**Analysis of Various NDT
Techniques to Determine Their
Feasibility for Detecting Thin
Layers of Ferrite on Type 316
Stainless Steel**

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September 1978

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**Pacific Northwest Laboratory
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ANALYSIS OF VARIOUS NDT TECHNIQUES
TO DETERMINE THEIR FEASIBILITY
FOR DETECTING THIN LAYERS OF FERRITE
ON TYPE 316 STAINLESS STEEL

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SUMMARY

A study was undertaken in order to determine the applicability of various NDT techniques for detecting thin layers of ferrite on type 316 stainless steel cladding. The ability to detect sodium-induced ferrite layers on fuel pins would allow an experimental determination of the fuel pin temperature distribution. The research effort was broken down into three basic sections of evaluation. Phase one consisted of a theoretical determination of the ferrite detection potential of each of the proposed NDT techniques. The second phase consisted of proof-of-principle experiments on the techniques that passed phase one. The third phase consisted of in-hot cell testing on actual EBR-II fuel pins.

Most of the candidate techniques were eliminated in the first phase of analysis. Four potential techniques passed the initial phase of analysis but only three of these passed the second analysis phase. The three techniques that passed the proof-of-principle section of analysis were a heat tinting, magnetic force and electromagnetic techniques. The electromagnetic technique was successfully demonstrated on actual fuel pins irradiated in EBR-II in the third phase of analysis while the other two techniques were not carried to the hot cell analysis phase.

The results of this initial technique screening study indicates that an electromagnetic and/or heat tinting ferrite layer NDT technique should be readily adoptable to hot cell inspection requirements. It was also concluded that the magnetic force technique, while feasible, would not readily lend itself to hot cell fuel pin inspection.

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1.0 INTRODUCTION

This report presents the findings of a ferrite surface layer detection study sponsored by the Fuels and Control Subdivision of HEDL. The study was initiated by R. J. Jackson, Manager of the Assembly Design and Performance Group, and was conceived as an initial analysis of multiple potential ferrite detection techniques to determine their detection capabilities and the feasibility of using them remotely in a hot cell.

A thin layer of ferrite (10 microns or less) is formed on 20% cold worked type 316 stainless steel fuel cladding during long term exposure to liquid sodium. It is thought that this layer is the result of selective leaching of elements such as Cr and Ni from the austentic surface, thus changing the chemical composition of a finite surface layer enough to result in a phase transformation from austenite to ferrite. The temperature regime under which this takes place is in the range of 565 to 705°C⁽¹⁾. The exact temperature at which ferrite begins to form is a function of liquid sodium exposure time and initial composition of the cladding.

Experimental results from unirradiated sodium loop tests and post irradiation examination of fuel pins from EBR-II have defined the ferrite formation temperature regime. The position where ferrite formation initiates on a given fuel pin can be used as a direct indication of temperature as the exposure time and cladding composition would be known. Therefore a technique for physically locating areas where ferrite has formed on a given pin would be useful for determining the mean surface temperature distribution of LMFBF fuel pins.

The primary objective of this study was to identify a nondestructive ferrite layer detection method(s) that would allow the surface distribution of the ferrite to be determined on a large number of drivers on a production basis. A secondary objective of this study was to assess the possibility of developing quantitative ferrite measurement techniques that would be suitable for detecting the ferrite layer thickness on a production basis. This study consisted of evaluating the applicability of various nondestructive testing methods for detecting a thin layer of ferrite on fuel pins. All recommended detection methods also needed to be suitable for use in a hot cell.

The effort was broken down into three basic analysis sections. In the first section various techniques were theoretically analyzed to determine if they had the potential to detect the presence of the ferrite layer. The techniques that passed this initial procedure were then subjected to limited proof-of-principle experimental testing in the second section. In this section of the study the experimental screening was carried out on one of three types of simulated fuel pin specimens. The first type consisted of sections of unirradiated fuel cladding that were elctroplated with pure ferrite to provide mock fuel pins. The second and third type had sodium-induced ferrite layers on their surfaces. Both were obtained from sodium loop materials, and included a 3.2 mm diameter type 316 stainless steel support rod and 1.27 cm I.D. type 304 stainless steel tubing. The type 316 SS rod had a 20 micron ferrite layer on the surface and the type 304 SS tube had the ferrite layer on the insidediameter. In the final section of the investigation, promising techniques were set up in the hot cell and tried on sodium-exposed, irradiated test fuel pins.

One potential complicating factor in the use of any of the ferrite detection methods investigated in this study is the presence of an intermittent iron oxide film on the fuel pins. This oxide coating is formed during the sodium removal procedure and is not associated with the in-reactor sodium exposure. The stain is not present on all fuel pins and it is not even present on the same multi-exposure fuel pins after every cleaning operation (see Figure 1). This stain is, however, a potential problem as there is some probability that this extraneous oxide layer is magnetic. In addition, the thinness of the sodium-induced ferrite layer that one desires to detect may prohibit a secondary cleaning operation to remove the oxide stain. Some of the potential stain related problems are mentioned under descriptions of the individual detection techniques but no experimental analysis into these problems were carried out under this study. This is a problem area that needs further study.

HEDL P23B PIN 9A

X181A

X181B

X181C

FIGURE 1. Fuel Pin Appearance After Multiple Exposures in EBR-II

2.0 CHARACTERIZATION OF FERRITE LAYER

The ferrite layers that form on irradiated fuel pins exposed to liquid sodium are the result of bulk and grain boundary diffusion of Cr and Ni to the fuel pin surface and subsequent leaching of these elements into the liquid sodium. Therefore, the layer thickness varies with exposure time and temperature. Maximum layer thickness of the order of 6 microns have been reported on fuel pins with a surface temperature of 705°C, exposed in-reactor for 5300 hours⁽¹⁾. In addition, the resultant ferrite layers are not only very thin but may also be discontinuous due to localized temperature perturbations in the fuel bundle.

The surface composition of the ferrite layers are approximately 11% Cr and 7% Ni depleted from an initial composition of approximately 17% Cr and 14% Ni. The phase transformation of austenite to ferrite results in a change in crystal structure along with the resultant change in magnetic properties, i.e., the ferrite layer is ferromagnetic and the austenite is not. The differences in properties of the austenite and ferrite that were used as principles for ferrite detection techniques are listed below:

1. Differences in chemical properties
2. Differences in crystal structure
3. Differences in magnetic properties

3.0 POTENTIAL TECHNIQUES

The various ferrite detection techniques evaluated in this study are outlined in this section. This includes a descriptive title of the detection mechanism and a brief description of the expected result. The technique listing is broken down under the three primary property differences between austenite and ferrite mentioned in the previous section.

Ferrite detect techniques based on differences in chemical compositions of the ferrite and austenite are listed below:

1. Differences in etching characteristics: Use a macro etch to distinguish between the ferrite and austenite surfaces.
2. Differences in heat tinting characteristics: Heat the pins in an

air atmosphere and observe differences in the oxide reflection properties of the ferrite and austenite.

3. Differences in anodizing characteristics: Selectively anodize the stainless steel or ferrite layer.
4. Differences in electroplating characteristics: Try for selective plating on either of the structures.
5. Differences in x-ray fluorescence characteristics: Measure the Ni/Cr ratio of the surface layers and expect to see a difference if ferrite is present.

Ferrite detection techniques based on differences in crystal structure are listed below:

1. Difference in x-ray diffraction characteristics: Detect ferrite by looking for reflections from the (110) plane of the ferrite structure.
2. Differences in ultrasonic characteristics: Detect ferrite by measuring the modulus of elasticity of the surface of the fuel pin.

Ferrite detection techniques based on differences in magnetic properties are listed below:

1. Differences in magnetic permeability: Detect ferrite by measuring the magnetic permeability of the fuel pins.
2. Differences in polarized light reflection: Apply a magnetic field to a given fuel pin and look at the difference in the reflections of the polarized light. Sections that are ferromagnetic would reflect light rays more than those areas where magnetic domains do not exist.
3. Differences in magnetic force characteristics: A magnetometer is used to measure the magnetic force of a ferrite layer.

4.0 RESULTS

The main objectives of this section is that of categorizing the various ferrite detection techniques under a pass-fail scheme and briefly discussing the reasons for their classification. The majority of the potential detect-

ion techniques were eliminated from the competition in theoretical analysis phase of this study. Only four techniques were taken into the second proof-of-principle phase, and one of these was eliminated in this stage.

Only one technique, the electromagnetic technique, was taken into the third phase of this study, the hot-cell testing, due to time constraints. This technique and the equipment used in the hot-cell testing are discussed in considerable detail in the latter part of this section.

The techniques investigated in this study are presented below, starting with the techniques that did not pass the phase one theoretical or/phase two proof-of-principle analyses. Then the techniques that passed phases one and two are discussed, and lastly the technique which was taken into phase three hot-cell testing is discussed.

4.1 FERRITE DETECTION TECHNIQUES REJECTED BY THEORETICAL ANALYSIS

The first phase of review of the proposed techniques of ferrite detection eliminated from further consideration several of the proposed techniques due to either technical infeasibility or inherent problems. Techniques that did not pass the theoretical consideration were:

4.1.1 Differences in Anodizing Characteristics

This method was eliminated from further consideration because the stainless steel releases O_2 gas instead of forming an oxide layer.

4.1.2 Differences in Plating Characteristics

This would depend on a change in electrochemical potential from one phase to the other, which are at nearly the same composition. Either a thin layer and/or a small change in chemical potential bias against selective plating. Further difficulties are encountered because the pin would require cleaning prior to plating and the cleaning operation might remove some of the ferrite. These inherent problems place a low priority on this technique.

4.1.3 Differences in X-ray Fluorescence Characteristics

This reasonably quantitative method looks promising at first glance. Both $Ni K_{\beta}$ and $Fe K_{\alpha}$ can be excited by either incident $Cu K_{\alpha}$ radiation or

possibly by utilizing the irradiated sample itself as an excitation source. The mass absorption coefficient for Cu K_α in Fe is $325 \text{ cm}^2/\text{gram}$, and the linear coefficient (μ_L) is 2568 cm^{-1} . The useful penetration is $1/2\mu_L = .0002 \text{ cm}$ or $2\mu\text{m}$. This would be perfect for the very thin ferrite layers.

The initial problem for this technique stems from the need for the powerful Cu K_α source and detectors for Ni K_β and Fe K_α that would be required to measure the Ni/Cr ratios. In addition, this method would not be rapid because of the small beam required due to the curved surface.

The big problem, however, would be to develop a detector system selective enough to measure low intensities of long-wavelength radiation, Ni K_β and Cr K_β , in the presence of an intense field of more penetrating radiation. A further complication is the possible presence of Fe_{55} and Ni_{59} . These isotopes decay by the K-capture process in which the characteristic Fe K or Ni K radiation is emitted. The half-lives are so long that these isotopes can not be eliminated by storage. If, as may be the case, the characteristic radiation from the K-capture decay were substantially greater than that excited in fluorescence, the whole method would be impracticable. These considerations lead to a pessimistic outlook for x-ray fluorescence as a ferrite detection technique on irradiated fuel pins.

4.1.4 Differences in Polarized Light Reflection

A polarized light source and detectors would be required for this technique to measure the reflectivity of the pin surface. This technique has some problems common to some of the other techniques, namely, the curved surface requires a very narrow beam and the stained surface may require cleaning. The need for a narrow light beam dictates that this technique, if it worked, would be extremely slow. These considerations indicated a low feasibility of success with this technique, and further experiments were not conducted.

4.1.5 Differences in Ultrasonic Characteristics

This is a surface technique in which one looks at velocity as a function of frequency of sound waves. In this technique a surface wave is set up between two transducers and the perturbation due to changes in the elastic

modulus of the surface layer is analyzed by computer. To get a 10-micron surface penetration would require a frequency on the order of 300 MHz, as the depth of penetration of the sound wave is proportional to frequency. This present a problem for state-of-the-art equipment. Another potential problem is that the surface stains formed during the cleaning process may cause perturbations in addition to the perturbation from the ferrite layers. Finally, if the technique did work it would only average the contributions of the ferrite layer over the distance between the transducers. In light of these considerations further development of this technique was not attempted.

4.1.6 Differences in X-ray Diffraction Characteristics

The technique would require a Cu K_α x-ray source and a detector. This technique suffers from some of the same problems as the x-ray fluorescence, namely, fuel-pin curvature and detector problems. For these reasons development of this technique was not attempted.

4.2 FERRITE DETECTION TECHNIQUES REJECTED BY PROOF-OF-PRINCIPLE ANALYSIS

The second phase of review consisted of limited proof-of-principle testing. Only one of the four proposed detection techniques that passed the theoretical analysis phase was eliminated in this second review phase. The reasons for its rejection are discussed below.

4.2.1 Differences in Etching Characteristics

Proof-of-principle experiments for selective etching of the ferrite layers were carried out on a sodium-induced ferrite layer on an austenite matrix. The specimens were sectioned from a 1.27 cm I.D. type 304 stainless steel tube that had extended exposure at 700°C in a sodium loop. The etching specimens were sectioned to expose the austenite matrix and the ferrite layer on the same surface to allow easy comparison. The seven etchants which were used to try to distinguish between the ferrite and the austenite are listed below.

• HCl/H ₂ O ₂ etchant #2	• 10% Oxalic Electrolytic 20 VDC
• Carapella's etchant	• Murakamis
• HCl/20 drops H ₂ O ₂	• 5% Nital
• 50 HCl/50 nitric	

Although the two structures have different chemical activities the etching technique did not reveal any apparent difference. The failure of this technique may be due to:

1. The layer thickness--too much material must be removed to show macroscopic results.
2. The chemical activities are not different enough to be distinguishable by a macro etch.

4.3 FERRITE DETECTION TECHNIQUES ACCEPTED THROUGH PROOF-OF-PRINCIPLE ANALYSIS

Three ferrite detection techniques were found to pass the proof-of-principle phase of this study. They were found to be able to distinguish between regions of austenitic stainless steel and ferrite-coated austenitic stainless steel. Test specimens analyzed in this section of the program included sections of as-received fuel cladding electroplated with various thicknesses of ferrite, a 316 SS rod that had a sodium-induced ferrite coating, and a 304 SS tube that had a sodium-induced ferrite layer on its inside surface. The results of the various tests run on these detection techniques are discussed below.

4.3.1 Differences in Heat Tinting Characteristics

Proof-of-Principle experiments were run for the heat tinting technique. Specimens were sectioned from a 3.2 mm type 316 stainless steel sodium loop support rod. In this case, the ferrite layer was on the surface of the solid rod and the austenite matrix was represented by the ends of the approximately 1 cm long specimens. In addition, 1 cm long specimens of unexposed FFTF fuel cladding were heat tinted at the same time to give a larger austenite surface for comparison. The ferrite layer and austenite matrix of the 3.2 mm type 316 stainless steel rod are shown in Figure 2, and the extension of the ferrite layer into the austenite matrix along grain boundaries is shown in Figure 3. The cladding and rod specimens were heat tinted at temperatures from 350°C to 600°C for various times. These results are shown in Figure 4 along with the test matrix. The cladding specimens (austenite only) did not show significant discoloration until 500°C. The ferrite coated rods showed considerable discoloration at 350°C and maximum discoloration at 400°C. Therefore, heat tinting shows promise as a ferrite detection technique though problems could result in fuel pin examination because:

FIGURE 2. Ferrite Layer on 316 SS Rod.
500X; As polished.

FIGURE 3. Ferrite Layer on 316 SS Rod.
250X; 10% Oxalic electrolytic
etch.

<u>Temperature - Time</u>	<u>316 SS Rod</u>	<u>316 SS Cladding</u>
350°C - 10 min
350°C - 20 min
350°C - 30 min
350°C - 60 min
400°C - 10 min
400°C - 20 min
400°C - 30 min
450°C - 10 min
450°C - 20 min
450°C - 30 min
500°C - 10 min
500°C - 20 min
500°C - 30 min
550°C - 5 min
550°C - 10 min
550°C - 15 min
600°C - 5 min

FIGURE 4. Comparison of Heat Tinted Ferrite and Austenite Surfaces

1. The ferrite layers are much thinner (5μ compared to 20μ) on actual fuel pins.
2. The stains from the cleaning process may obscure the results.

4.3.2 Differences in Magnetic Force Characteristics

Proof-of-principle experiments were run on cladding specimens exposed for various tints and temperatures in a sodium loop. Very thin layers of ferrite were formed on the outside surface of the specimens. A Aminco-Brenner Magne-Gage, which utilizes a magnet and calibrated spring, was used to measure the magnetic force. The sodium loop specimens showed a larger magnetic force than the as-received cladding. Specimen with plated iron also showed a predictable response when known ferrite thicknesses were used, indicating that a calibration curve could be developed for quantitative results. Although the magnetometer shows promising results, it is a very delicate instrument and remote operation would be difficult. In addition, this technique measures the magnetic force only at the point of contact and therefore is only useful for examining very small areas.

5.0 IN-CELL VERIFICATION OF ELECTROMAGNETIC TECHNIQUE

5.1 TECHNIQUE FEASIBILITY

This section of the report describes some basics of electromagnetic testing technology and how this technology was applied to detection of ferrite layers on FFTF fuel pin cladding. The text includes a background of the technology explaining how specimen parameters such as conductivity and permeability are detected, and a discussion of the specific techniques used for hot cell inspection of fuel pins during this program.

5.2. BACKGROUND

Alternating current electromagnetic tests deal primarily with two specimen parameters: electrical conductivity and magnetic permeability. Detection of these parameters is performed by placing a search coil so that its electromagnetic field intercepts the test specimen as shown in Figure 5. The complex impedance of the coil is detected by the instrument and is used to interpret specimen parameters.

FIGURE 5. Implementation of an Eddy Current Test.

Detection of conductivity related effects is based on the following events:

1. The alternating current in the search coil develops a primary field H_p which links with the specimen and induces potential differences in it.
2. The potential differences cause circulating or eddy currents to flow in the specimen.

3. The eddy currents produce a secondary electromagnetic field H_s which links with the coil and induces a secondary voltage in it.
4. The secondary voltages are detected by the instrument as a change in the equivalent impedance of the coil. The coil is connected as one leg of an impedance bridge in the instrument, and the secondary voltages alter the current delivered to the coil by the bridge, resulting in a change in the equivalent impedance of the coil.
5. The Fourier amplitude coefficients A and B of the secondary voltage are detected and output by the instrument. They are used to interpret a variety of material properties, including conductivity, thickness, flaws (voids or inclusions), and probe-to-specimen spacing (liftoff).

In the event that the specimen has magnetic properties; e.g., its permeability is greater than that of free space, the primary field of the coil is provided with a flux path of lower reluctance, and the net flux density will be increased. This results in an increase of coil inductance, and an increase of the imaginary component of the coil impedance. This effect can be used to measure specimen permeability or thickness of magnetic coatings.

5.3 FUEL PIN INSPECTION TECHNIQUE

The arrangement used for inspecting the fuel pins is shown in Figure 6. The distinguishing feature here is that an absolute test was used in contrast to the conventional differential defect test. One of the two coils in a conventional differential probe was used for inspection while the other coil was replaced by a reference coil back at the instrument. The conventional probe is detailed by HEDL drawings H-3-40356 and H-3-40357, and the reference coil was 65 micro-henry device wound on a 9.5 mm bobbin. HEDL instruments in place at the hot cell facility were used for data acquisition. These included an Automation, Industries EM3300 eddy current instrument and a Gould 220 two channel strip chart recorder.

The absolute test was used because it provides a continuous reading of specimen parameters, whereas the differential test responds only to differences between areas inspected by the two coils and is better suited for a defect test. A test frequency of 10 kHz was used to minimize the eddy current response to the cladding wall while maintaining high sensitivity to

FIGURE 6. Fuel Pin Test Arrangement

magnetic effects in the cladding. At this frequency the test is quite insensitive to presence of the stainless steel cladding material and has no discernable probe motion response. However, a strong response is obtained from calibration tubes with less than 1 micron of iron electroplated onto the outer surface.

Higher test frequencies were evaluated for the purpose of limiting the penetration of eddy currents into the cladding. Limited penetration would render the test less sensitive to any magnetic or metallic components inside the fuel pin. The evaluation showed that 100 kHz was the highest frequency which could be successfully used before the permeability response merged with the cladding eddy current response. Above this frequency it became very difficult to separate the two indications. The reduction in eddy current penetration of the cladding was minimal at this frequency, and the evaluation showed that a frequency of 1 MHz would be required to achieve the desired limitation.

A test frequency of 10 kHz was selected based on the above information and also because the responses to probe temperature and eddy currents in the cladding merged at this frequency. This means that the quadrature output channel can be made free of both eddy current and probe temperature indications while still responding to magnetic effects. Performance of the test is shown in Figure 7. This data was taken during a run over a calibration specimen which consisted of four cladding samples coated with electroplated iron mounted on a plastic rod. This calibration specimen was used both outside and inside the hot cell. An example of a specimen cross-section is shown in Figure 8.

The top recording trace of Figure 7 contains a mixture of information on cladding conductivity or thickness, probe temperature and permeability. It is primarily used to indicate the presence or absence of a fuel pin in the probe. The lower trace is free of the two undesired effects and responds to both the thickness and the permeability of the magnetic layer. As indicated by the response to sample 1, which has only a small plated area in its center, the lower channel has no response to conductivity or thickness of the cladding. Samples 2, 3 and 4 have increasing thicknesses of electroplated iron on their outer diameters. Therefore, not only does the electromagnetic technique

detect ferrite but, a calibration curve could be developed to give quantitative ferrite volume results.

Electromagnetic tests performed on actual irradiated fuel pins were run on six different fuel pins and three wire wraps. Figure 9 shows the results of a test run on a pin as a function of fuel pin structure. The permeability response is composed of two different components in the region of the fuel column and plenum. Near the top of the fuel column the permeability response increases slowly to a maximum and then decreases over the plenum region. This behavior is similar to that observed by Weber et al.⁽¹⁾ and is thought to be associated with the sodium-induced ferrite layer. The second component of the permeability response is the symmetrical hump in the lower section of the fuel column. The hump was located in a different position on each of the fuel pins, but the permeability maximum was located at a nearly constant cladding O.D. temperature of $460 \pm 10^\circ\text{C}$ and I.D. temperature of $495 \pm 5^\circ\text{C}$. A similar magnetic response has been observed in the French fuel pins from Rapsodie⁽²⁾ and in irradiated 316 stainless steel⁽³⁾ and also, type 321⁽⁴⁾. The origin of the permeability response is thought to be very small highly dispersed superparamagnetic particles. If this phenomena can be well defined it would be useful in defining the fuel pin temperature distribution.

5.4 SET-UP PROCEDURE

The set-up procedure used for hot cell examination of fuel pins is as follows:

1. Set EM3300 controls: Frequency - - -10 kHz
Sensitivity - -0.1
Phase - - - -9.8
Outputs - - - -1/2 volt/div.
2. Connect recorder: Channel 1, 100 mv/div. to vertical eddy current output.
Channel 2, 200 mv/div. to horizontal eddy current output.
3. Connect probes: Search coil to one input of EM3300.
Reference coil to other input through 50 ft. of coiled coaxial cable of the same type used for search coil.

CONDUCTIVITY
0.5 volt/div

PERMEABILITY
0.5 volt/div

FIGURE 7. Test Response for Calibration Specimen

FIGURE 8. Six-Micron Layer of Plated Ferrite on 316 SS Cladding. 500X; 2% Nital etch.

FIGURE 9. Electromagnetic Evaluation of an Irradiated Fuel Pin

4. Balance the EM3300 instrument.
5. Perform fine adjustment of phase control until a temperature change of the reference coil produces an indication on the CRT which is totally contained in the horizontal channel.
6. Draw the calibration specimen through the probe and adjust gain until permeability indications on recording trace have the same amplitude as the master calibration run.
7. Perform fuel pin examination.

6.0 CONCLUSION AND RECOMMENDATIONS

This survey of techniques for the detection of a thin ferrite layer on type 316 stainless steel has revealed two promising techniques, a heat tinting and an electromagnetic technique. Both techniques were given proof-of-principle tests on simulated fuel pin material, and the electromagnetic technique was shown to work in a hot cell environment on actual fuel pins exposed in EBR-II. Both techniques need further study, however, before either will be ready for production run analysis usage.

Heat tinting experiments on unirradiated, sodium-induced ferrite on 316 SS revealed that very distinct color differences were present between the oxide formed on the stainless steel and that formed on the ferrite. The optimum heat tinting temperature range, as indicated by this research, is 350 to 400°C. It should be remembered, however, that the heat tinting work was done on specimens with a substantial ferrite layer thickness, and that no research directed towards determining the minimum layer thickness needed for ferrite detection was attempted in this study.

The electromagnetic technique equipment used for the hot cell was essentially the in cell equipment currently installed for NDT analysis of fuel pins. The only equipment modification that was needed was the fabrication of new detection coils. This indicates that an electromagnetic detection system could be installed as an add-on to existing electromagnetic NDT equipment. This technique is not, however, without its potential problem areas. The major problem area encountered in this study was the presence of

a super-paramagnetic radiation-induced phase forming in the SS bulk material in addition to the sodium-induced ferromagnetic surface layer. This additional phase resulted in a bell shaped permeability curve being formed as a function of temperature that was readily detected by the permeability measurement techniques employed in this study.

There is a significant potential that the presence of the bulk phase will become a positive attribute. It may be possible to use this phase as a means to determine the average use temperature of the fuel pins, as appearance of the phase seems to be confined to a certain temperature regime. This would be a positive attribute if further research proves that the presence of the bulk phase and surface layer ferrite can be separated and that the formation characteristics of both can be defined.

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Thomas J. Davis (3)

Technical Information (5)
Publishing Coordination (2)

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