FIGURE 13

An actual integrated test system in a tube mill in India is shown in figure 14.

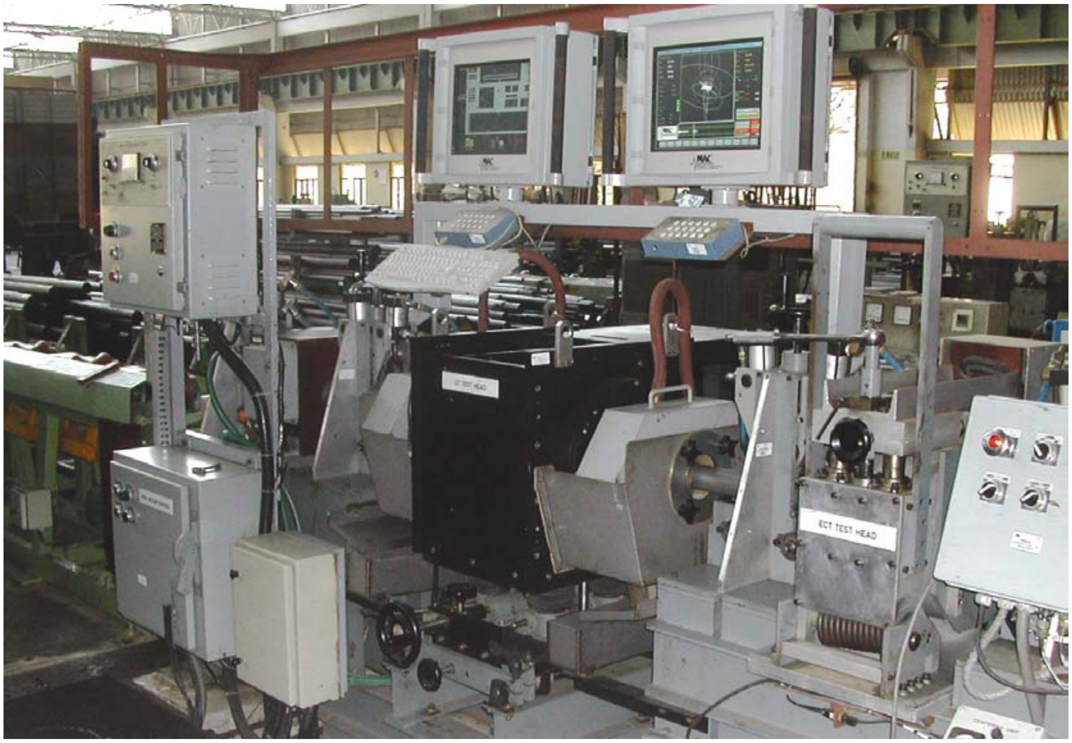


FIGURE 14
Multi test eddy current and ultrasonic test system

FLUX LEAKAGE – A GOOD CHOICE IN MANY CASES

As an alternative to the use of a rotating transducer ultrasonic head, a prominent US producer of drawn over mandrel tubing has, for many years, successfully used a rotating flux leakage head, as shown in Figure 15, which incorporates rotating D.C. electromagnets and multi element sensor arrays. When used on steel tubes the flux leakage method can provide some of the advantages of the ultrasonic method and the eddy current method and is less susceptible to missing defects because of orientation but is not as sensitive to ID defects as ultrasound, especially in wall thicknesses greater than 15 mm. Because of this limitation, this solution will not be adequate to test oil country pipe with 40 mm wall thickness to the level of a 2mm deep notch on the ID. In this case, the choice would be ultrasonics.

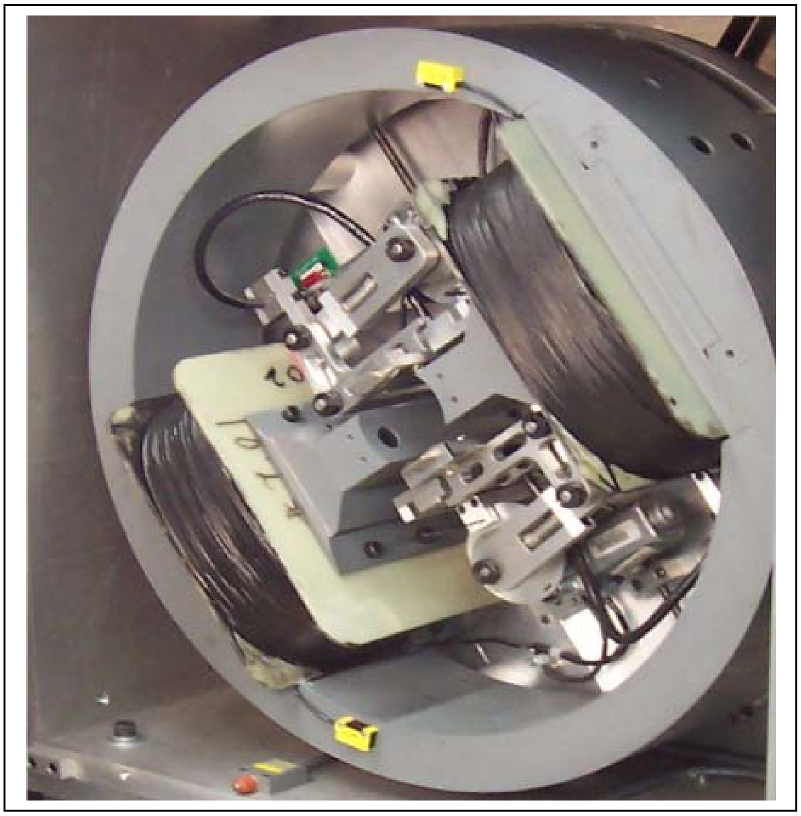


FIGURE 15
A rotary flux leakage headplate assembly with magnetizing coils on either side. The probe assemblies that house the test probes are shown at the top and bottom. The rotary system is used to detect longitudinal defects such as laps and weld line defects in 15 mm heavier wall magnetic tubular products. The use of arrays or small sensors in the probes enables detection of drilled holes as small as .8 to 3 mm, depending upon wall thickness

TESTING ALL OF THE PRODUCT ALL OF THE TIME

A major concern when using rotating systems where either the testing apparatus is rotated or the tube or pipe is rotated is coverage of the tube length along the longitudinal axis for defects of a maximum length when running at an acceptable through speed. This is generally not a problem for rotating flux leakage systems, which can employ multiple sensors of appropriate size to repeatably detect the specified defect. However, it does present a formidable challenge in the case of UT inspection systems as treated by Mr. Terry Banach in the paper "Ultrasonic Test Coverage Planned Versus Actual" (3). An obvious corollary to the need for the NDT systems to keep up with tube production is their availability. As tasks are added and the number of solutions increased, the specter of downtime must be factored in. It is certainly incumbent upon suppliers of NDT equipment for tube inspection to provide systems with better reliability, in spite of their increased complexity - no small task, but one that is being accomplished as can be seen from some of the examples presented here.

Perhaps a good example of the ongoing developments in improving performance and reliability is to examine a typical rotating ultrasonic transducer head as shown in FIGURE 16. Although many of these rotating heads are in service, certain sources of vulnerability have now been engineered out. New versions do not require seals, which are at risk of developing leaks that can precipitate major breakdowns. The devices on the left of the rotary are now rotating transformers that have replaced the rotating capacitor banks shown as the means of transferring UT signals from the rotating transducers to the UT instrumentation. In order to facilitate the use of the more reliable transformers, portions of the electronics have been moved onto the rotary where they also create the opportunity to efficiently use more transducers or linear transducer arrays. Details of these improvements were presented by Mr. John Venczel at the ITA Conference on New Technologies for Tube & Pipe Production a TUBE05 in Prague, Czech Republic. (4)

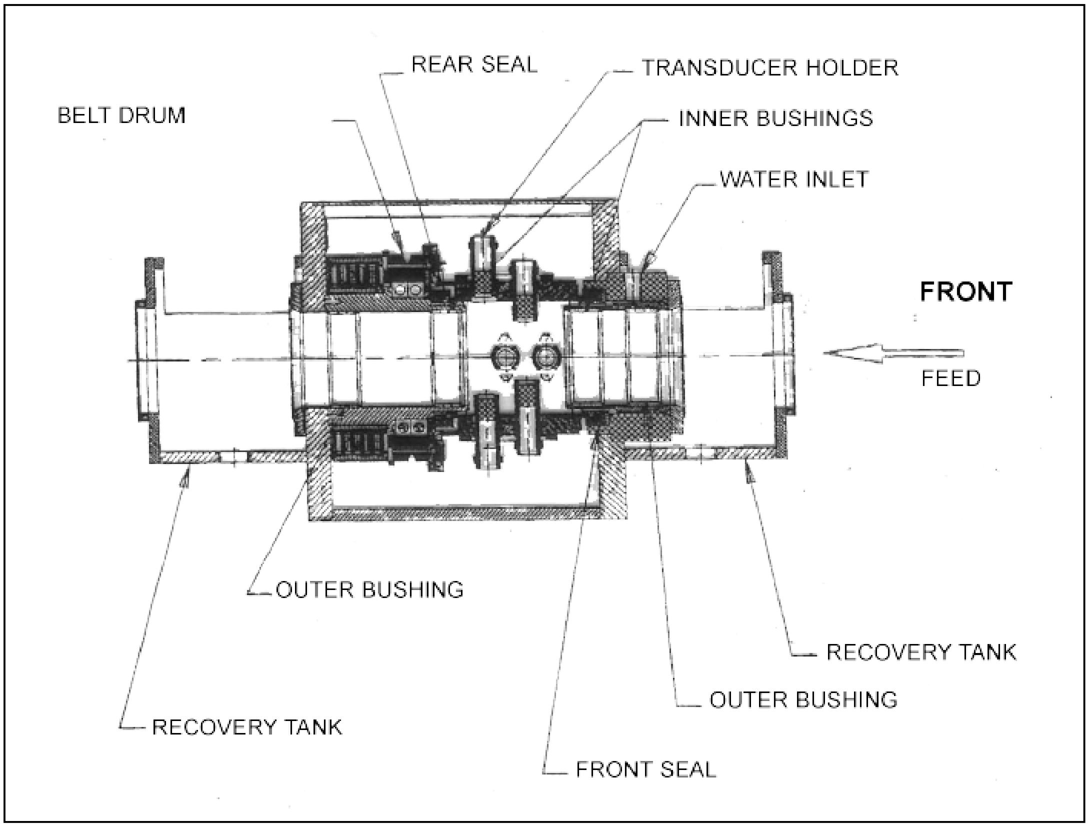


FIGURE 16
U.T. Rotary

So far, we have concentrated upon limiting what may be the major contributor to the cost of tube inspection – unjustified rejects. Another important factor is system availability which, along with maximizing throughput speed and minimizing changeover times, affects overall productivity. In a world of six-sigma quality and just in time delivery, the new imperative has become ship excellent product within short lead times, without delays, and reduce costs at the same time. Obviously, in this kind of competitive environment, the reliability of NDT systems that sometimes run twenty-four seven, including maintenance requirements, is an important consideration when choosing NDT systems, and a major design requirement being met by NDT equipment suppliers. Equally important is the responsibility of the tube manufacturer to present a tube in a condition and orientation that will not damage a well-engineered NDT system.

PHASED ARRAY – A NEW APPROACH TO THE PROBLEM

Although it has not been broadly applied to tube inspection to date, phased array technology is beginning to provide an option that alleviates the coverage problem, especially on smaller diameters, by surrounding the tube with transducer arrays like the one in Figure 17 which is a typical 128 element concave array. In a practical application using similar arrays, Figures 18 and 19 demonstrate the capability of a system that uses six arrays of 128 segments each to inspect tubes in the diameter range of 17.2 mm to 56.4 mm. They illustrate clockwise and counter-clockwise shear wave for OD and ID defects, and longitudinal waves for lamination-type defects and wall thickness measurement. Electronically timing the excitation and reception of echoes creates focusing and virtual scanning with shear and longitudinal mode beams. This system operates with throughput speeds up to 2m/second and changeover times of 10 minutes or less.

FIGURE 17
128 element concave transducer array

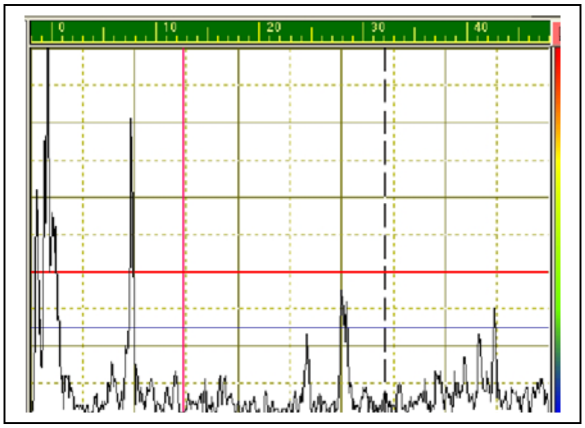


FIGURE 18
Phase array screen display of a 0.1 mm deep x 5 mm long longitudinal ID notch (at throughput speed of 120 m/minute.

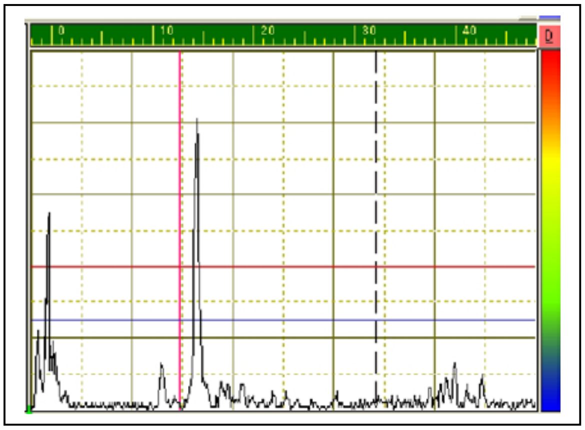


FIGURE 19
Phase array screen display of a 0.1 mm high x 5 mm long OD longitudinal notch (at throughput speed of 120 m/minute.

"Conventional phased array inspection techniques consist of setting virtual probes along the Phased Array, by programming the aperture (group of elements firing or receiving together) with a delay pattern to provide the same effect as a focusing lens. The electronics are usually fast enough to scan different settings at each transmitted pulses, so-called cycles or time slots. This operation can be considered as running the inspection with virtual probes that are scanned one after the other. The advantage against single element probe requires one transmitted pulse, and this affects the inspection speed. It affects the speed as much as it increases the PRF (Pulse Repetition Frequency) and results in ghost echoes that must be avoided." (5)

Some basics are covered in the following information from Imasonic SA. (6) The phased Array concept concerns multi-element transducers. Each element of these transducers is connected to a different electronic channel, either directly or through multiplexors, according to electronic device performances. Each element can be activated or not for each shot. The size and location of the active aperture of a phased array transducer depend on the activated elements. An electronic delay can be applied to each electronic channel when emitting and receiving the signal to/from the transducer elements. The setup corresponding to all the delays of a given shot is called Delay Law. Each delay law defines a different acoustic beam with particular direction, focusing distance and lateral resolution.

This technique requires probes with very low acoustic and electric cross coupling between the elements, so that all the elements could be fired independently. Thanks to their 1-3 structure, Imasonic piezocomposite materials are completely adapted to this feature.

In electronic scanning, the beam is electronically translated by alternatively firing a given number of elements of a linear or circular array phased array transducer, illustrated in Figure 20.

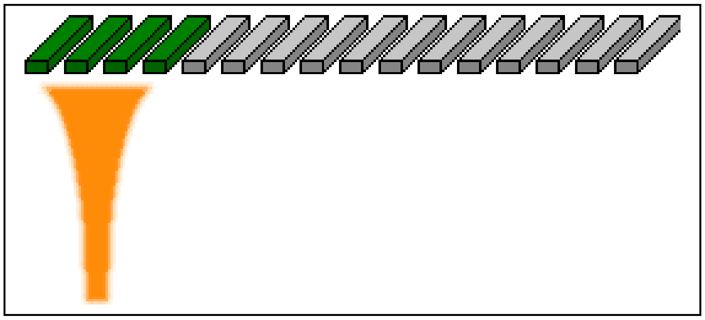


FIGURE 20 – Electronic Scanning

This technique is an alternative to mechanical translation of a single element probe. The advantages are faster inspection, no mechanical movement required, or reduction of scanline number and the possibility of combining with electronic focusing and beam steering (see below).

In electronic focusing, the beam is electronically focused by applying symmetrical delay laws to the different elements of a linear or annular phased array transducer as illustrated in Figure 21.

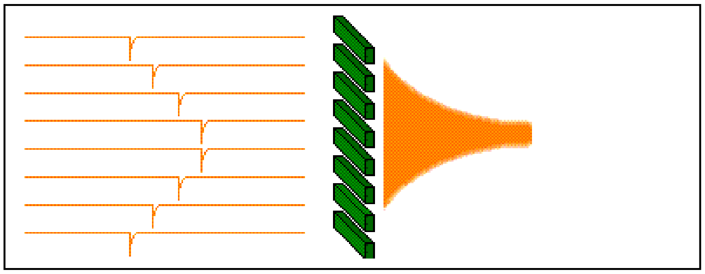


FIGURE 21 – Electronic Focusing

The advantages are: only one probe can focus at each depth, faster inspection of complete volume of thick pieces with dynamic focusing, electronic focusing can compensate focusing aberrations due to cylindrical interfaces. It should be noted that electronic focusing can be used in addition to a cylindrical, spherical or aspherical mechanical pre-focusing of the transducer.

In Electronic Steering the beam is electronically deflected by applying delay laws to different elements of a linear, circular or matrix array, as illustrated in Figure 22. Linear and circular arrays allow for 2D beam steering, while matrix arrays allow for 3D beam steering.

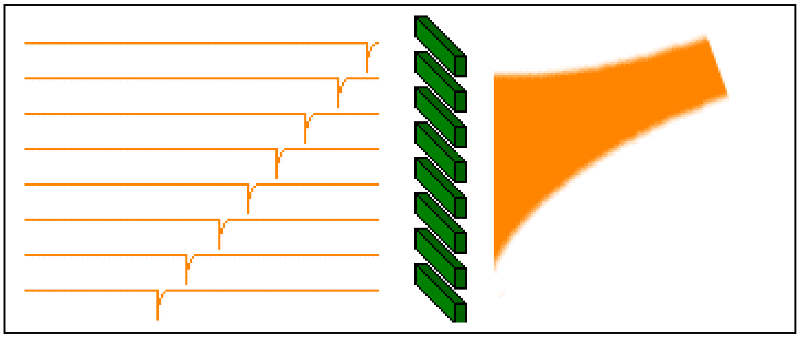


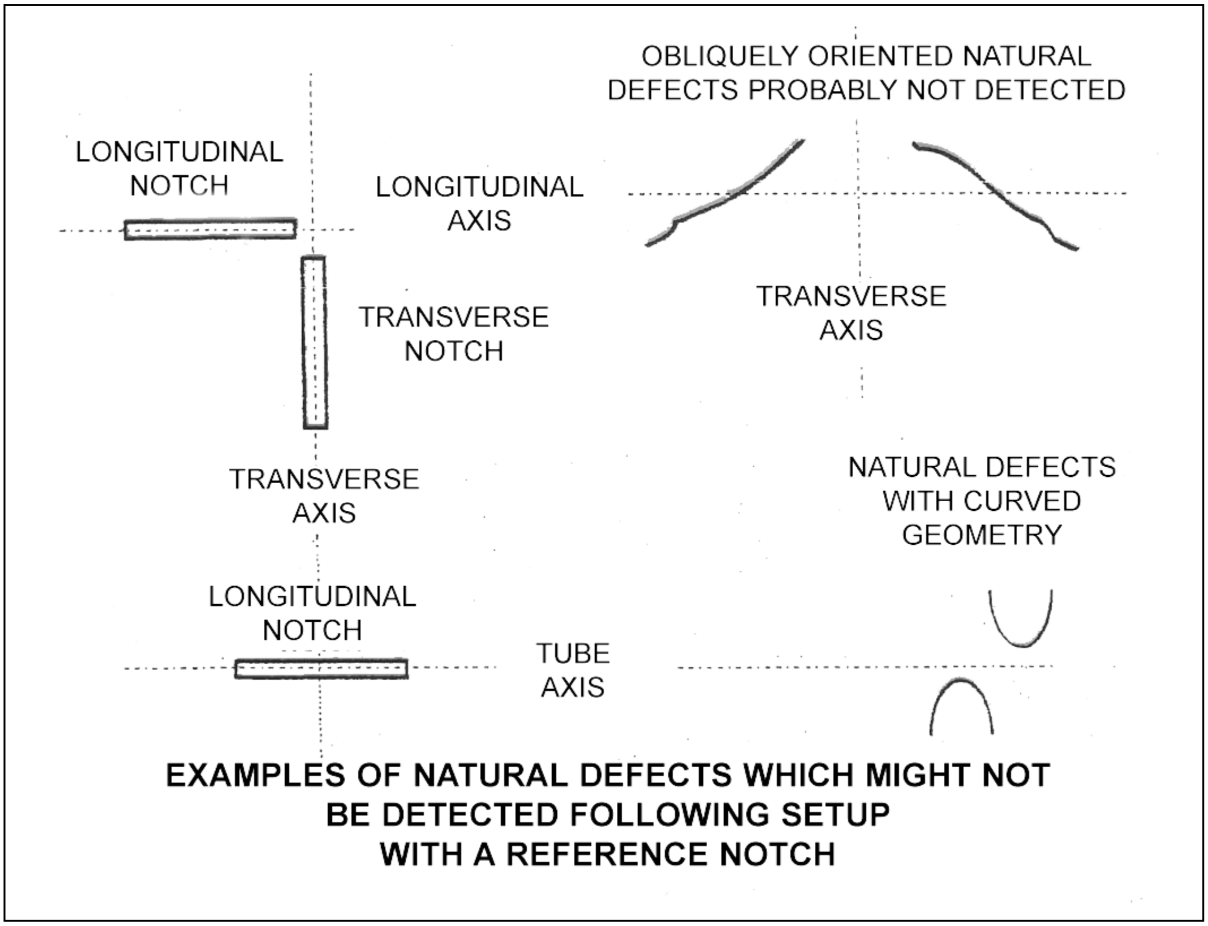
FIGURE 22 – Electronic Steering

This technique is an alternative to using different angled transducers. The advantages are: only one transducer is required for inspection at variable angles; faster inspection of complex geometry pieces, and the advantages of this technique can be combined with those of electronic focusing. It should be noted that to optimize beam characteristics, electronic deflection can be used in addition to a mechanical pre-deflection with a wedge.

A newer technique called Volume Focusing holds out the possibility of using the identical type of array, but fewer or them while providing the same capabilities. “The transmitted pulse is generated all along the probe, with a delay pattern so that the generated wave keeps consistency, does not diffract, and irradiates all the volume that has to be inspected. A massive parallel and powerful calculation in the electronic then makes the spatio temporal de-correlation of the signal. The imaging of the flaw pattern becomes then available for more data processing, usually oriented for evaluation. This technique, as a particular case of the tomography processing, overcomes the limitations of conventional phased array inspection techniques.

Multi-modes inspection consists only in doing more calculation with the electronics. The PRF does not have to be high to get very high speed of inspection, then, the problem of ghost disappears. But the whole concept is based on the fact that a consistent transmitted wave is used for an inspected whole section of the part. The Volume Focusing technique uses consistent wave, resulting from all elements of the probe, such as a plane wave, cylindrical wave, spherical wave or others.“ (5)

More recently, customers are asking for equipment that will respond to oblique defects which spiral around the tube in either a left or right-handed direction, as is illustrated in Figure 23. This is especially a concern for oil country customers using seamless steel tubing. The response to this demand may come from phased array ultrasonic technology, especially this relatively new version that uses volumetric focusing.



EXAMPLES OF NATURAL DEFECTS WHICH MIGHT NOT BE DETECTED FOLLOWING SETUP WITH A REFERENCE NOTCH

FIGURE 23

CONCLUSION

Perhaps the best way to conclude this discussion is with an admonition to the interested parties - the tube buyers, producers, and NDT system suppliers. In the heat of competition, there is a temptation to require nearly impossible conditions for applying NDT on the part of the tube buyer; to attempt to produce and test the tube to meet the conditions on the part of the manufacturer, and the continuing efforts by NDT system suppliers to offer capabilities that are not required. When done indiscriminately, if these conditions are fulfilled, it may be at unaffordable costs. Obviously, in this forum, specific interactions possible between the three participants can only be portrayed with the limited examples presented. However, the spirit and type of information exchange, if replicated, in individual circumstances, will result in continued progress toward reducing tube failures based upon knowledge and cooperation toward preserving and fairly distributing profits.

NOTES:

(1) ASTM – Annual Book of ASTM Standards 2005, Section Three, Metals Test Methods and Analytical Procedures. Volume 03.03 Nondestructive Testing, published by ASTM International.

(2) Handout Material:

“Discrimination of Metal Differences Using Electromagnetic Comparators”

“Flaw Detection Using Encircling Coil Eddy Current Systems”

“Flaw Detection by Use of Probe Type Eddy Current Systems”

“Flaw Detection Using Ultrasonic Test Techniques

Magnetic Analysis Corporation, Mount Vernon, New York USA

(3) “Ultrasonic Test Coverage Planned Versus Actual” Terrance R. Banach

(4) “Performance Improvement of Rotary Ultrasonic Testers”, by John Venczel at the ITA Conference on New Technologies for Tube & Pipe Production a TUBE05 in Prague, Czech Republic. Available PDF at www.mac-ndt.com or from
Magnetic Analysis Corporation, 535 South 4th Avenue, Mount Vernon, NY 10550

(5) Excerpts on Phased Array, courtesy of Dominique Braconnier, KJTD

(6) Excerpts on Phased Array, courtesy of Imasonics SA

APPENDIX

FIGURE LIST

“NONDESTRUCTIVE TESTING FOR MULTIPLE CONDITIONS IN TUBE AND PIPE”
by DONALD N. BUGDEN

ULTRASONIC TEST COVERAGE PLANNED VERSUS ACTUAL

By:Terrance R. Banach - Magnetic Analysis Corporation

ULTRASONIC TEST COVERAGE PLANNED VERSUS ACTUAL

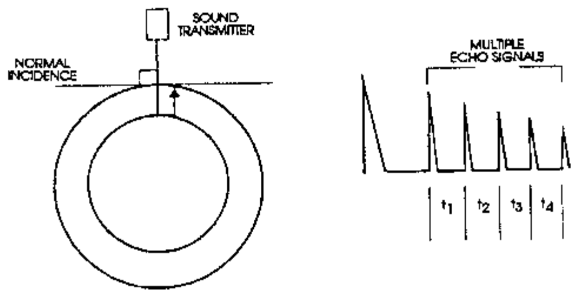
1. INTRODUCTION

Tube Mill déja vu ???

The plant manager is angrily pacing back and forth in the quality assurance office. He turns toward the desk of the QA manager. Excitedly he says, "Charlie, we worked for seven months to get this order from our first major offshore customer. We shipped them the first half of the order and they find four pieces with huge spiralling seams down the entire length of the tubes. I've just spent the past three days over there defending our case that all of our outgoing products are inspected thoroughly. I saw the pieces myself. Charlie, I'm telling you this defect condition was so gross that you could easily detect it visually."

Charlie is sitting at his desk staring sickly at his desk pad. The giant monthly planning calendar on the pad shows that tomorrow he is .... was going to start his first vacation in two years. He finally looks up and starts, "Look, I'll call Jackson, the NDT supervisor, up here immediately. This stuff was supposed to have been inspected 100% by UT___

Does this bring back an unpleasant memory? Hopefully not. However, the intention of the following information is to clarify and, perhaps, minimize the potential for just the kind of occurrence described above.



WALL THICKNESS IS DIRECTLY PROPORTIONAL TO THE TIMES (t1, t2, t3, & t4) BETWEEN THE MULTIPLE SIGNALS

FIG. 1

1.1 SOME BASICS

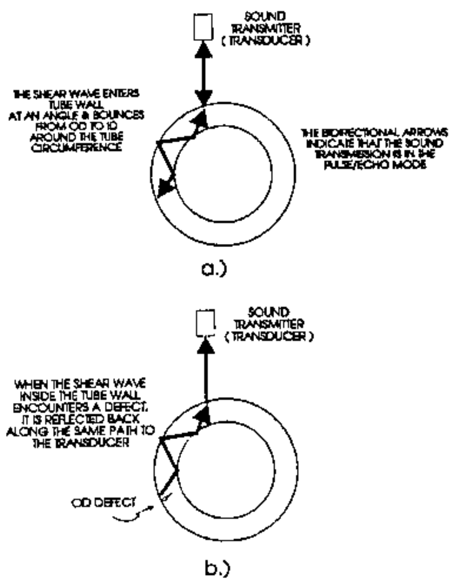
In an effort to address the broad cross section of personnel in the tube mill, a very simplified introduction or review will be initially provided. At the risk of violating some of the more theoretical tenets of ultrasonics, the discussion and diagramming of ultrasonic beam theory will be kept to single axis beam and single plane descriptions. Where necessary, expansion beyond this simple approach will be applied.

1.2 TUBE RELATED ULTRASONIC FUNDAMENTALS

Basically, when ultrasound is transmitted into a tube, it is actually the transmission of a *mechanical* disturbance, at the molecular level, into the material structure. Just as audible sound is transmitted via a mechanical disturbance of air molecules, so is sound transmitted through the tube body via its molecular structure. The two most frequently used forms of sound propagation in tube inspection are termed the compressional or longitudinal mode and the shear or transverse mode.

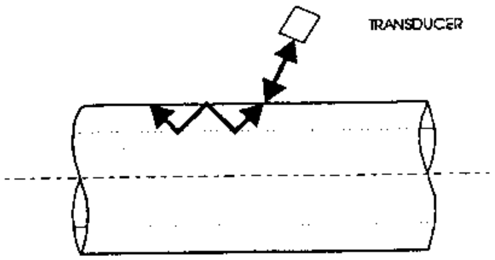
The compressional mode is characterized by the cyclical "pushing together" and "pulling apart" of the molecules along the direction of propagation inside the material. Whereas, the shear mode is characterized by the shearing or slipping motion of the molecules perpendicular to the propagation direction in the material.

Compressional or longitudinal waves are frequently applied to tubing to measure wall thickness. Occasionally they are also used to detect lamination type defects inside the tube wall. Fig. 1 shows that the application of the compressional sound mode, normal to the surface of the tube, produces a set of multiple echoes whose signals can be used to measure thickness.



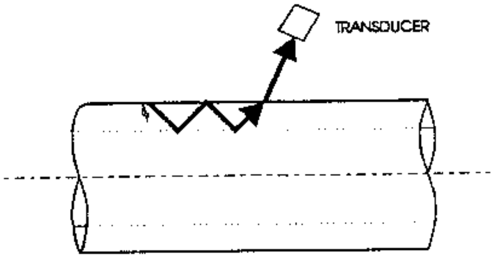
CIRCUMFERENTIAL TEST

FIG. 2



SHEAR WAVE ENTERS TUBE WALL AT AN ANGLE & SKIPS FROM ID TO OD ALONG THE TUBE AXIS

a.)

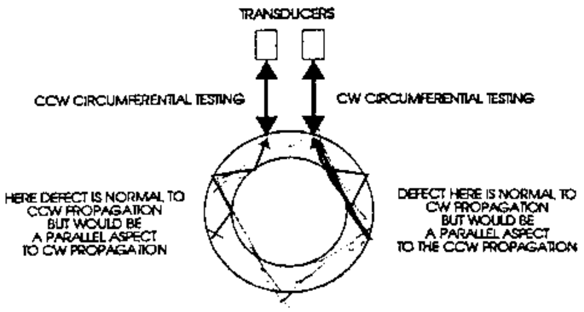


WHEN THE SHEAR WAVE ENCOUNTERS A DEFECT INSIDE THE WALL IT IS REFLECTED BACK ALONG THE SAME PATH TO THE TRANSDUCER

b.)

AXIAL TEST

FIG. 3



TWO DIRECTION CIRCUMFERENTIAL TESTING

FIG. 4a

Shear waves are most commonly used to detect defects in tubing. They are typically either transmitted circumferentially around the tube or axially down the length of the tube. Fig. 2 and 3 show that the circumferentially transmitted sound is used to detect axial defects such as seams, while the axially transmitted sound is used to detect circumferential or transversely oriented defects.

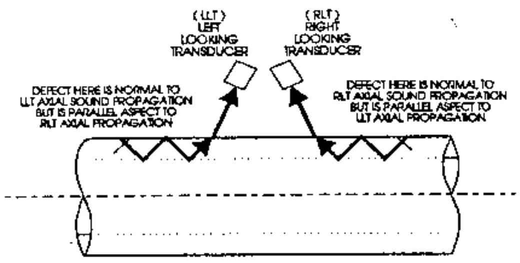
Ideally to receive an echo, the sound transmission must encounter the defect at normal incidence or right angles to the plane of the defect. To minimize missing a defect due to its plane of orientation, two directional testing is most commonly applied to the inspection. This approach, shown in Fig. 4 is employed in both circumferential and axial testing. The figure also indicates that a defect could remain undetected when its plane of orientation is essentially parallel to the sound propagation direction.

1.3 COMMONLY USED TRANSDUCER SOUND BEAMS

The sound transmission, which we have been discussing , is obtained by using an ultrasonic transducer. The heart of this transducer assembly is a device called a piezoelectric element. The phenomenon of piezoelectricity is reciprocal. That is, if electrical energy is applied to the element, the element can convert it into mechanical energy. Likewise, when mechanical energy is applied to this same element., the mechanical energy can be converted into electrical energy. This phenomenon lends itself very well to ultrasonic inspection, where the same transducer is used as both a transmitter and a receiver of sound energy. This mode of inspection is often termed pulse/echo testing. It is so termed because first a pulse of sound energy is transmitted into the tube. Then if any reflective conditions exist, such as a defect, the sound energy is reflected back to the transducer. This reflected energy is called an echo.

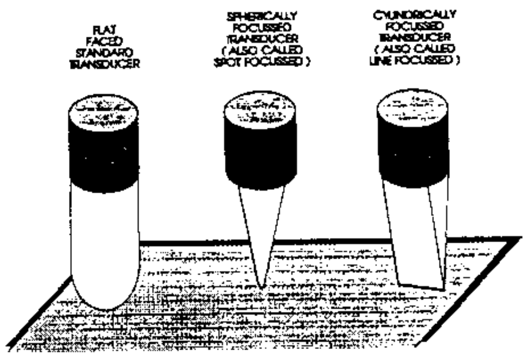
A standard transducer has a flat face. However, when a flat faced transducer is used to transmit sound into material with a curved surface, a large quantity of the incident sound energy is lost. Unfortunately since tubes have curved surfaces, the application of a standard transducer is not useful under most circumstances.

To better accommodate the curved surface of tubing, a transducer can be constructed with a curved lens attached to its face. Two common versions of these lenses exist. One is called a spherical lens, while the other is called a cylindrical lens. The purpose of a lens is to focus the sound energy either spherically or cylindrically. The prime benefit with regard to tubing inspection, is that focussing minimizes the amount of lost incident sound energy on the curved surface of the tube.



TWO DIRECTION AXIAL TESTING

FIG. 4b



COMMON TRANSDUCER BEAMS

FIG. 5

of a lens is to focus the sound energy either spherically or cylindrically. The prime benefit with regard to tubing inspection, is that focussing minimizes the amount of lost incident sound energy on the curved surface of the tube. Fig. 5 diagrams the virtual envelope for the sound beam volume resulting from each type of lens.

Although, either spherically or cylindrically focussed beams can be used during tube inspection, the cylindrical focus is chosen more frequently. This choice often stems from the desire to increase testing throughput speeds. A discussion of this relationship will occur later in this paper.

Fig. 6 shows a diagram of both the spherically focussed beam, often called a spot focussed beam, as well as a cylindrically focussed beam, often called a line focussed beam. Included in these diagrams are descriptive dimensions and nomenclature ordinarily used to describe the characteristics of each beam type.

In spite of all these characteristic being very important to establish good tube inspection setups, we will concentrate primarily on the beam length "BL" for the objectives of this article.

1.4 FACTORS GOVERNING VOLUMETRIC TEST COVERAGE OF THE TUBE BODY

As was stated in section 1.3 above, the line focussed transducer provides the beam of choice most often for tube inspection. We will now examine how this beam shape plays its role in producing full body test coverage of the tube.

Two actions must take place to insure complete test coverage of each tube length. First, to inspect the entire circumference of the tube, either a transducer beam must rotate around the tube or the tube must rotate continuously in front of a stationary transducer beam. Second, the tube must be fed lineally past a rotating beam or fed with helical motion past a stationary beam.

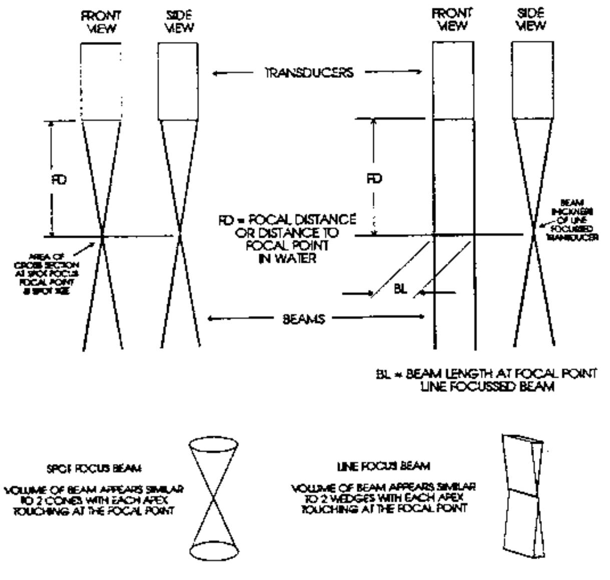
When these two actions are provided by the inspection system, a virtual paint stripe helix, of width equal to the beam length, will be described about the length of the tube.

Fig. 7 shows diagrams of three helical test path conditions:

1.)Undertesting or barber pole testing
2.)One hundred percent helical test coverage
3.)Overlapped helical test coverage

For a given beam length "BL", these three helical test path conditions are controlled by the speed of rotation and the linear throughput velocity of the tube. An additional term often used to express this combination linear and rotational motion is pitch. Pitch represents the linear advance of the tube per one revolution of either the transducer or the tube. To provide complete tube body volumetric coverage, either condition 2.) (100 % helix) or 3.) (overlapping helix) can be used. Although the 100% helical coverage should be adequate, the overlapped helical coverage will increase your coverage insurance and consequently improve your detection repeatability.

Earlier, the terms pulse / echo were used to describe the ultrasonic test method applied to tube inspection. The term pulse suggests that the transmission of the sonic energy



BEAM DIMENSIONS FOR SPOT & LINE FOCUSSED TRANSDUCERS

FIG. 6

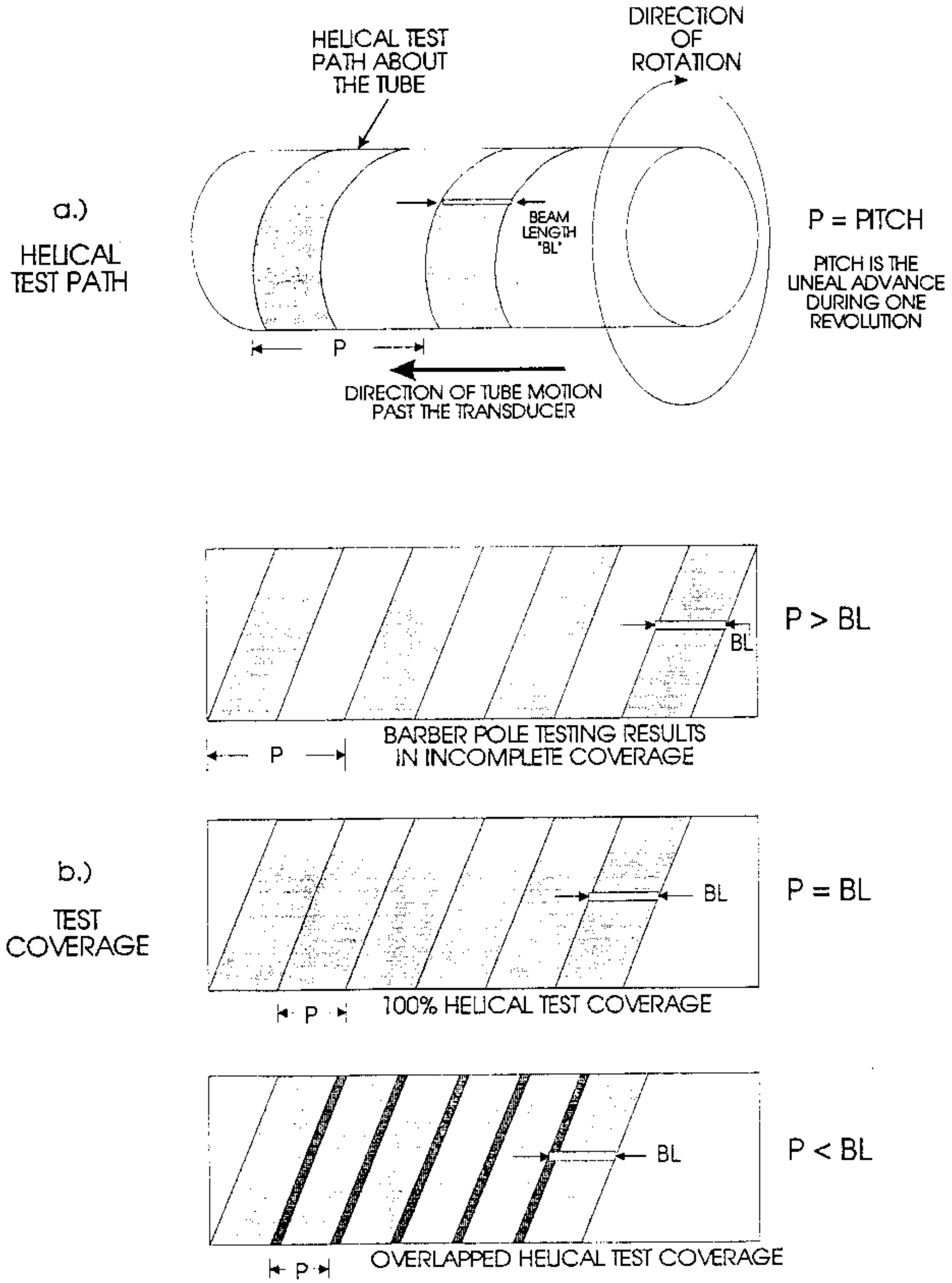

a.)
HELICAL TEST PATH
HELICAL TEST PATH ABOUT THE TUBE
DIRECTION OF ROTATION
BEAM LENGTH "BL"
P
DIRECTION OF TUBE MOTION PAST THE TRANSDUCER
P = PITCH
PITCH IS THE LINEAL ADVANCE DURING ONE REVOLUTION
b.)
TEST COVERAGE
BL
P > BL
P
BARBER POLE TESTING RESULTS IN INCOMPLETE COVERAGE
BL
P = BL
P
100% HELICAL TEST COVERAGE
BL
P < BL
P
OVERLAPPED HELICAL TEST COVERAGE

FIG.7

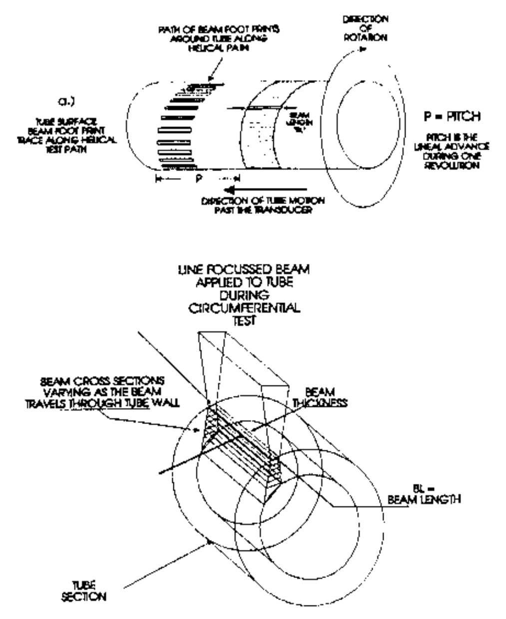


FIG. 8

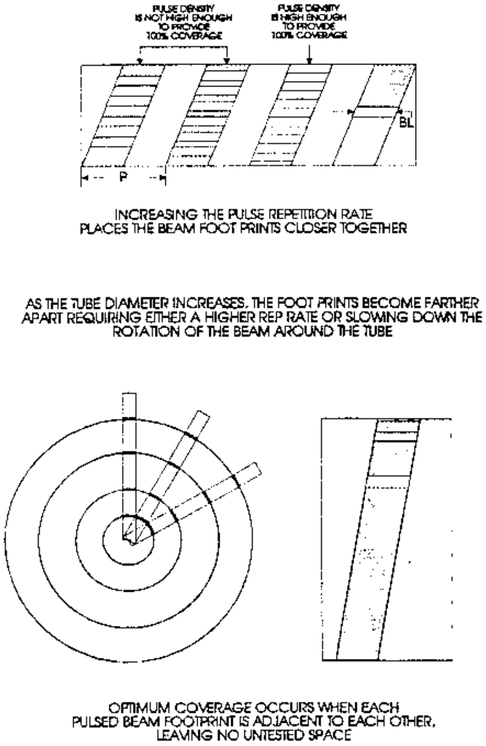
o the tube is not continuous. This is actually the case. Pulses or bursts of sound energy, as opposed to continuously emitted sound energy, are transmitted into the tube wall. The rate at which these transmitted pulses of sound energy are repeated is called the pulse repetition rate. Very often pulse repetition rate is shortened to "Rep Rate" or abbreviated to PRR. Fig. 8 and 9 depict this concept as applied to test coverage. The diagram shows that the beam essentially generates a foot print on the tube surface as well as planar beam cross sections continuously throughout the tube wall while the tube is being inspected.

2. CALIBRATION STANDARDS

As with all measurement situations, it's necessary to have some type of calibration standard available to check the functional operation of your system. Ultrasonic testing is not an exception to this rule. Typical test calibration standards should be made from the same material and the same OD and wall as the tubing product that you anticipate testing.

2.1 REFERENCE NOTCHES AND TEST STANDARDS

The next requirement is to create some form of standard defect. To achieve this, reference notches are placed in the wall of the calibration standard tube. The notches are oriented in the same general direction as the defect conditions being sought by the inspection. Fig. 10 shows some of the more common reference notch geometries used in a typical calibration standard. These notches should be prepared carefully according to stringent specifications. This is important because they represent the calibration



INCREASING THE PULSE REPETITION RATE PLACES THE BEAM FOOT PRINTS CLOSER TOGETHER

AS THE TUBE DIAMETER INCREASES, THE FOOT PRINTS BECOME FARTHER APART REQUIRING EITHER A HIGHER REP RATE OR SLOWING DOWN THE ROTATION OF THE BEAM AROUND THE TUBE

OPTIMUM COVERAGE OCCURS WHEN EACH PULSED BEAM FOOTPRINT IS ADJACENT TO EACH OTHER, LEAVING NO UNTESTED SPACE

FIG.9

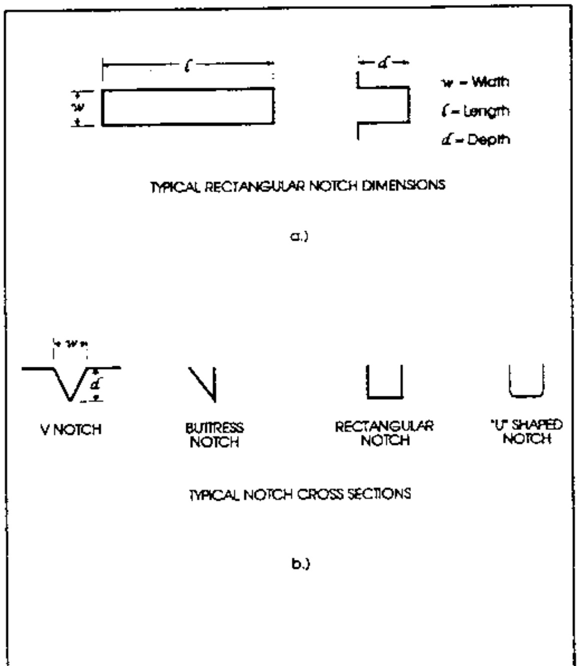


FIG.10

standards by which you will repeatedly judge the performance of your ultrasonic testing system. A primary goal of using these standards is to insure that your testing system is making consistent measurements of the echo signals received from each of the notches.

Fig. 11 shows variations in notch orientations and geometry. The orientation chosen for each notch is based on imitating the orientation of the defective condition that you wish to detect. Notch geometry is also based on imitating a simplified geometric representation of the conditions you wish to detect.

Although all of these standard notches can be useful, the most frequently used in the tube and pipe industry are longitudinal and transverse rectangular notches. To insure uniform detection sensitivity across the tube wall, these longitudinal and transverse notches are placed both on the OD and the ID of the tube.

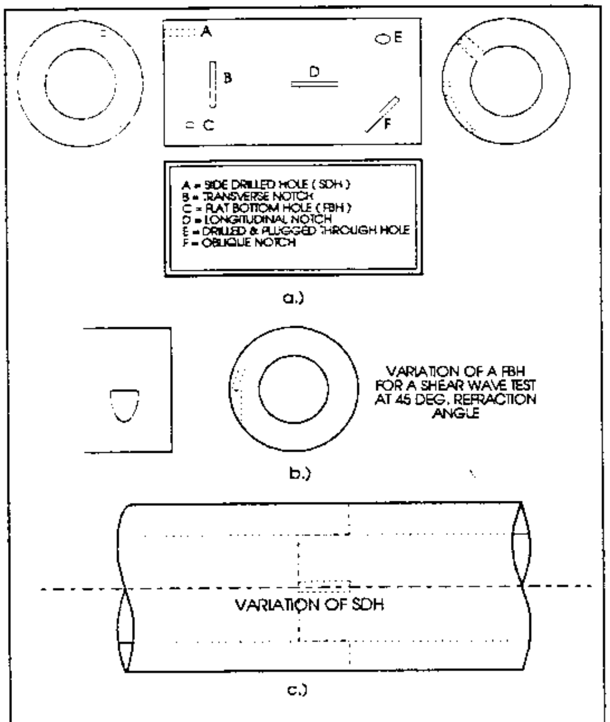
Reference notches less frequently used are the oblique notch, flat bottom holes side drilled holes and drilled & plugged through holes. These additional calibration reference standards are more often used in API specified testing procedures.

2.2 CONSIDERATION OF INITIAL DIFFERENCES BETWEEN DESIRED TEST COVERAGE AND RESULTS

Up to this point, we have looked at a few ultrasonic tube inspection basics. We have also introduced the role played by reference notches in this inspection. Now lets begin to examine a few typical questions about test coverage relevant to this introductory material.

2.2.1How small a defect can be detected ?

This or some variation in wording of this question is certainly the most frequently asked question concerning ultrasonic inspection. The most appropriate response as applied to production is unfortunately another question. How slowly are you willing to run your inspection line? When viewed strictly from a detection capability standpoint, it probably can be safely stated *pretty* small. However, it doesn't appear that anyone is actively making "The Smallest UT Defect Ever Found" entries into the "Guiness Book of



REFERENCE NOTCH ORIENTATIONS & GEOMETRIES
FIG.11

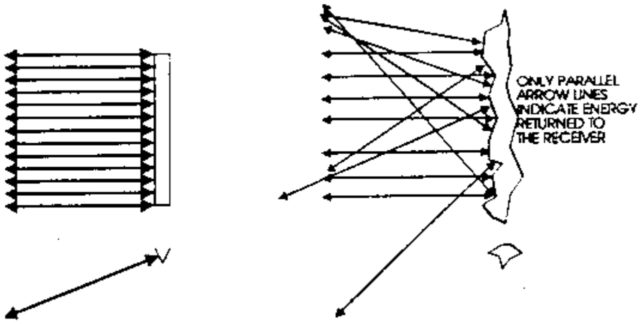
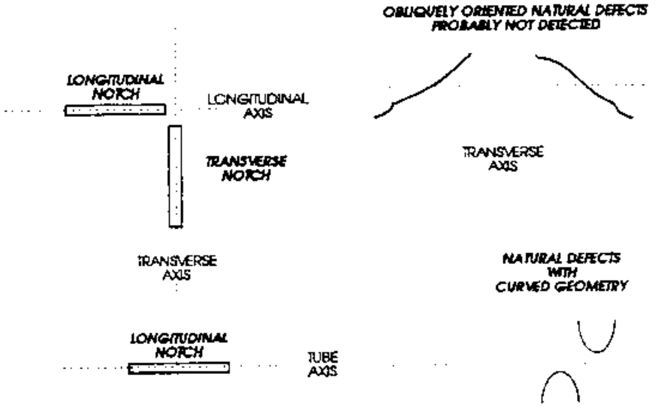


DIAGRAM COMPARING THE RETURN SIGNAL ENERGY FROM A NOTCH AS OPPOSED TO A LARGER SIZE NATURAL DEFECT WITH AN IRREGULAR SURFACE AREA

FIG.12



EXAMPLES OF NATURAL DEFECTS WHICH MIGHT NOT BE DETECTED FOLLOWING SETUP WITH A REFERENCE NOTCH

FIG13

Records".

Seriously, there is no single simple answer to such a question. To deal with this question as directly as we can, we should first consider a term not yet discussed. -"Sensitivity"- Sensitivity is a term frequently used in ultrasonic inspection to describe the ability of the system to detect small discontinuities. The greater the sensitivity of a system, the greater is its ability to detect the presence of small defects. However, increased sensitivity also means more susceptibility to the detection of other tube material conditions which would not normally be considered defect conditions.

Let us consider a test in which we are going to use longitudinal and transverse notches for our calibration references. Typically, notch depths are specified as a percent of the tube wall thickness. The smaller the notch depth and length dimensions, the greater the system sensitivity required to detect these reference notches. Normally these longitudinal and transverse notches are placed on both the OD and ID of the tube wall. Thus using smaller calibration notches enables us to establish higher sensitivity to smaller defects in the inspected tubing.

Now let's think about some possible nondefect conditions which your tubing material could possess that might provide echo signals similar to the calibration notches. Similar signals could be derived from material conditions, resulting from the production process, which are oriented in the same plane as the calibration notch and which are able to provide an integrated area equivalent to the notch virtual reflection area. Table 1 shows some example conditions.

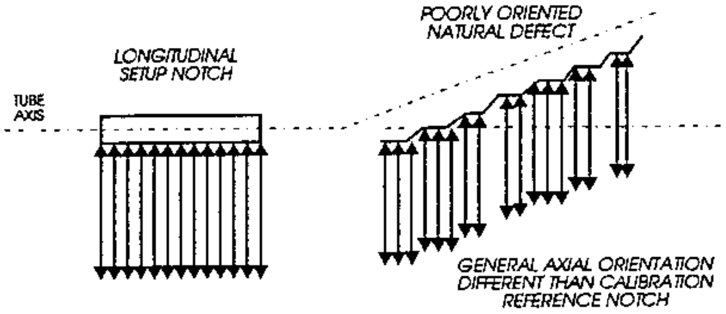
Why might these often acceptable conditions cause a problem? In a typical automated inspection system, the reference notch echo signal strength is used to establish an alarm threshold setting. When a return echo signal level crosses this setting, the system provides an alarm signal output which can be used to control an audible and/or visual alarm as well as some form of marking and sorting system. If the signal strength from the acceptable material condition is strong enough to cross the alarm threshold, then this material condition will also provide an alarm output just as a defect condition similar to the calibration notch would. Conventional commercially available UT equipment today has a limited means of discrimination against these conditions.

The tubing sorted into your reject bins will thus contain tubes with other than defect conditions. If these material conditions are acceptable to you as the manufacturer and the small reference notch sizes are required as a standard by your customer, a major economics problem exists. You can live with bad production yields - you can modify your production process to improve upon these conditions - of course you can also give up the particular customer for that product!

2.2.2 The product material conditions are excellent but the customer demands the use of a relatively small reference notch size. What problems might be encountered?

The smaller the defect that you are seeking the higher the sensitivity required. At higher sensitivities there is always the chance that your reject bin will end up containing a few marginal as well as some good tubes. However, when this is minimal, it is usually far more acceptable than ending up with rejects delivered to your customers' plants.

Aside from this condition, there is one other *price* paid as you are required to inspect for smaller and smaller defect sizes. As your inspection is required to detect decreasing defect sizes, you will generally need to also decrease your transducer beam



EXAMPLE CASE IN WHICH POORLY ORIENTED DEFECT COULD PROVIDE ADEQUATE RETURN SIGNAL ENERGY FOR DETECTION

FIG.14

length. Later we will discuss the relationship of beam length to notch length and test coverage in more detail. For now, it is sufficient to accept this statement so that we can examine the results.

Reconsider the discussion of the helical test path around the tube. In this discussion we stated that the helical advance during one test revolution must be equal to or less than the transducer beam length. This was stated as a necessity to provide one hundred percent or better inspection coverage. As we mentioned in the previous paragraph, there is a price. - Speed! - Smaller beam lengths require that you reduce the product testing throughput speed. Table 2 shows the testing throughput speeds resulting from various beam lengths when one hundred percent test coverage is desired. If testing path overlap is desired, the speed is further reduced in proportion to the amount of percentage overlap. This table also shows a means of doubling your speed, for a given beam length, if your system has the capacity to allow you to add a second transducer, with the same beam length, diametrically opposed to the first transducer.

2.2.3 Although an excellent test setup is established using calibration notches, can actual defects still avoid detection?

Yes. Keep in mind that each setup is calibrated with a particular reference notch which has a specific orientation direction as well as a specific reflection area. Any natural defect which does not adequately match the orientation and reflection area might not be detected. Natural defects tend not to be perfect, smooth machined replicas of the reference notch. Fig. 12 shows how the irregular surface of a natural defect, in a valid detection plane, with a size comparable to the calibration notch results in less reflected signal energy than the notch. When a natural defect reflection signal exceeds the alarm threshold, all that can truly be said is that the actual area of the defect must in general be larger than the notch.

Fig. 13 shows other conditions which could cause a natural defect to remain undetected. Basically, any time there is a noticeable deviation of a natural defect's planar orientation from the orientation of the reference notch used to calibrate the inspection system, that defect *may* remain undetected. Why is the term "may" used in the previous statement ? The natural defect may in fact contain enough properly oriented irregularities, in its planar cross section to provide sufficient return energy to be detected. This can even occur in spite of the overall orientation of this natural defect. Fig. 14 provides an example of a poorly oriented defect which could still be detected.

3. THE COMMON ENTRY POINTS FOR HUMAN ERROR

Sooner or later the human factor can enter as a source of error in the detection scheme. The results can be either excessive false detection or undetected defects.

Probably the two largest contributions of human error in ultrasonic testing are insufficient experience and inadequate training. The experience factor unfortunately requires time. However training and experience can be made to work "hand in hand". In fact good training programs can significantly lessen the amount time required for each operator to become seasoned with training. A simple single class in ultrasonics "doth not an operator make". The training should be frequent. Often a regimented program of one hour a week can serve both as training and a sounding board for current testing problems. In any case continuous training will result in vastly su-

MATERIAL CONDITION	CONDITION WHICH PRODUCER NORMALLY CONSIDERS ACCEPTABLE
SURFACE CONDITIONS	Surface conditions, such as handling marks, long scratches, production marks,'approach the size of the reference notch. The result is that they could also be detected.
GRAIN STRUCTURE	Excessively large grain structure could also be detected as random noise.
WELD ZONE ANOMALIES	OD or ID weld zone anomalies may be considered acceptable by the manufacturer. However, if they approach the size of the reference notch, they can often be detected and can result in false alarm conditions.

TABLE 1.

TABLE 2A

(100% COVERAGE with ONE CHANNEL in each cw & ccw DIRECTION)

BEAM LENGTH IN		FEED @ 3600RPM IN		FEED @ 2500RPM IN		FEED @ 1800RPM IN	
INCHES	millimeters	FPM	meters/min	FPM	meters/min	FPM	meters/min
0.0625	1.5875	18.75	5.72	13.02	3.97	9.38	2.86
0.1250	3.1750	37.50	11.43	26.04	7.94	18.75	5.72
0.1875	4.7625	56.25	17.15	39.06	11.91	28.13	8.57
0.2500	6.3500	75.00	22.86	52.08	15.88	37.50	11.43
0.3125	7.9375	93.75	28.58	65.10	19.84	46.88	14.29
0.3750	9.5250	112.50	34.29	78.13	23.81	56.25	17.15
0.4375	11.1125	131.25	40.01	91.15	27.78	65.63	20.00
0.5000	12.7000	150.00	45.72	104.17	31.75	75.00	22.86
0.5625	14.2875	168.75	51.44	117.19	35.72	84.38	25.72
0.6250	15.8750	187.50	57.15	130.21	39.69	93.75	28.58
0.6875	17.4625	206.25	62.87	143.23	43.66	103.13	31.43
0.7500	19.0500	225.00	68.58	156.25	47.63	112.50	34.29
0.8125	20.6375	243.75	74.30	169.27	51.59	121.88	37.15
0.8750	22.2250	262.50	80.01	182.29	55.56	131.25	40.01
0.9375	23.8125	281.25	85.73	195.31	59.53	140.63	42.86
1.0000	25.4000	300.00	91.44	208.33	63.50	150.00	45.72

TABLE 2B

(100% COVERAGE with TWO DIAMETRICALLY OPPOSED CHANNELS in each cw & ccw DIRECTION)

BEAM LENGTH IN		FEED @ 1800RPM IN	
INCHES	millimeters	FPM	meters/min
0.1250	3.1750	37.50	11.43
0.2500	6.3500	75.00	22.86
0.3750	9.5250	112.50	34.29
0.5000	12.7000	150.00	45.72
0.6250	15.8750	187.50	57.15
0.7500	19.0500	225.00	68.58
0.8750	22.2250	262.50	80.01
1.0000	25.4000	300.00	91.44

TABLE 3
FREQUENT OPERATOR PROBLEMS

SYMPTOM	POSSIBLE CAUSE	CORRECTION
Poor Repeatability	Insufficient pulse repetition rate. Feed throughput speed too high or rotational speed too low. Poor transducer setup Centering is poor.	Increase pulse repetition rate. Lower rotational speed. Adjust feed speed per revolution to be less than one beam length. Readjust transducer setup. Readjust centering mechanisms.
False Alarms.	Pulse repetition rate is too high (wrap around condition exists) Poor transducer setup. Air bubbles trapped in water system.	Reduce the pulse repetition rate. Readjust the the transducer settings. Remove or purge air from the water system.
Poor Detectability.	Poor transducer setup. Centering is poor. Transducer is defective. Electronic instrumentation is defective.	Readjust transducer setup. Readjust centering mechanisms. Replace transducer. Repair defective instrumentation.

perior operators who will help preserve the company 's customers.

Another contribution which can reduce the amount of human error is a well organized general testing method. This should be a procedure detailing all the steps for each type of transducer setup. All operators should be required to adhere to the same procedure. The reward will be traceability to a problem source when problems do arise.

Some of the more common operator problems can be found in Table 3. Poor repeatability is probably one of the most frequent operator problems. Poor repeatability simply means that if the test standard is run three times through the system you detect the reference notches only once or twice.

False alarms can be examined by running "known to be good" tubing through the system. There obviously should be no alarms for these tubes.

In rotational inspection systems it is imperative that the centering be good. The lack of good centering can cause either poor repeatability or poor detectability. Poor detectability is simply the inability to detect the notches.

4.0 RELATIONSHIP OF TEST COVERAGE & THROUGHPUT SPEED TO THE RATIO OF BEAM LENGTH TO NOTCH LENGTH

Next we will use four figures, coupled with discussions of each figure, to study the effects of beam length to notch length ratios on ultrasonic testing.The four figures (CASES I ... IV) diagram the effects of a transducer beam while it rotates around a tube, as it is driven concentrically through the center of rotation. As the notch passes under the rotating transducer, it is desirable that it does not pass by so quickly that the transducer beam is unable to intercept the notch. This condition is controlled by two primary factors, the linear velocity of the tube (throughput speed) and the speed of rotation of the transducer beam around the tube (RPM).

To meet the above desired interception condition, we will select a linear velocity and rotational speed combination which will insure 100% or more surface coverage of the tube. Since the circular motion of the transducer is at a ninety degree angle with respect to the linear motion of the tube, the resulting path of the transducer beam on the tube surface is helical. The term used to describe this helix will be Pitch " P ". Pitch, as previously defined, is the lineal distance through which the tube travels during one revolution of the transducer around the tube.

Normally the transducer beam used to test a tube is cylindrically focussed. This causes the beam to appear as a line (actually a narrow rectangle) on the tube surface. For this discussion, we will just assume that the line has adequate width and only concentrate on the length of this beam line. The length of the line will be called the Beam Length " BL " . For 100% coverage during the ultrasonic test, the Pitch " P " must equal the Beam Length " BL ". For greater than 100% coverage, the Pitch " P " must be less than the Beam Length " BL ".

The remaining parameter which must now be considered, is the Notch Length " NL ". As stated earlier, the prime purpose of the notch, is to provide an " ideal " defect standard which bears reasonable geometrical resemblance to the defect being sought. The relationship between notch length " NL " and beam length " BL " and also the pitch " P " will be discussed as well as shown diagrammatically in the four figures included as CASES I through IV .

4.1 THE INTERPRETATION OF THE INTERCEPTION DIAGRAMS

Although this discussion includes four diagrams listed as Case I, II, III and IV. the basic structure of each diagram is the same for all four cases. Therefore, to aid the reader with the interpretation of each diagram, we will describe the significance of all the symbols (lines, words, abbreviations, & alphanumerics) contained in these diagrams by referring only to the Case I diagram. At the top of each diagram we find an arrow tipped line pointing to the right. This arrow indicates the feed direction. This is the direction in which the tube, along with its corresponding standard notch, passes the rotating transducer beam. On the left hand side of the diagram, we find the column headed with the words "Interception Condition." Below this heading we find the numbers #1, #2, and #3. Each of these numbers (#'s) brackets a descending sequence of lines progressing to the right in the direction of feed. The thick horizontal lines grouped within each bracket set represent the interception condition or percentage of coincidence of the beam length with the notch. Since the notch is constantly moving to the right, through the zone of the rotating transducer, it can enter the zone so that it becomes immediately 100 % coincident with the beam as in Interception Condition #1. That is, the notch enters the beam test zone at the part of the beam revolution about the tube just at a point in time during which the notch length intersects with 100% of the total beam length.

Interception Condition #2 shows a condition where the notch has just entered the rotating beam test zone (1st REVOLUTION). Here the notch coincides with only 25% of the beam length. One complete revolution later (2nd REVOLUTION) , the beam length coincides with the remaining 75% of the notch length.

Interception Condition #3 shows that the notch length is coincident with 50% of the total beam length during the 1st REVOLUTION after its entry into the beam testing zone. At the end of the next complete rotation (2nd REVOLUTION) around the tube, the beam intersects the last 50% of the notch length.

Although only three or four Interception Conditions are shown for each Case, there exists an infinite number of possibilities. We have minimized the diagrammed conditions to merely three or four limiting conditions. This was done in an effort to highlight primarily the limits of interception.

Each of the four Cases depicts the interception conditions resulting from the relationships between notch length " NL ", beam length " BL ", and pitch " P ". We will now proceed to evaluate the relationship of these four Cases to detection repeatability, detection alarm levels, and false alarms. However, we will repeat one important point before we begin the discussion of each Case. **For 100% or greater coverage during testing**, " P " must be equal to or less than " BL ".

4.2 CASE I

Case I shows that while the material with the notch passes under the rotating beam, a signal can be detected which is always equal to or greater than 50%. Therefore if the notch signal amplitude is maximized on the display for 100 % full screen height (FSH), then the alarm level can be set to slightly below 50 % FSH to insure repeated detectability. This is not unreasonable since with the notch length equal to the beam length and hence beam lateral cross section, the signal to noise ratio achieved on a typical ultrasonic transceiver can often be quite good. The disadvantage of this approach is that during the actual testing for defects, an alarm could also occur on a defect whose equivalent length is 50% of the test notch length. In addition, at these lower alarm level settings increased false alarms will occur due to the decreased alarm level signal to noise ratio. The advantage is the achievement of maximal testing speed while maintaining 100% coverage at reasonable low receiver gains. In essence this approach provides a 200% defect overtest, which may or may not be acceptable under certain quality requirements.

4.3 CASE II

Case II indicates that during any time in which the notch passes the rotating transducer beam, there will be at least one signal capable of being detected with 100% FSH amplitude. Following signal maximization to 100%FSH, the alarm level can be set to just under the 100% alarm level. This should insure detection repeatability. Since the notch length is greater than the beam length, good signal to noise ratios at reasonably low receiver gains should be achieved. With this setup, during actual testing, the alarms should occur from defects with lengths close to the notch length. In this case 100% coverage has been maintained. The cost of this approach is that the maximum speed which can be utilized is one half of that achieved in Case I. This results from the fact that while the pitch "P" is still equal to the beam length "BL", it is only one half of the pitch "P" in Case I. However, this case represents the optimal test approach; and it is the most popular approach used to achieve test repeatability with optimally high throughput speeds.

4.4 CASE III

Case III demonstrates the approach where the beam length "BL" is two times the notch length "NL". The pitch "P" has been set equal to the beam length to achieve 100% coverage. As can be seen during any time in which the notch is passing through the rotating beam, at least one signal with an amplitude greater than 50% FSH should be detected. To insure repeatability of detection requires that the alarm level be set to just below 50% FSH after having maximized the signal for 100% FSH. The problem here is that the notch length is only half of the beam length. This can result in a smaller percentage return of the transmitted energy from the transducer beam than that which occurred in the previous Cases I and II. Often correspondingly higher receiver gains are required with the consequence of a poorer signal to noise ratio. In turn, an increase in the number of false alarms can result. Thus 100% coverage could be maintained at higher throughput speeds, but at the probable cost of more false alarms. Here also the defects detected could be double the size of the test notch as in Case I. Once again overdetection of defects with sizes below the standard notch would occur. Moreover, because of the longer beam length, as compared to the calibration notch length, the inspection system becomes more sensitive to long shallow surface scratches with depths less than that of the reference notch.

4.5 CASE IV

Finally Case IV shows the test approach using a beam length "BL" two times the notch length "NL". However the pitch "P" is set to one half the beam length or equal to the notch length. The result of this approach is essentially 200% surface coverage. Furthermore, throughout the time in which the notch is moving under the transducer beam, at least one signal with an amplitude of 100% FSH should be detected. Insured detection repeatability requires the alarm level to be set slightly below 100% FSH. As in Case III, the notch length is equal to one half the beam length. Once again this can result in a similar smaller percentage of reflected energy with the consequential need for higher receiver gains. However, the resulting lower signal to noise ratio is somewhat offset by the allowance of a higher alarm level. This means false alarms could be reduced below those which could be obtained under the conditions in Case III. Unfortunately at this 2:1 beam length to notch length ratio, large thin surface scratches can also be detected at the 100% FSH alarm threshold. This stems from the ability of the longer beam length to integrate the reflected energy from this type of surface flaw to produce a large enough signal for an alarm. Thus, detection repeatability can be plausibly achieved at the same speed as in Case II, but at an increased false alarm probability due to surface conditions.

At this point Case II positions itself as the optimal approach. Detection repeatability with a low probability of false alarms can be provided at half the maximum speed available to maintain 100% test coverage.

Once your optimal beam length is established, you can now determine the approximate material throughput speed for your ultrasonic test. Returning to Table 2, you will find throughput speeds related to beam length and rotational speed. You will also find information discussing a means to double your testing speed by using two transducers diametrically opposed. This approach requires you to use two transducers, each with the same beam length as selected in Case II. Then if you place them directly opposite each other in the rotational system, you can increase the throughput testing speed to twice that allowed with a single transducer for 100% coverage.

5. LIVING WITH THE DIFFERENCES BETWEEN PLANNED AND ACTUAL TEST RESULTS

Actually, the key is knowing and understanding the differences between ideal inspection expectations and actual test results. The intent of this information was not to paint a negative image for ultrasonic inspection. On the contrary, being armed with such knowledge enables you to address these problems and make your ultrasonic inspection system perform to its best. Keep in mind, that tube mills throughout the world are successfully using ultrasonic testing. Their success results from being knowledgeable about the inspection process.

Remember the prime reason for inspection is to prevent bad products from reaching your customers. High throughput speed can save time and thus money. However, if it allows defective material to reach your customer, the money saved by production speed will be greatly overshadowed by the money lost due to customer dissatisfaction.

5.1 CLOSING LIST OF ACTIONS WHICH CAN IMPROVE THE QUALITY AND PRODUCTIVITY OF THE ULTRASONIC INSPECTION PROCESS.

5.1.1 Material defects are distinctly related to each manufacturing process. Adequate knowledge of their characteristics will enable the optimal selection of reference notches appropriate for a good inspection.

5.1.2 Overtesting may improve the chances of finding occasional defects not normal to your particular manufacturing process.

5.1.3 Strip chart recorders can also aid in the detection of defects not normal for your process or that may be oriented differently than your selected calibration notches. The signal energy, returned from a defect, which is not oriented in the same reflection plane as the reference notch, may not be adequate to cross the alarm threshold. However some return signal energy normally does exist. These echo signals would appear on the strip chart recorder trace as an abnormal trace pattern. The operator, having observed this condition, can either retest or simply manually reject the tube.

5.1.4 Strip chart recorders can also aid the operators in developing their setup skills. If due to the cost of recording paper, it is preferable to not use the recorder continuously while production testing, it should still be seriously considered as an aid during setups and calibration. It provides a solid record of each final setup established before beginning each production test.

5.1.5 Continuously train and upgrade your operators' skills. As the operators grow in their knowledge of the system, the inspection process will continue to improve in efficiency. This will result in optimum performance.

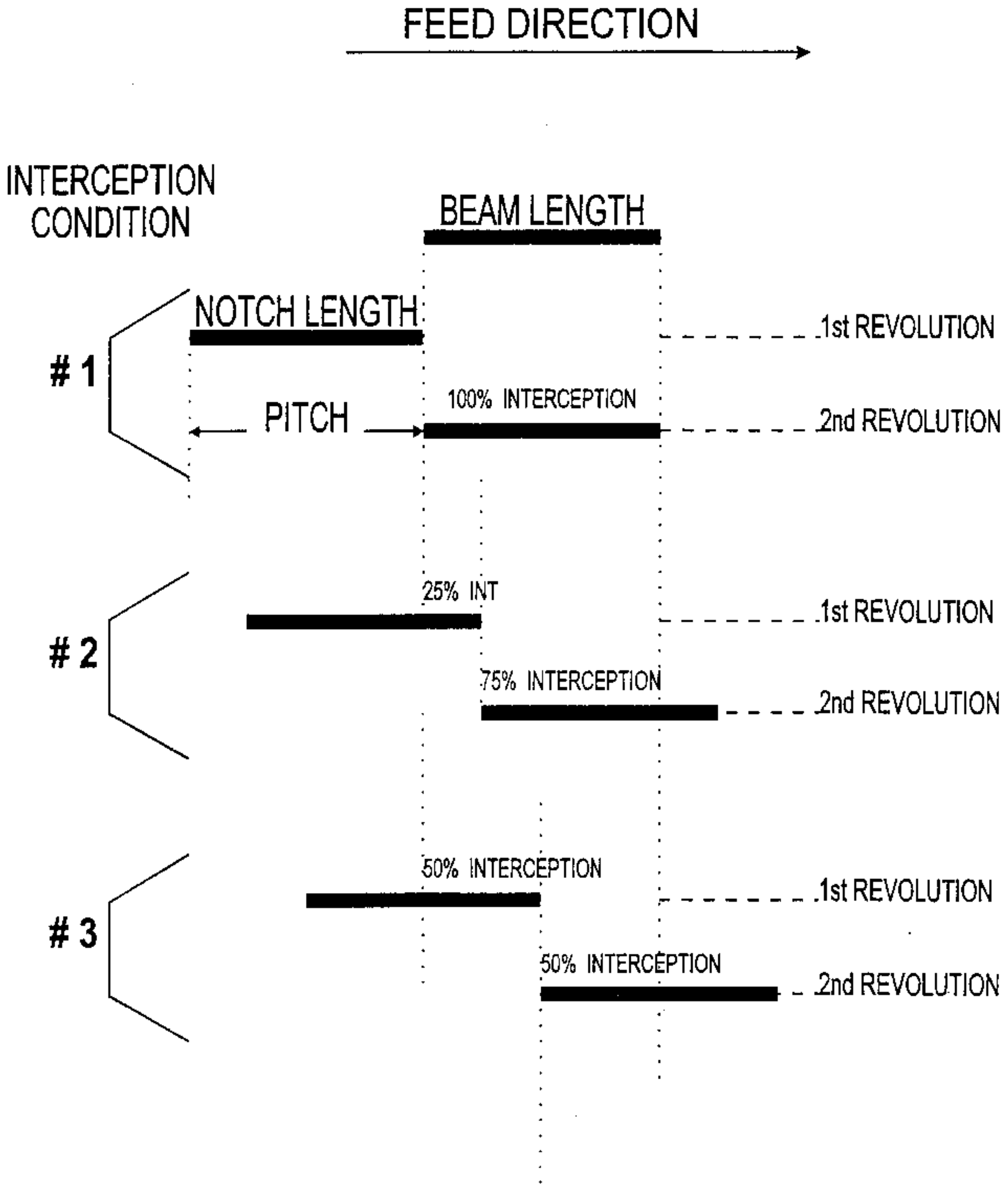
5.1.6 When the customer specifies small reference notches to obtain a tighter inspection, reduce the beam lengths. It may even be necessary to revert to spot focus beams. With a reduction in feed speed you will then be able to meet his requirement.

5.1.7 There is no one single transducer that will handle all of your different customer requirements. Establish an evaluation system to select different transducers which are more appropriate for different customer specifications.

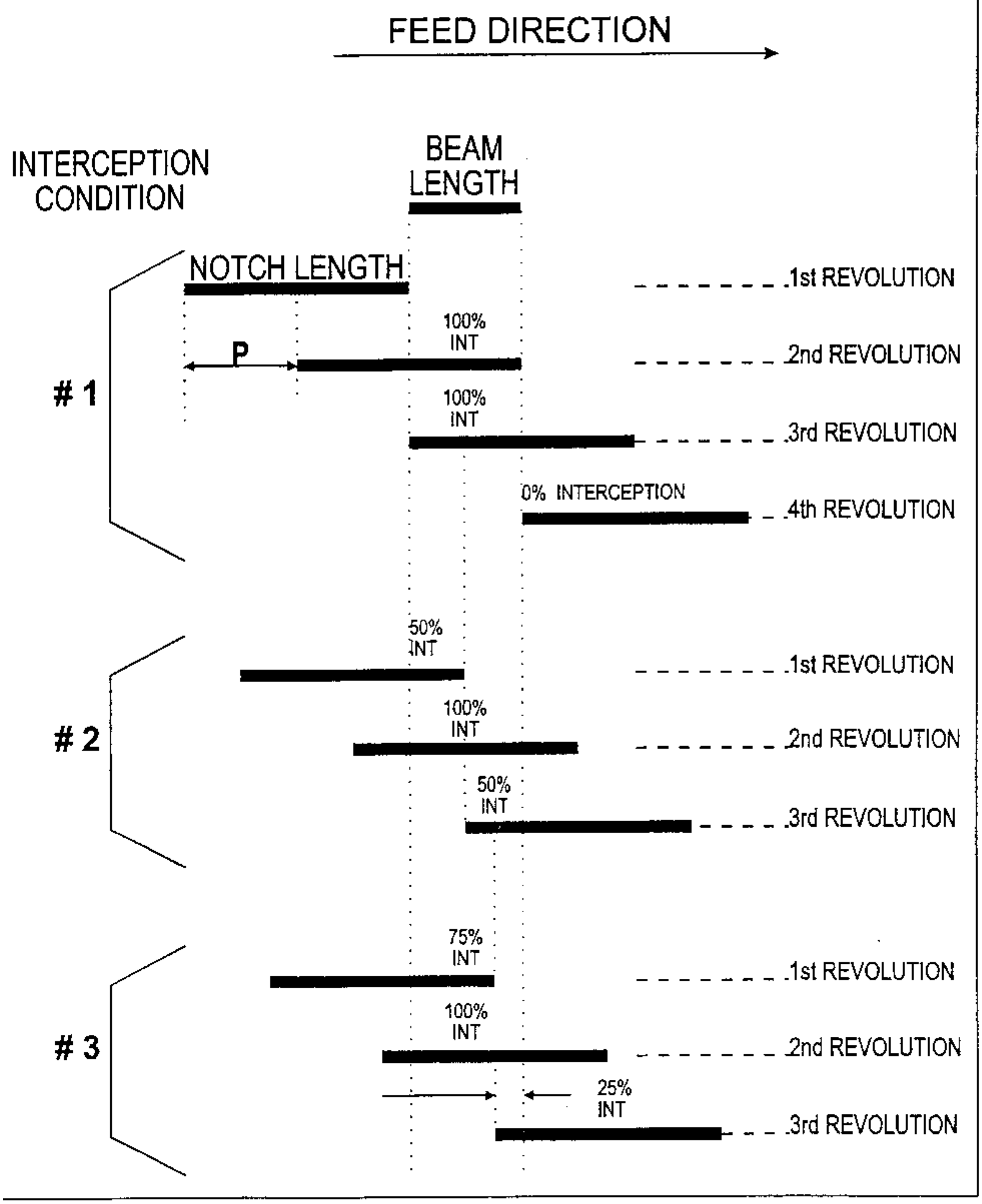
5.1.8 In addition to the standard calibration reference notches, add special "V" notches with an angle appropriate for use with your test shear wave angle. This enlarged setup target will speed up operator setup times by presenting a simpler target as the means of a first order setup. It also provides a better indication of having truly established the correct shear wave angle.

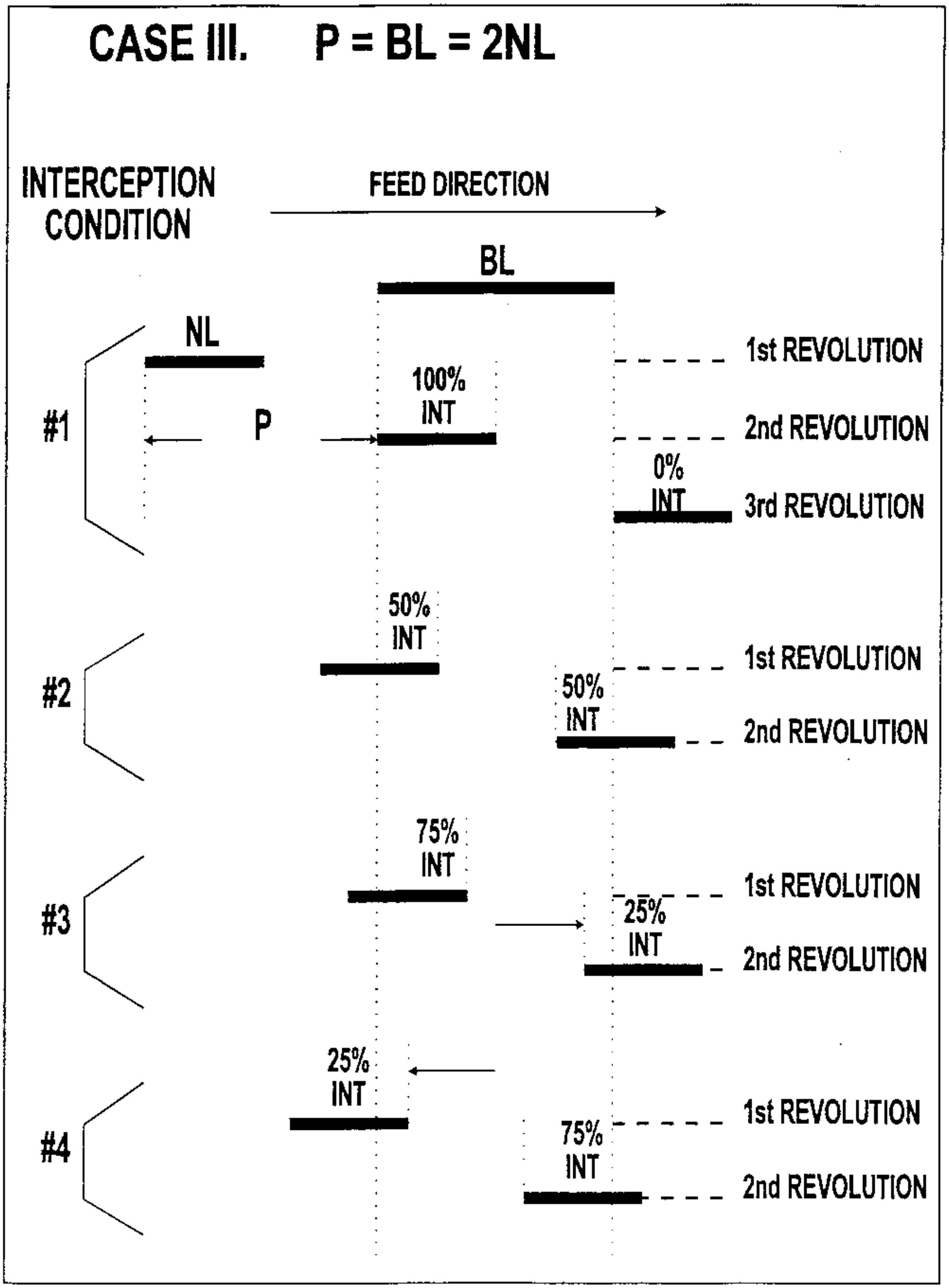
5.1.9 Back up your ultrasonic system with an "in line" NDT method such as eddy current or flux leakage. This can often allow you to undertest in some areas with UT while allowing a higher throughput speed without the loss of detection capability. The use of this form of synergism will add some initial costs to your inspection system. However, the costs may be recovered within a reasonable time frame due to the increased production test speed.

CASE I. BL = P = NL

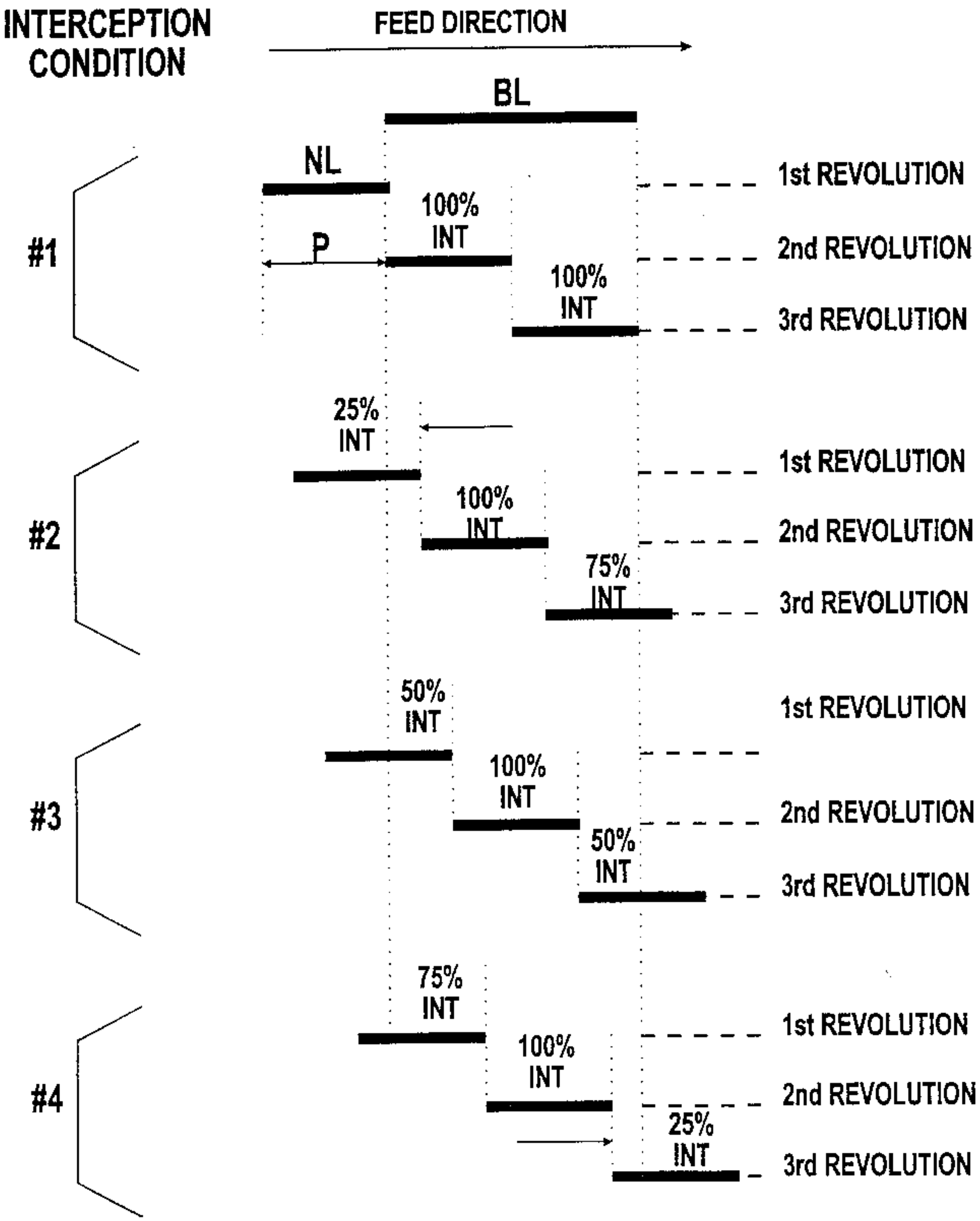

FEED DIRECTION
INTERCEPTION CONDITION
BEAM LENGTH
NOTCH LENGTH
1
PITCH
100% INTERCEPTION
1st REVOLUTION
2nd REVOLUTION
2
25% INT
75% INTERCEPTION
1st REVOLUTION
2nd REVOLUTION
3
50% INTERCEPTION
50% INTERCEPTION
1st REVOLUTION
2nd REVOLUTION

CASE II. BL = P = ½NL




CASE III. P = BL = 2NL
INTERCEPTION CONDITION
FEED DIRECTION
BL
NL
#1
P
100% INT
0% INT
1st REVOLUTION
2nd REVOLUTION
3rd REVOLUTION
#2
50% INT
50% INT
1st REVOLUTION
2nd REVOLUTION
#3
75% INT
25% INT
1st REVOLUTION
2nd REVOLUTION
#4
25% INT
75% INT
1st REVOLUTION
2nd REVOLUTION

CASE IV. BL = 2NL & P = NL OR P = 1/2BL



MODERN ULTRASONIC WALL THICKNESS MEASUREMENT SYSTEMS, FACTS & MYTHS

by Terry Banach*

Today, monitoring wall thickness has the potential to provide tube manufacturers with much valuable information. Most obviously, wall measurement can be used to insure that each tube shipped to the end user has a wall which is within the anticipated thickness limits. Welded tubing can be profiled to enable the producer to monitor the weld zone quality. Drawn and extruded tubing can be examined to determine its eccentricity condition.

Ultrasonics can provide the means to monitor these tube wall parameters. When coupled with additional parameter measurements, such as some form of OD measurement, even tube ID can be measured. Today, with the advent of low cost computers and powerful but user friendly software, ultrasonic thickness systems can be linked to this computing power to provide process system control. Such control systems can supply data which can in turn be used to manually or automatically remedy a straying process condition.

However, as with all techniques, ultrasonic wall thickness measurement has its limits and caveats. This article will discuss the basics of ultrasonic wall measurements. It will expose the reader to the facts about these systems as well as some of the myths held by wall thickness equipment advocates.

*Magnetic Analysis Corporation
535 South 4th Avenue
Mt. Vernon, NY 10550 - 4499
USA; Phone: 914-699-9450; Fax: 914-699-9837