Argonne National Laboratory

**NONDESTRUCTIVE INSPECTION OF
EBR-II FUEL-JACKET TUBING
USING ELECTROMAGNETIC TECHNIQUES**

by

**Thomas H. Busse, Donald R. Wood,
and Norman S. Beyer**

MASTER

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Special Materials and Services Division

May 1967

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I. INTRODUCTION

This report describes an inspection of approximately 136,000 ft of EBR-II fuel-jacket tubing conducted nondestructively using eddy-current techniques. The work was done by the Quality Evaluation Section of the Laboratory's Special Materials and Services Division. Although a complete description of the inspection equipment is included, emphasis is placed on various techniques in application of existing instrumentation to the inspection problem. Production details as well as the results obtained through the use of these techniques are included.

The object of the inspection is to eliminate all tubing that might prove detrimental when used for jacketing in the assembly of EBR-II fuel elements. Quality requirements specify that wall defects or localized reduction of wall thickness equal to or greater than 10% of the wall thickness are cause for rejection.

II. INSPECTION INSTRUMENTATION

The system of components used for the inspection of this tubing is shown in Fig. 1. The heart of the system is the Pulsed Eddy Current Flow

Fig. 1
Eddy-current Apparatus Used for Inspection of EBR-II Fuel-jacket Tubing

Detector in the lower central portion of the test bench. This detector produces pulses for the encircling inspection coil, which subsequently returns signals containing flaw information to the detector for further processing. Tubes undergoing inspection are conveyed through the encircling coil by the tubing conveyor on the bench. Flaw information emerges from the detector in the form of voltage pulses of various amplitude. These pulses or "signals" are directed to a penmotor recorder for display and interpretation. Inspection personnel use this permanent recording to precisely locate flaw areas along the tube itself and, following the test, to extract data for the statistical analysis of the results. The penmotor recorder is located at the right in Fig. 1. Also visible in the figure is the test bench, which allows convenient racking of the tubing. This provides a smooth flow of tubing and helps keep inspection efficiency high. In addition, the rubber-covered racks protect the delicate tubing wall from potential physical abuse.

The Pulsed Eddy Current Flaw Detector used for this examination is shown in the upper part of Fig. 2. It was designed by R. G. Myers,¹ formerly of the Laboratory's Metallurgy Division. Of general interest are several other systems,^{2,3} also developed at Argonne. The instrument shown in Fig. 2 has proven its capability in the detection of minute flaws, as will be further discussed later in this report. The power supply (shown in the lower portion of Fig. 2) was commercially available at the time of construction (June 1963); however, any power supply providing +500 V reg at 100 mA, +300 V reg at 200 mA, and 0 to -100 V reg at 5 mA, is sufficient. The supply must have 6.3 V ac for filaments, and because thyratrons are used in the flaw detector, it should have time-delayed high-voltage sections. A range of adjustability for the high-voltage sections on the order of $\pm 25\%$ may ease instrument setup and operation and is therefore desirable.

The basic theory of operation is more readily understood with the aid of the block diagram of Fig. 3. Top and bottom views of the Pulsed Eddy Current Flaw Detector (constructed by the Laboratory's Electronics Division) are shown in Fig. 4. The schematic diagram is shown in Fig. 5, to further assist anyone interested in specific details. A multivibrator consisting of a 12AU7A twin triode generates square waves and thus establishes the instrument's fundamental pulse-repetition rate. The multivibrator frequency is adjustable, and in principle the exact setting within the range of 2-3 kHz is not critical. The actual operating frequency was therefore set at 2.4 kHz, the 40th multiple of the power-line frequency. Although the multivibrator is not triggered by the power line, this frequency setting might help ensure long-term frequency stability.

Output from the multivibrator is used as a trigger to fire the coil driver circuit. This consists of the 884 and 502A thyratrons. The 502A drives large pulses of current through the excitation coil of the differential-type encircling coil at the established repetition rate.

150-451

Fig. 2. Pulsed Eddy Current Flaw Detector and Power Supply

150-444

Fig. 3
Block Diagram of Pulsed Eddy Current
Flaw Detector

150-452

Fig. 4. Top and Bottom Views of Pulsed Eddy Current Flaw Detector

Summing the outputs from the differential pickup coils produces very little output from a well-balanced encircling-coil assembly if the tubing specimen is homogeneous. The heterogeneous condition resulting from a flaw or other discontinuity will unbalance the electrical status of these two pickup coils, thus producing an output signal. This signal is amplified by one half of a 12AT7 twin triode and a 6AQ5A pentode.

The amplified signal is now rectified to provide an average dc level. This level is monitored by a 50- μ A meter in a bridge circuit consisting of two 12AU7A twin triodes. This meter is useful in achieving good balance of the encircling coil.

Any change in the dc level is further amplified by the 6BH6 pentode and the 12AU7A twin triode. A portion of this amplifier circuitry includes a filter network tuned to approximately 13 Hz. This frequency optimizes signals resulting from flaws conveyed through the encircling coil at a fixed velocity of 12 ft/min and minimizes the effects of tube noise that contains a multitude of frequency components. At this point, the signal is fed to the penmotor recorder. It is also further amplified by a 12AU7A twin triode and a 6AQ5 pentode. This amplifier contains the AUDIO THRESHOLD control, which determines the signal amplitude required to activate the alarm. The alarm consists of a marker relay and an alarm relay. The marker relay may be used to control external equipment such as a tube marker for flaw location, or an event marker on the penmotor recorder. The output of an audio oscillator, a 6Y6G pentode, is connected to the speaker through the alarm relay contacts. Any flaw that produces signals of amplitude greater than the audio threshold level, causes the instrument to produce a distinctive audio "beep."

Fig. 6. Exploded View of Differential-type Encircling-coil Assembly

The differential encircling coil should be thought of as part of the instrument. Each inspection coil is balanced and matched to a specific flaw detector, and coils are not interchangeable with other flaw detectors even if they are believed to be of identical design. The exploded view in Fig. 6 shows the basic elements of a coil assembly and the physical relationships between them. We might best describe the coil assembly by beginning with the tubing itself. In this instance, the tubing OD is 0.174 in. The tube specimen, inner coil form, and outer form all

fit together coaxially. The inner form is essentially a cylindrical nylon bobbin formed by drilling a 0.177-in.-diam (No. 16 drill) hole through a 2-in.-long, 0.5-in.-diam rod. Three slots, each 0.030 in. wide, are cut to a depth that leaves 0.015 in. of material surrounding the central drill hole. These slots are separated by $1/64$ in. The cylindrical outer form, with a 0.5-in. ID and a 1-in. OD, protects the delicate inner form and provides convenient mounting for electrical terminations, mounting brackets, etc. The longitudinal slot in the outer form permits the windings to be connected to these terminals.

Each of the three windings consist of 100 turns of No. 40 enameled copper wire. All three are wound in the same direction. The windings are held within the slots by the application of Q-Dope after the required 100 turns are completed. Each of the three leads coming from the innermost part of the coil are temporarily soldered together as shown at point A in Fig. 6. Temporary electrical connections are made to the flaw detector; i.e., pulse output to C, left input to B, and right input to D. With the instrument turned on and a short piece of tubing in the coil form, the meter indicates output from the coil as the result of an unbalance between the two pickup coils, B and D. Touching the wires should produce an audible beep if the audio threshold is not set too high.

The procedure at this point is to balance the two pickup coils as nearly as possible. Removing one turn from one of the pickup coils either raises or lowers the meter reading. Since balance is achieved with the lowest possible meter reading, the process of adding or subtracting turns to the appropriate pickup coil continues. A reading of less than 40% of full-scale deflection should be achieved in this manner. Bear in mind that after the coil is balanced, it will be inserted into the outer form, and all winding leads must pass through the longitudinal slot in the outer form. As the near-balance condition approaches, the leads may not be in the desirable longitudinal arrangement and it may be necessary to work with the lead from the opposite pickup coil as well. Once the lowest possible meter reading is achieved with all leads arranged to pass through the slot, the inner form is fitted into the outer form. The meter reading should be continuously observed during this fitting process to be certain that the balance is not inadvertently disturbed. The entire process is difficult and tedious, and work should proceed slowly.

In all probability, the coil will still not be optimumly balanced at this point. If the preliminary balance is satisfactory, however, the inner and outer forms should be locked together by means of the setscrew shown in Fig. 6. Also shown are the electrical insulators, which have been previously attached to the outer form. Winding leads should now be permanently soldered to the appropriate insulators. Permanent connections to the flaw detector can now be made using RG-62A/U cable. Final balance is achieved by shunting both pickup coils with a resistance and possibly some capacitance.

Resistors of about 500 Ohms are used to damp the coils from ringing. Slightly varying the value of one or both of these resistors should improve the balance. Once again, the lowest possible meter reading should be sought. In some cases, the balance can be improved further by shunting these pickup coils with some value of capacitance, on the order of from 5 to 50 pF. Resistance and capacitance values for this procedure are obtained solely by trial and error. Hopefully, a final meter deflection of about 20% of full scale will be achieved, for this is considered a "good" coil.

The usual procedure in finishing the coil assembly is to pot the electrical components within some form of mold. This will ensure a physically more rugged assembly. It should be emphasized that Fig. 6 is presented only as an example. Although several coils were constructed as shown,* several modifications could be made at the discretion of the builder. For example, the outer form need not be round, since a square shape may lend itself to easier mounting on the conveyor. Bringing the leads to BNC connectors rather than directly to the cables may be desirable. In fact, the coil assembly pictured in Fig. 1 includes a precision potentiometer as one of the balancing resistors, which allows precise balancing as well as experimental unbalancing.

Operation of the flaw detector is quite straightforward as evidenced by the minimum number of controls (see Fig. 2). Initially the power supply voltages are adjusted to the values indicated earlier. Precise setting of the audio threshold (if used) is made during the rigorous setup procedure discussed in Section III below. The instrument is used almost exclusively with the function switch in the OPERATE position. When the function switch is in the TEST position, the alarm amplifier is disabled and the meter sensitivity is doubled. This can be useful when the instrument meter is used to precisely locate a flaw in a tube. The OFF position disables the meter as well as the alarm (see Fig. 5).

During past operation of the instrument, inspection personnel have removed all power to the flaw detector after the normal day's work, applying power again the following morning. Under these conditions, average life of the 502A thyratron in the coil driver circuit was approximately 176 hr. Applying filament voltage and thyratron bias voltage continuously and turning only the high-voltage supply on and off each day extended thyratron life to approximately 1000 hr. Thyratron failure is characterized by the sudden appearance of stray "beeps" from the audio alarm, followed shortly thereafter by a zero reading on the meter. Total failure can be prolonged slightly by making the bias voltage less negative. A fresh thyratron should be operated at least 8 hr to assure continued stable operation. Aside from this thyratron replacement, the instrument is very stable with little change in performance over long periods of time.

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*Original coil assemblies used Micarta inner forms. Nylon has been substituted for longer wear, but has not yet been used as of this writing.

The conveyor system shown in Fig. 1 was specially designed here at the Laboratory for this application. Although its design is versatile enough to be used in other systems, specific features such as the 12 ft/min specimen velocity and its overall length, including many support rollers, make it particularly suitable to the inspection of the EBR-II jacket tubing. The conveyor drive motor imparts motion to the tubing through the two spring-loaded rubber drive rollers, one on each side of the encircling-coil assembly. Both spring-tension and drive-roller height adjustments are incorporated into the design. The reversible motor allows the tubing to be conveyed in either direction. The inspection coil is mounted on a small adjustable platform, which is attached to the conveyor. This arrangement allows accurate axial alignment of the coil to the tubing.

The penmotor recorder, also shown in Fig. 1, is a general-purpose instrument which has been slightly modified. Actual recorder requirements for this inspection system call for one channel (either rectilinear or curvilinear) with approximately 1 V/cm deflection sensitivity and a paper velocity of 5 mm/sec. A variable-input attenuator is desirable as will be explained in Section IV. Electric writing is not required. With the inspection system operating in a normal manner, a typical tube containing two flaws produced the penmotor recording shown in Fig. 7. The information contained in such a recording trace is discussed in more detail in Section III below.

150-446

Fig. 7. Typical Penmotor Recording of a Tube Containing Flaws

III. INITIAL INSPECTION SETUP

As stated in the specifications for inspection, tubing having discontinuities representing changes in wall uniformity of 10% or greater should be rejected. The fundamental goal in adjusting the inspection equipment is to ensure that this requirement is fulfilled. Ultimately, the absolute capability of any inspection instrument is a function of its design performance in relation to the present "state of the art." It is therefore necessary to determine the capability of this inspection system. We must be confident that 10% of wall flaws are indeed being detected if these flaws are cause for rejection.

Some systematic procedure must be established for the logical setup of this inspection system. The use of artificial defects for this purpose is quite popular. Notches, drill holes, and other artificial defects provide a convenient method of obtaining flaws of controlled dimension, which substitute for flaws that might occur naturally. The ability to duplicate these artificial "standards" with fairly high accuracy also attributes to their widespread use.

A second, and perhaps more difficult, approach was selected as a method to set up the equipment for this inspection. The method relies primarily on information obtained from naturally occurring defects to certify the actual capability of the system. In addition to evaluating the true system performance, this method provides some insight to the relationships between the instrument response and naturally occurring defects. During the actual production inspection, the instrument response alone, for the most part, will determine the rejectability of a flaw. Ideally, then, some correlation should be established between the maximum depth of a flaw and the instrument response to it. Establishing such a correlation is the crux of the entire setup problem. Instrument response is a function of many factors, flaw depth being only one. Analysis of many naturally occurring flaws provides useful information for selecting reject levels with regard to signal amplitude. In addition, the nature of the flaws that might be expected to occur in the production inspection is revealed. Such information could conceivably point up manufacturing-process weaknesses, which could be corrected at an early stage. Detection of surface erosion as a result of improper pickling might serve as an example.

Initially, the flaw detector and recorder are adjusted to provide an indication of the tube noise. This is typically represented in Fig. 7. At this point, the procedure begins with the inspection of a quantity of tubing that has been randomly selected from the total production quantity. This is not always possible, but the goal nevertheless is to analyze a representative sample of the total population of tubing to be inspected. In practice, the sample used for setup will probably be taken from the first 10 to 20% of the production quantity. As a result, statistical calculations concerning

predictions of reject rate, average tube noise, and other numerical data will only apply to the actual batch of tubing being sampled. A change in manufacturing performance at a later date can produce marked changes in the inspection results with no indication of this in the early sample.

With this in mind, a sample is taken from the largest quantity of tubing available. Good results can be obtained with sampling quantities of 1000 ft.⁴ While the sample is being inspected, which should be done without interruption, one or more tubes are removed and retained as performance "reference tubes." Ideally, each reference tube should contain a small, medium, and large flaw indication. These reference tubes are used to keep the instrument adjusted to the same level of performance throughout the inspection. The sample tubing and the respective recordings should be handled carefully so that any tube can be matched to its recording at a later time. Some numbering and/or marking system should be used.

Upon completion of the sample inspection, the recordings will probably contain approximately 30 to 275 flaw indications. The search to determine what caused these indications is best accomplished by a destructive metallographic analysis. This is a time-consuming process, so probably not all the flaws as indicated on the recordings can be analyzed. The real question becomes: What is the smallest signal amplitude in response to a flaw that is 10% of the wall or greater, in depth? The smallest signal, regardless of what caused it, is one that is just above the average peak noise of all the tubes. If the noise is very high, small signals could be masked by it. The metallographic analysis would logically begin, then, with those flaws that produced signals that are reasonably small, yet clearly above the noise. One method of locating the flaw on the tube is to use the scaling factor between the specimen and paper velocities. For OD flaws that are visible under magnifications of 10 to 30X, this method of location is often adequate. In the preparation of flaw samples for metallographic examination, the procedure is to try to locate the flaws under this low-power magnification so that they can be marked as precisely as possible.

Often, defects are not on the OD, and an improved method of locating them would be helpful. One procedure has been used successfully; however, extra care is required to effect the desired results. From the coil description earlier in this report and Fig. 6, in particular, a heterogeneous tubing condition in the region of one pickup coil as compared to the other coil will disturb the electrical balance and thus alter the "summed" output of the coil assembly. Using the scaling factor method just outlined, the flaw area is placed into the center of the coil assembly. With the conveyor motor off, the tube is moved slowly back and forth by hand. As the discontinuity passes through the coils, the meter on the flaw detector dips slightly for one pickup coil and rises slightly for the other. As the flaw passes from one pickup coil to the other, the meter swing should go from one extreme to the other quite rapidly. With the Pulsed Eddy Current Flaw

Detector function switch in the TEST position, the swing of the meter is exaggerated, making it easier to read. Stopping the tube at midpoint in this swing should place the discontinuity directly under the center excitation coil. If this coil is midway between the ends of the coil form or assembly, the tube can easily be marked at each side of the coil. Halfway between these two marks should be an accurate indication of the flaw location.

If no defect can be observed in the immediate vicinity of this location on the OD, the tube is cut at approximately $1/2$ in. on both sides of the flaw area. This allows observation of the ID under low-power magnification. Often the actual flaw is located in this way, and its exact location is marked on the OD with ink for the metallographer. If the flaw is not visually observed, the ink mark is placed at the location indicated by the Pulsed Eddy Current Flaw Detector. All observations and suspicions are also passed on to the metallographer.

The primary purpose of the metallography is to determine the actual maximum depth of each specific flaw. With this information, the individual setting up the inspection equipment uses his discretion in determining which indicated flaws will be further analyzed. He must continue the process until he finds at least one and hopefully several flaws, with depths of 10% of wall or less, which have occurred naturally and may reoccur during the production inspection. Careful attention to the instrument response is important, since he must also be satisfied as to the minimum-amplitude signal for these 10% of wall flaws. Predicting how many flaws should be analyzed is difficult. Based on past experience, 20 flaws might be a reasonable number to provide a fair cross section of the various flaw types.

Flaw depth is only one of many factors that determine the signal amplitude in response to a defect. By virtue of the inherent design characteristics of a differential-type coil, some flaws of considerable depth could conceivably pass through the coil without detection. For example, in a low-noise tube a void which was 26% of the wall in depth was metallographically examined and produced a signal that was just equal to the average peak noise of the batch. Had the average noise of that tube been higher, the signal, and consequently the defect that caused it, would have been passed off as inconsequential. This is unfortunate, but foolproof flaw-detection systems do not exist. In fact, the purpose of this entire setup procedure is to precisely determine the capability of the inspection system, and a knowledge of its shortcomings is of great importance. This example indicates that the safest inspection with this system can only be achieved if all signals above the tube noise are rejected. On the other hand, examples could be cited where flaws with depths of less than 10% of wall were responsible for signals with amplitudes considerably higher than the tube noise. How frequently these situations might occur is a reasonable question. Answering it accurately requires an unreasonable

number of metallographic samples. Ultimately, in setting up this equipment, we are trying to determine what signal amplitude constitutes the proper reject level. What is the probability of passing flaws for various reject levels?

A flaw can be defined as any discontinuity that produces a signal above the noise. Signals masked by the noise are meaningless because there is no way of dealing with them. By this definition, a flaw's depth may or may not be equal to or greater than 10% of the wall thickness. Determining the ratio of flaw depths above and below 10% of the wall has not been attempted because of the unreasonable amount of work. The theoretical maximum probability of passing flaws for a specific signal amplitude or discriminator level can be defined as the ratio of the number of signals passed to the number of unit lengths passed. For example, if the tube noise was 4 mm of recorder-pen deflection, and the discriminator level was set at 6 mm, all flaws producing signals between 4 and 6 mm would be passed. If the usable or unit length of the tubing was 18 in., as it is for EBR-II fuel-pin jacketing, then the number of 18-in. lengths passed, i.e., containing no signals above 6 mm, would be counted. If 100 acceptable 18-in. lengths contained nine signals of less than 6 mm, the maximum probability for passing signals and thus flaws as defined earlier, would be 9 divided by 100, or 0.09. Under these conditions, then, every 100 acceptable 18-in. lengths could theoretically contain nine flaws with depths equal to or greater than 10% of the wall. This is the worst possible condition and is not likely to occur.

150-447

Fig. 8. Probability of Accepting Flaws as a Function of Discriminator Level

The maximum probability of passing flaws can be determined for various reject or discriminator levels directly from the sample recordings. This probability for a sample of 200 18-in. lengths (300 ft), taken from 13,884 ft is shown in Fig. 8.* The plotted curve of the data shows that the confidence in the inspection falls off rapidly as the discriminator level is raised above the noise level. Clearly, the tube noise is largely responsible for the ultimate confidence level that might be achieved. Tube noise is the result of many factors. Past experience has indicated the predominant factor to be a combination of minute nicks, scratches, dents, and other surface irregularities. Singularly, these defects are of little or no consequence, but quite often they occur in clusters which may be detected as a larger singular flaw. Careful manufacture and handling of this tubing

*This tubing sample was taken from the production inspection discussed in Section IV below.

can keep this surface noise to a minimum. It should be re-emphasized that flaw signals masked by tube noise cannot be discriminated against.

Because the information obtained from such a sample is representative of the entire batch from which it came, fairly accurate predictions can be made concerning that batch. If the manufacturing process is consistent from batch to batch, as it should be, these predictions will be valid for the entire production quantity. For example, the level of tube noise for the sample should be the same as that for the batch. The number of signals and their mean amplitude can be predicted. Reject rates of the sample for various discriminator levels can be predicted. A reject rate of 27% was predicted for a specific batch. The actual reject rate after the batch was inspected was 26.3%, an error of only 2.7%. The entire production quantity consisted of five batches with an actual reject rate of 22.5% for all five batches. Based on the original prediction of 27%, the prediction error was 16.6%.*

The instrument setup procedure as outlined thus far should give a clear indication of the system capability as well as some insight as to the actual tubing quality. In this manner, the flaw detector and associated equipment described earlier have clearly demonstrated their ability to detect naturally occurring defects whose depths are equal to or even less than that called for in the specifications. The photomicrographs in Fig. 9 were approximately 8, 7.7, 6.6, and 4.3% of the wall and had pen deflections of 16, 15, 5, and 6 mm, respectively.

The discriminator level to be used for the production inspection can be selected at this point. From the standpoint of highest inspection confidence, the discriminator level should be set at the recurrent peak noise level. We cannot change the fact that rejectable flaws can and do occasionally produce signals that are masked by the noise. On the other hand, with the discriminator at this level, the slightest increase in noise level can make the reject rate intolerable. The final decision becomes a matter of economy versus inspection confidence. In terms of rejected tubing, what price are we willing to pay for the highest possible assurance that a minimum number of rejectable flaws will inadvertently be accepted? Reject rate of the tubing sample for various discriminator levels could easily be plotted from the recording data. Such a curve in conjunction with the curve of Fig. 8 would place the two factors clearly in perspective. Application of this jacket tubing has been considered critical enough to merit not only a 100% inspection but an inspection at the highest confidence level. Therefore, the actual production inspections discussed in Sections IV and V were made with the discriminator level set just above the noise level. If the audio alarm incorporated into the flaw detector is used, the AUDIO THRESHOLD control is adjusted so that any signal above the selected discriminator level will cause the alarm to trigger.

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*Reject information was taken from the production inspection discussed in Section IV below.

A (No. 16)

75X

B (No. 61)

140X

C (No. 62)

140X

D (No. 63)

140X

150-440

Fig. 9. Flaws with Depths Less Than 10% of Wall, Which Were Detected by the Pulsed Eddy Current Flaw Detector.

The setup procedure as outlined may appear rather complex and involved. Generally speaking, this has to be done only once. With the true capability of the instrument established, it does not need to be re-established when another job is set up. However, if the differential coil or the tubing material was changed, then we would need to re-establish that the system is capable of meeting the inspection requirements.

Because much of the setup procedure yields information about the quality of the tubing and provides data for making predictions of relative importance, the procedure was expanded for the evaluation of several tubing lots. The purpose of the evaluation was to examine three lots of tubing from an equal number of vendors for the purpose of selecting a vendor to supply tubing in a larger quantity at a later date. The lots being examined were not random samples of production tubing, but all three lots were being evaluated on an equal basis. The first batch of production tubing shipped from the successful vendor was sampled and compared to the evaluation lot. Many of the tubing quality "indicators" brought out by the setup procedure compared favorably. Both samples were 900 ft in length, and 90 flaw indications or signals were counted for the evaluation sample as compared to 83 signals for the production sample. The number of 18-in. sections displaying flaw signals were 74 and 66, respectively. The mean amplitude of all signals present was 5.25 and 4.50 mm, respectively. These comparisons indicate that the overall quality of the production sample is somewhat better than the evaluation sample. This is especially evident in the recurrent peak-noise figures, which were 3.60 mm for the evaluation sample and 2.54 mm for the production sample. This might be explained by the extra handling required in the manufacture of a small quantity of tubing. For each sample and also for the production inspection, the discriminator level was 4.0 mm. The actual reject rate for the evaluation sample was 12.3%, as compared to 11% for the production sample. The 11% becomes a prediction of the reject rate for the total production quantity, barring any changes in manufacture. With 48,000 ft inspected before a known change (change in heat) occurred, the actual reject rate was 9%. This represents a prediction error of approximately 18%. On the other hand, the production batch that was sampled was 11,644 ft and had a reject rate of 10.7%. Here the 11% prediction was in error by 2.7%.*

One other interesting observation can be made concerning location of flaws. A reasonable number of flaw signals are randomly selected from the initial sampling quantity. As in the preparation for metallographic analysis, under low-power magnification the location of the various flaws is hopefully determined. Twenty flaws from the evaluation sample were observed visually, and approximately 70% appeared on the OD, 20% appeared on the ID, and 10% could not be observed. In comparison, the production sample had 81% on the OD and 6% on the ID, and 13% could not be observed for a total of 16 observations. Several of the flaws from the evaluation sample were metallographically examined. Figure 10 shows some of the typical flaws encountered.

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*Reject information was taken from the production inspection discussed in Section V below.

A (No. 41)

200X

B (No. 43)

100X

C (No. 45)

100X

D (No. 46)

100X

150-442

Fig. 10. Typical Flaws Encountered While Evaluating Tubing for Selection of a Vendor

IV. FIRST EXAMPLE OF A PRODUCTION INSPECTION

With the inspection system adjusted according to the procedure outlined in Section III, approximately 57,000 ft of tubing was inspected for flaws. About 43,000 ft of this was welded tubing, the remainder being seamless. As discussed in the setup procedure, specifications called for tubing containing discontinuities of 10% of wall or greater to be rejected. Comparative analysis between the seamless and welded types failed to reveal any significant difference in the response characteristics of the Pulsed Eddy Current Flaw Detector. Tubing dimensions and material being identical, this might well be expected. In the course of setting up for this inspection, several flaws were carefully examined metallographically. Figure 11 shows four of these, representing typical flaws encountered.

Although the inspection setup is by far the most difficult part of the job, definite considerations must be made with regard to the physical task of inspecting the tubing. The work involved is not generally regarded as challenging; however, inspection personnel must use good judgment concerning instrument adjustments and data interpretation. Because of the critical application of this tubing, conscientious individuals must be selected to perform the work.

The conveyor system determines the theoretical maximum rate at which tubing can be inspected. In this instance, specimen velocity is set at 12 ft/min, allowing for a maximum of 720 ft/hr. In practice, this figure is substantially reduced to approximately 175 ft/hr. There are many reasons for this reduction. Each tube was conveyed through the coil twice, once in each direction. This alone cut the production rate by more than a factor of two. Much of the setup procedure established earlier evolved out of the setup for this job. At that time, we discovered that a flaw could escape detection while passing through the coil in one direction yet show up in the other direction. Not knowing how often this condition might occur, we decided to inspect the tubes in each direction to retain a high level of inspection confidence.

Once a flaw was detected and located on the tube, the flaw area was crimped with an ordinary pair of pliers. Mutilating the bad portions of the tubing in this manner provided a foolproof method of preventing accidental usage of any tubing section containing a flaw. A simple scale was constructed, which, when placed next to a tube recording, would show (in inches from either end of the tube) the location of any flaw. A ruler or scale attached to the inspection bench aided in the rapid location of these flaws along the tube. This crimping process also contributes to the total reduction in the rate at which the tubing is inspected.

At the time of this inspection, the test-bench tubing racks shown in Fig. 1 did not exist. As a result, physical handling of the tubing was somewhat slow and cumbersome. In fact, production is slowed by a long list of

A (No. 8)

90X

B (No. 11)

100X

C (No. 17)

100X

D (No. 18)

60X

150-443

Fig. 11. Typical Flaws Encountered during Inspection of 43,000 ft of Tubing

incidentals, which include: receiving and unpackaging of tubing, keeping the recorder supplied with ink and paper, inspection-system adjustment and maintenance, record keeping, ordering of supplies, shipping of completed tubing, and interruptions to inspection personnel.

The inspection required approximately 1200 manhours to complete. Since this was spread over $10\frac{1}{2}$ calendar months, equipment performance remained rather stable during this period. During this inspection, thyatron failures in the Pulsed Eddy Current Flaw Detector became a problem. Once corrected, as explained in Section II, the instrument proved to be quite reliable. Because the inspection was being done reasonably close to heavy machinery, electrical disturbances on the power line were at times rather troublesome. Arc-welding equipment, for example, was responsible for noise transients on the power line, which were difficult to suppress. As a result, erroneous flaw information would be recorded. These signals would be observed and screened out in the process of inspecting the tubes one or more times in each direction. Occasionally these erroneous signals would appear while no tube was in the inspection coil, quickly alerting the inspector to the presence of this condition. This condition further contributes to inspection slowdown.

Although not specifically a part of the eddy-current inspection, samples of tubing were periodically submitted for chemical analysis. A sample, consisting of a short length of tubing, which is properly identified, marked, and recorded, was prepared after approximately every 2000 ft of inspected tubing. For the welded tubing, metallographic samples were also prepared on a periodic basis for analysis of weld-zone quality. Preparation of these samples also subtracts from the time that may be devoted to the actual inspection.

There was only one serious problem during the inspection. When approximately 46,000 ft of tubing had been inspected, the differential inspection coil wore out. With tubes being inspected in each direction, the coil had actually endured more than 92,000 ft of tubing. Since only 0.015 in. of Micarta separates the tubing from the actual coil winding, the coil life is limited by mechanical abrasion. Coil life is largely a function of the tubing surface condition. Besides the noise evident in the penmotor recordings, noisy tubes also have a more abrasive effect on the coil assembly.

The main problem at this point was time. Construction of a new coil assembly could require approximately 2 weeks. For a new coil assembly, the system capability would have to be re-established to verify that the required performance level was still being maintained. With these delays, the required completion date for the inspection could probably not be met. Examination of the worn coil revealed that the coil windings were exposed to the ID of the assembly. Further examination revealed that the coils

were still electrically intact since no windings were opened or short-circuited. In view of these findings, we decided to attempt a repair of the worn coil assembly.

A Unimat lathe was used to align the worn coil assembly and the proper size drill coaxially with the utmost care and precision. With this arrangement, the rotating drill could be passed through the coil assembly. Checks for electrical continuity between the rotating drill and the coil leads verified, to some extent, that the drill was not in contact with the coil. At this point, the coil was "backed" away from the drill and completely filled with an epoxy. After the epoxy had fully cured, a hole was drilled through it leaving approximately 0.015 in. of epoxy where the Micarta had worn away. The repaired coil assembly was again installed on the conveyor. Eddy-current inspection of the performance reference tubes indicated that the electrical performance of the coil had not changed and therefore the coil restoration was successful. With the inspection of the remaining 11,000 ft of tubing using the repaired coil, the entire tubing quantity was completed within the required time period.

Since the coil-to-tube distance decreases as a result of coil wear, the amplitude of the flaw-detector signal increases accordingly. Flaw-detection characteristics do not seem to change; there is only a gradual increase in amplitude of all signals. This effect of coil wear is easily compensated for by attenuating the signals to be recorded by an amount equal to the amplitude increase. A recorder having a variable-sensitivity control or input attenuator is ideal for making this adjustment. Once again, the reference tubes are used as the source for signals in compensating for coil wear.

With regard to reject rate, results of the completed inspection were mentioned briefly in Section III. The inspection results are summarized as follows:

Quantity of welded tubing inspected	42,984 ft
Quantity of seamless tubing inspected	13,925 ft
Total reject based on 18-in. lengths (welded)	22.48%
Total reject based on 18-in. lengths (seamless)	28.83%
Total time required for inspection	1,268 manhours

V. SECOND EXAMPLE OF A PRODUCTION INSPECTION

In many respects, the second inspection was identical in nature to the first example cited in Section IV above. Tubing application, dimensions, and defect specifications were all identical, as was the inspection equipment. A newly constructed and balanced coil assembly was substituted for the repaired coil. Eddy-current response to the original performance

reference tubes indicated that the flaw-detection characteristics of the new coil were very close to those of the repaired coil. As a result, minimal effort was required to re-establish that the inspection system had retained its capability in meeting or even exceeding inspection requirements. Metallographic analysis of several flaws also indicated what types of flaws might be encountered during the production inspection. Typical defects are shown in Fig. 12.

This inspection involved approximately 80,000 ft of tubing, all of which had seam welds. To keep the tube surface noise at a minimum, the tubing manufacturer shipped all tubes individually wrapped in protective paper. In addition, tube ends were plugged for protection and to keep foreign material from the ID. These precautions were beneficial, but unpacking proved to be quite time-consuming. Instead of crimping bad portions of tubes containing flaws, all defect areas were physically cut out of the tube. The defective tube sections were reboxed to be returned to the tubing manufacturer. This removal of flaws further slowed inspection of the tubing.

Despite these factors, inspection rates for this job were considerably higher than those for the previous job, averaging approximately 300 ft/hr. This increase over the 175 ft/hr for the first job is attributed mainly to the fact that most tubes were inspected in one direction only. Experience gained through prior inspections indicated that the actual probability of passing a flaw that is detectable in one direction only is so low that the cost of inspection in both directions is not justified. However, tubes that displayed defect signals after one pass were inspected in the opposite direction to verify that such signals were not the results of noise transients on the power line. Therefore only tubes that were good from end to end on the first pass were inspected just once and accepted as good.

The tubing was racked as shown in Fig. 1. This arrangement contributed greatly to the ease with which tubing could be inspected efficiently. Since most tubes were 9 ft long, requiring 45 sec to inspect in one direction, it was generally possible to remove flaws from the previous tube and be ready to handle the next, before the time fully elapsed. Since tubes containing flaws were inspected again in the opposite direction, there was an additional 45 sec to locate the defects using the scale described in Section IV.

Equipment performance during this inspection was for the most part equal to that of the previous example. There was no change in the failure rate of the thyratron in the flaw detector. One of the 12AU7's in the meter circuit failed, but this was considered a normal failure. Trouble also developed in the power supply, and it became impossible to maintain 500 V at the output of that portion of the supply. Through routine troubleshooting procedure it was determined that the biasing resistor of the

A (No. 52)

150X

B (No. 54)

150X

C (No. 67)

140X

150-441

D (No. 71)

100X

Fig. 12. Typical Flaws Encountered during Inspection of 48,000 ft of Tubing

regulator control amplifier had changed value. Replacing this resistor restored the power supply to its original operating condition. The precise reason for the resistor failure has not been determined.

As indicated briefly in Section III, 48,000 ft of tubing was inspected before the vendor began supplying tubing manufactured with a different heat treatment. This change resulted from an inadequate supply of raw material with the original heat. As a result, long delays occurred before resumption and final completion of the inspection. Because of the dissimilar qualities of the two heats, this report covers only the first 48,000 ft. Most of the information and all predictions concerning reject rate based on previous tubing samples do not apply to tubing manufactured with the new heat treatment. The inspection results for the first 48,000 ft are as follows:

Total reject rate based on 18-in. lengths	9%
Approximate total time required	850 manhours

VI. CONCLUSION

Approximately 140,000 ft of tubing has been inspected, within about two and a half years, using the equipment and techniques described here. Long-term equipment performance may generally be regarded as very good. Equipment component failures detailed in this report were all minor, the resultant downtime being minimal. This is significant because a routine preventive maintenance program for the inspection system was virtually nonexistent. Before each major inspection, the system received a thorough maintenance check. This consisted of cleaning and lubricating the conveyor system, adjusting and lubricating the recording instrument, and a general check of the performance of the Pulsed Eddy Current Flaw Detector. Any obvious discrepancy in the operation of the Flaw Detector could also be corrected at this time; however, precise performance characteristics were considered more thoroughly during the inspection setup.

Based on the life of the inspection coils for the two jobs cited in Sections IV and V, it was concluded that coil life in general is about 90,000 ft, this being the total footage actually passed through the coil. Since many factors control coil wear, such as coil-to-tube alignment accuracy and tubing surface roughness, this figure should be regarded only as a rough prediction. Remember also that this information is based on the use of Micarta as the inner coil-form material. Information regarding wear on the coil form using nylon, as advocated in Section II, is not available at this time, but the use of nylon should provide a much longer coil life.

The objectives for these inspections have been clearly presented in the initial specifications. Retrospectively, we may conclude that these

objectives have been met. At least there is no knowledge of component failures as a direct result of shortcomings in the eddy-current inspection. Of the thousands of feet of tubing inspected, in only one instance have we passed a detectable flaw that should have been rejected. The most likely explanation to this is that of human error, and other such oversights may have occurred which escaped later detection. However, this type of hazard is always present in any inspection. The conclusion of primary importance is that this inspection equipment and technique can detect naturally occurring flaws of the specified depth. This knowledge, coupled with the fact that on this basis significant quantities of tubing have been rejected from all the inspections to date, indicates that many serious flaws might have been incorporated into reactor fuel assemblies without this inspection.

In each inspection, all tubing had been previously 100% eddy-current inspected by the manufacturer. This not only confirms the need for this second more critical inspection, but the reject rates point up an obvious need for improved primary inspections. We would suppose that both inspection equipment and technique could be improved; however, this is surmised on the basis of our inspection results and not on an analysis of the inspection operation of the tubing vendors.

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REFERENCES

1. Personal communication with C. J. Renken of the Metallurgy Division, Argonne National Laboratory.
2. Renken, C. J., Progress Report on Nondestructive Testing by Electromagnetic Methods, ANL-6414 (July 1962).
3. Renken, C. J., A Pulsed Electromagnetic Test System Applied to the Inspection of Thin-walled Tubing, ANL-6728 (Mar 1964).
4. Wallis, W. Allen, and Roberts, Harry V., Statistics: A New Approach, The Free Press, MacMillan Co., New York (1956).