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STUDIES IN NONDESTRUCTIVE TESTING WITH POTENTIAL FOR IN-SERVICE INSPECTION OF LMFBRs*

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INTRODUCTION

Firm detailed requirements have not been established in the United States for the in-service inspection (ISI) of Liquid-Metal Fast Breeder Reactors (LMFBRs). However, although not directed specifically toward such applications, several development programs in nondestructive testing at the Oak Ridge National Laboratory (ORNL) have shown probable benefit. The technology includes work in radiography, ultrasonics, and eddy currents.

RADIOGRAPHIC METHODS

Although radiography is normally not considered as a major contributor for nuclear ISI because of problems with the radiation background, limited applications have been made. These include special work in hot cells and radiography of reactor components in low-radiation-level environments. A development study[1] at ORNL, which led to the installation of an x-ray unit in a hot cell, demonstrated the feasibility of performing radiography despite rather high radiation background. A comparison was made of the relative radiographic quality on a radiographed specimen as successively greater amounts of background radiation (from a ^{60}Co source) were superimposed on the initial exposure. We demonstrated that up to 32 R of radiation could be tolerated without severe loss of sensitivity (as measured by a plaque-type penetrameter). For even greater levels of background radiation, experiments were conducted with chemical reduction

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using Farmer's reducer as a bleaching agent on the overexposed film. We showed that the tolerance to radiation could be increased up to more than 300 R. For example, Fig. 1 is a reproduction of an x-radiograph made of a highly radioactive ^{60}Co gamma-ray source. This source produced a radiation field at the plane of the film of about 12,000 R/hr. During the short exposure, the film was subjected to about 200 R of background gamma rays from the source.

Another area of development in radiography with potential benefit for ISI is radiographic image enhancement. Because of the inherent difficulties in performing radiography in a reactor system, the quality of the as-processed image may not be optimum for best interpretation. Many organizations have conducted developmental studies of techniques and equipment for image enhancement, including sophisticated computer systems, television circuitry, and optical approaches. The work at ORNL emphasized video techniques[2] using magnification and contrast enhancement.

Significant benefits were demonstrated in both visibility of image detail and quantitative dimensional measurements in radiographs that had unavoidable poor image quality.

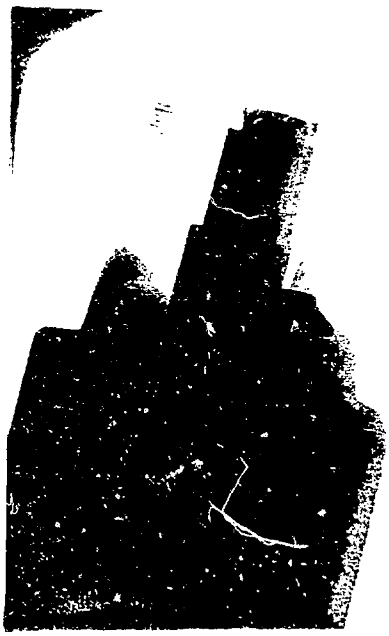

Fig. 1. Radiograph of a 5-Ci ^{60}Co Capsule.

EDDY-CURRENT METHODS

With the exception of ISI of steam generator tubing, eddy currents have not been utilized heavily in postoperation reactor examination. However, with appropriate advances, there are many areas of application wherein eddy currents should be useful. Among the problems that must be overcome for application to LMFBRs are variations in signal due to coil-to-specimen spacing (lift-off), effects of temperature [200°C (400°F) and higher] on the coils and specimens, and the effect of variations in magnetic permeability in some alloys. Developmental programs at ORNL have addressed these needs.

Theory

Significant advances in the theory of electromagnetic induction of eddy currents and the development of mathematical models to simulate inspection conditions have increased the basic understanding of the inspection method.[3–5] (The cited references are typical and not exhaustive.) Many of these models have been programmed for computer solution. The models and programs contain all the significant variables in an eddy-current examination [e.g., the electrical, magnetic, and dimensional properties of the specimen; the configuration of the inspection coil(s); and the operating parameters of the instrumentation]. Therefore, the programs can be used to design optimum eddy-current techniques and probes and to accurately predict the attainable results before experiments. Supplementary computer programs for instrumentation allow optimum design of the circuitry with improved stability and accuracy. Application of the techniques at ORNL for solution of new problems has demonstrated significant savings in time and cost and improved performance, with excellent correlation between the design predictions and experimental results. Figure 2 is an example of some of the typical design results for technique development and prediction of results. These curves for the detection of flaws on the near surface of thick specimens (e.g., for cracking in pipe or vessel walls) allow determination of the optimum conditions of coil size and operating frequency and predict the instrument response to flaws having different depths.

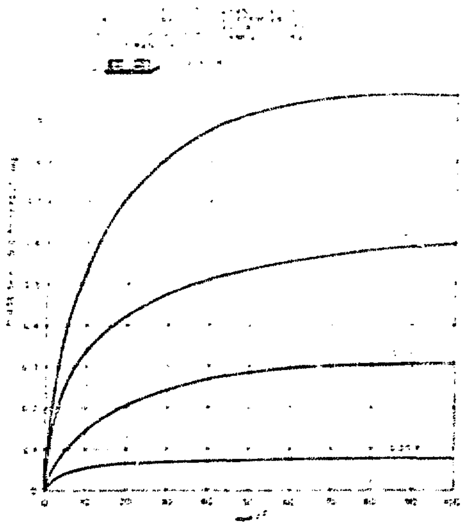

Fig. 2. Calculated Curves for Optimized Eddy-Current Technique and Predicted Performance for Flaw Detection on the Surface of Thick Specimens.

Instrumentation

The computer programs cited above have provided beneficial input to optimized design of several phase-sensitive eddy-current instruments that feature excellent stability and sensitivity and relative insensitivity to changes in lift-off (coil-to-specimen spacing). Lift-off sensitivity can be particularly troublesome in automatic or remote scanning systems that may be necessary for ISI. Two typical applications of the instrumentation will be briefly described.

One application was for the remote postoperation inspection[6] of control rods (actually thin-wall cylinders) for the High Flux Isotope Reactor (HFIR) at ORNL. The neutron-absorbing materials were tantalum and Eu_2O_3 clad with 0.38 mm (0.015 in.) aluminum. The inspection was performed to measure the thicknesses of both the residual cladding and an oxide layer on the cladding and to detect cracks as shallow as 0.254 mm (0.001 in.) in the cladding. Figure 3 is a photograph of the instrument, a simple mechanical scanning system, and the inspection probe on an unirradiated control rod used during calibration. Figure 4 is a photograph of the inspection being performed at the bottom of the deep

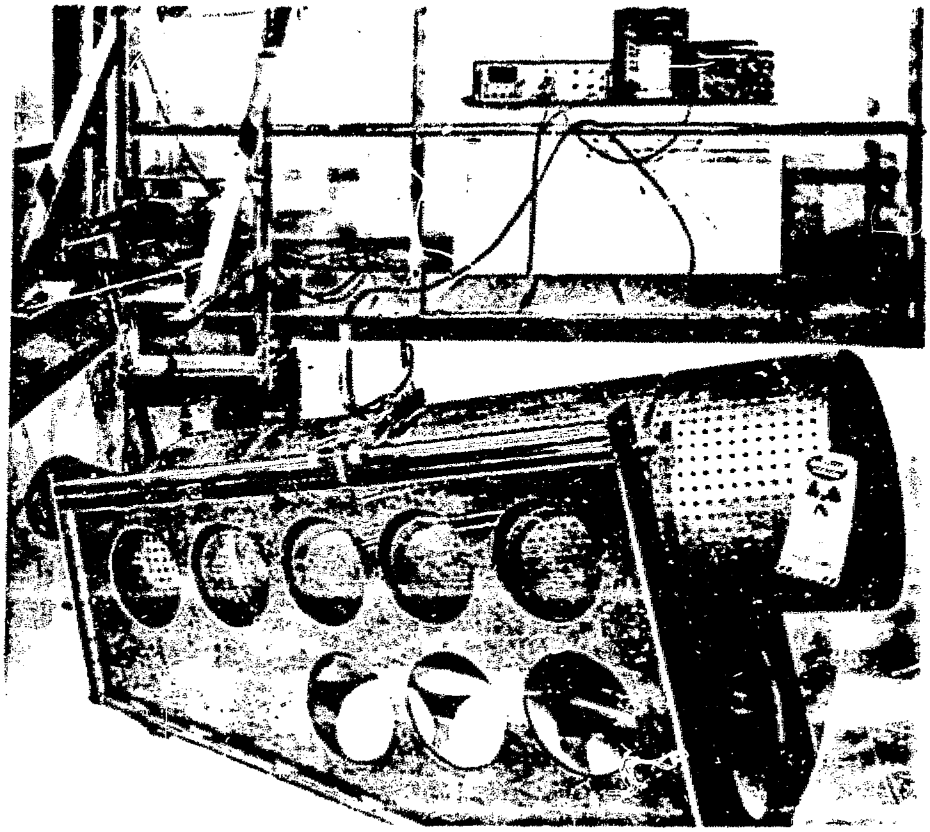

Fig. 3. Phase-Sensitive Eddy-Current Instrument and Scanner for Inspection of Reactor Control Rod (Cylinder).

pool of water. The glow is caused by the Cerenkov effect and is an indication of the very high levels of radiation. All desired inspections were successfully accomplished.

Another application is currently being developed for the ISI of steam generator tubing for an LMFBR.[7] The tubing is 2 1/4 Cr-1 Mo alloy, a ferromagnetic material. Except for the production inspection of ferromagnetic tubing, eddy-current techniques are not generally considered to be beneficially applicable to such alloys. A significant problem is the fact that the inspection must be performed from the bore of the tube which has an inner diameter of 10.16 mm (0.400 in.) and a wall thickness of 2.77 mm (0.109 in.). However, we have demonstrated that, with

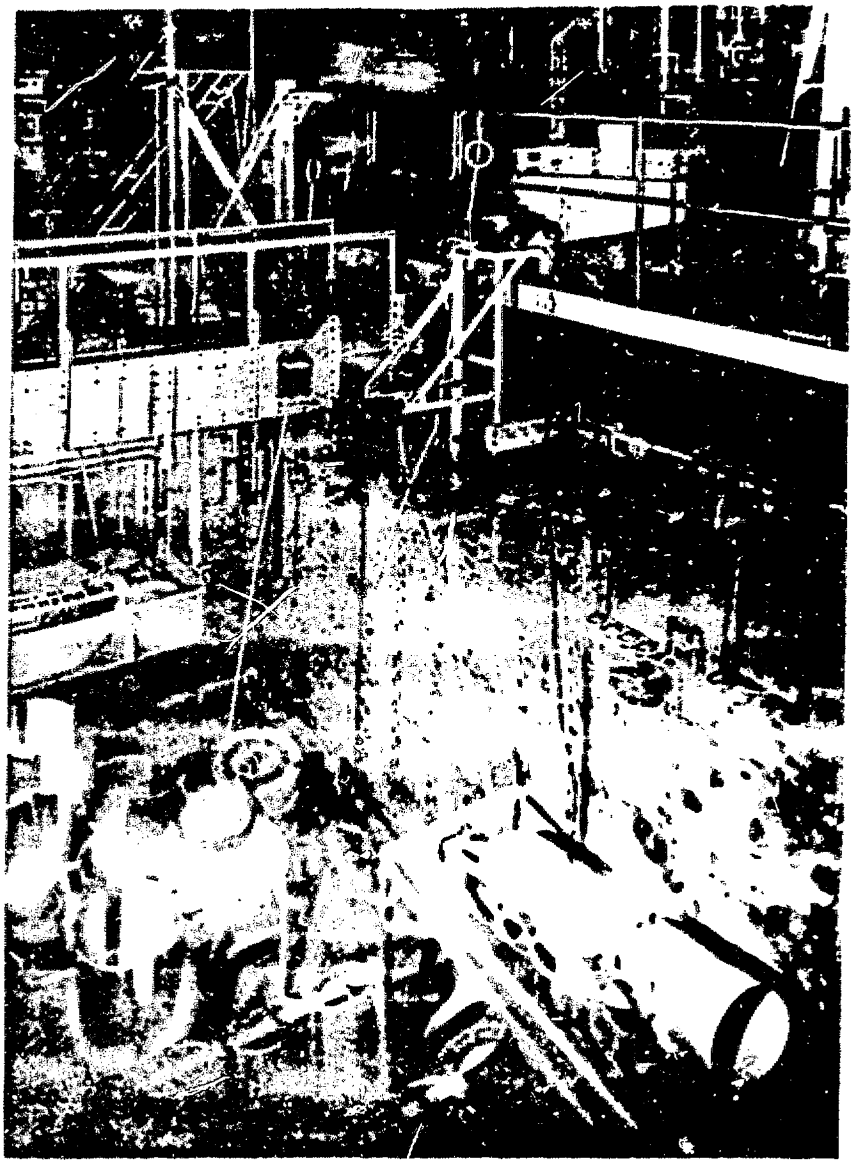

Fig. 4. Eddy-Current Inspection Being Performed on Highly Radioactive Reactor Control Rod (Cylinder).

computer-designed coils such as conceptually shown in Fig. 5, the tubing can be adequately magnetically saturated to allow eddy-current inspection of the entire wall thickness. To overcome potential ambiguities due to variations in different properties such as conductivity, permeability, thickness, diameter, and the presence of flaws will require multifrequency, multiparameter techniques. This advanced instrumentation is being developed.

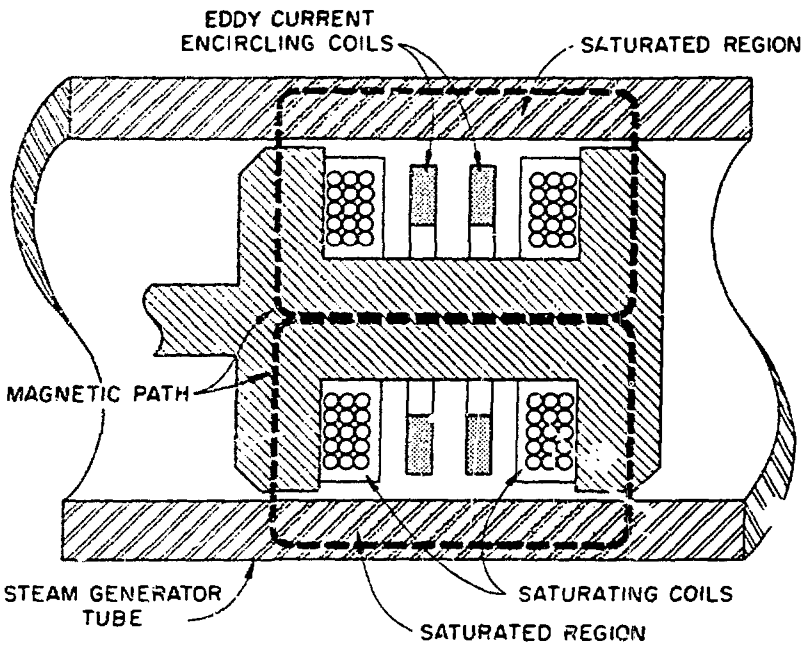

Fig. 5. Conceptual Drawing of Bore-Side Magnetic-Saturation Eddy-Current Probe for In-Service Inspection of Steam Generator Tubing.

For ISI of light-water reactors, ultrasonics has been the prime nondestructive testing method for volumetric examination in the radioactive environment. Although the method has proved to be very beneficial as a qualitative detection tool, there are needs for improvement to obtain more quantitative data on the dimensions of flaws for better determination of significance based on fracture mechanics. Studies at ORNL in ultrasonic-frequency analysis[8–11] (again the cited references are typical and not exhaustive) have demonstrated the feasibility of making quantitative measurements of both flaw size and orientation without regard to the overall amplitude of the reflected signal. For example, Fig. 6 shows ultrasonic spectra in reflections obtained from a 3.18-mm-diam (0.125-in.) reflector at several different angular orientations from normal with the incident beam. The spectrum at normal incidence is quite similar to that of the transmitted pulse. Note the changes in maxima and minima at various frequencies in the spectra as the angle changes. Since two unknown properties of a flaw (a dimension and an orientation) affect the observed frequency spectrum, at least

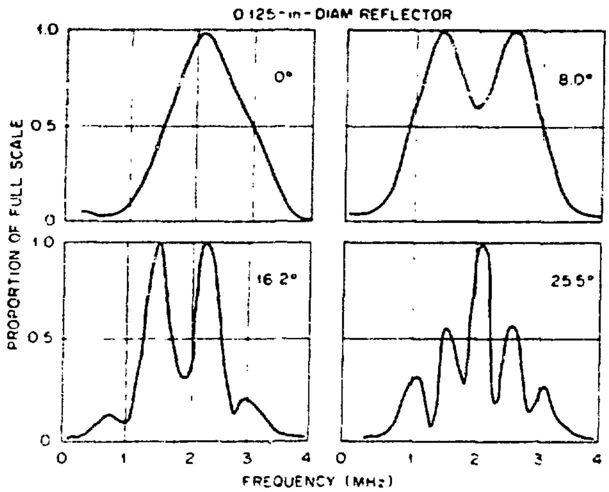

Fig. 6. Ultrasonic Spectra from 3.2-mm-diam (1/8-in.) Reflector at Different Angles of Incidence.

two interrogations are required to isolate each. One-, two-, and three-transducer techniques have been studied for simplified multiple evaluations, and Fig. 7 is a sketch of one of the two-transducer arrangements. Figure 8 is a special test block of steel containing flat-bottomed drill holes with different diameters and orientations. A rubber replica of the holes is also in the photograph. With the frequency-analysis technique, we were able to accurately determine both size and orientation of each reflector, using only the reflection spectra with the ultrasound introduced from the top surface of the block. Further developments are expected to produce inspection techniques that can be applied for ISI.

Another ultrasonic technique that is currently being developed[7] for the bore-side inspection of tube-to-tubesheet joints for steam generators should also be applicable for the ISI of steam generator tubing. As noted in the section on eddy currents, the reference tubing is 2 1/4 Cr-1 Mo with an inner diameter of 10.16 mm (0.400 in.) and a wall thickness

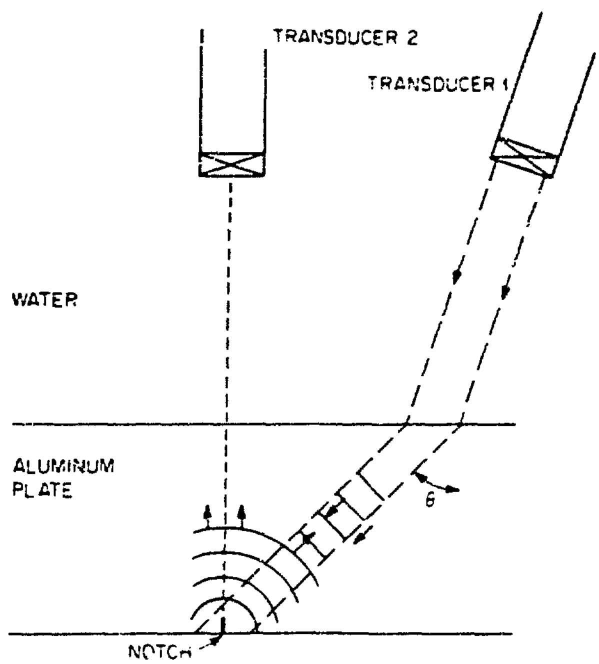

Fig. 7. Two-Transducer Arrangement for Flaw Characterization Using Frequency Analysis.

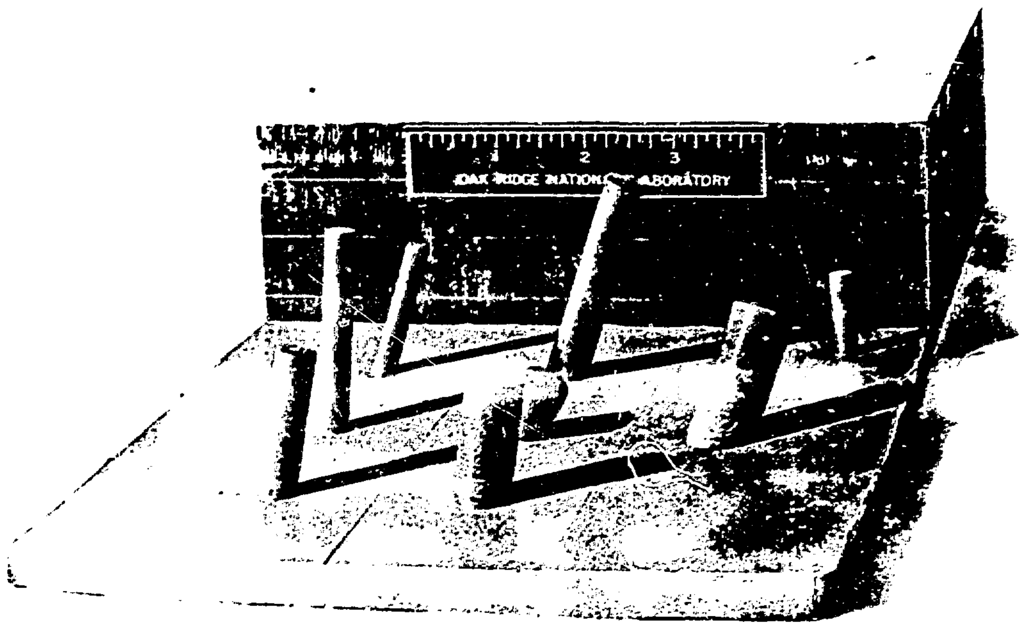

Fig. 8. Steel Block with Rubber Replica of Machine Flaws used for Frequency Analysis Studies.

of 2.77 mm (0.109 in.). Figure 9 is a photograph of a prototype probe being studied for the ultrasonic inspection. The small-diameter [≈3 mm (1/8 in.)] ultrasonic beam is transmitted parallel to the bore to impinge on a reflector that diverts the sound into the tube wall at the desired angle. Reflections from discontinuities may be detected by the initial transmitting transducer or by a secondary receiver. Figure 10 is a schlieren photograph of the output of an experimental probe. The schlieren technique is used to confirm the design and performance of new transducers. The bore-side ultrasonic probes have been shown to have sensitivity adequate to detect a flaw 50 μm (0.002 in.) deep in the 2.77-mm (0.109-in.) wall.

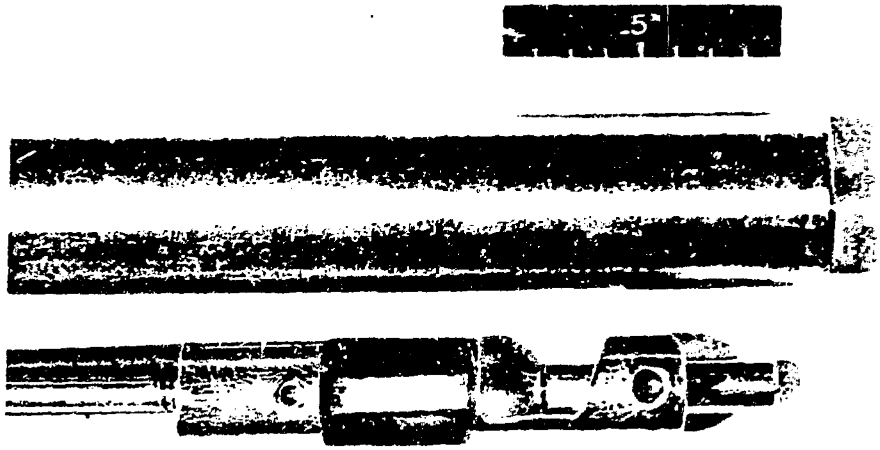

Fig. 9. Modular Ultrasonic Probe Being Studied for Inspection of Tube-to-Tubesheet Joints for Steam Generators.

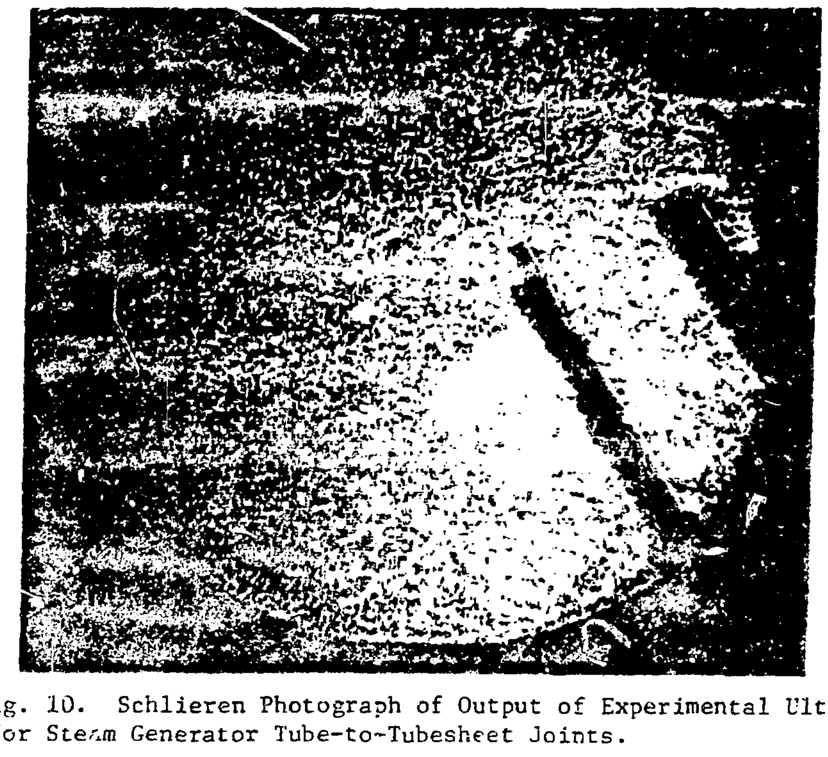

Fig. 10. Schlieren Photograph of Output of Experimental Ultrasonic Probe for Steam Generator Tube-to-Tubesheet Joints.

SUMMARY

A variety of nondestructive examination techniques have been and are being developed at ORNL with potential for ISI in LMFBRs. Among these are radiographic techniques for radiation environment and image enhancement, advanced eddy-current techniques and equipment for flaw detection and thickness measurement and ISI of steam generator tubing, and ultrasonic methods for quantitative flaw evaluation using frequency-analysis and bore-side ultrasonic techniques for steam generator tubing. Further developments should result in positive application to ISI.

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