ARGONNE NATIONAL LABORATORY
9700 South Cass Avenue
Argonne, Illinois 60440

THE NONDESTRUCTIVE TESTING
OF BRAZED JOINTS

by

Akira Kannō*

Metallurgy Division

Program 12.1.11

November 1964

*Now at Ship Research Institute, Tokyo, Japan

Operated by The University of Chicago
under
Contract W-31-109-eng-38
with the
U. S. Atomic Energy Commission

DISCLAIMER

This report was prepared as an account of work sponsored by an agency of the United States Government. Neither the United States Government nor any agency Thereof, nor any of their employees, makes any warranty, express or implied, or assumes any legal liability or responsibility for the accuracy, completeness, or usefulness of any information, apparatus, product, or process disclosed, or represents that its use would not infringe privately owned rights. Reference herein to any specific commercial product, process, or service by trade name, trademark, manufacturer, or otherwise does not necessarily constitute or imply its endorsement, recommendation, or favoring by the United States Government or any agency thereof. The views and opinions of authors expressed herein do not necessarily state or reflect those of the United States Government or any agency thereof.

DISCLAIMER

Portions of this document may be illegible in electronic image products. Images are produced from the best available original document.

TABLE OF CONTENTS

	<u>Page</u>
I. INTRODUCTION	7
II. TESTING SPECIMENS	8
III. TESTING BY X-RAY AND NEUTRON RADIOGRAPHY	9
A. Standard Fault	9
B. X-ray Radiography of Standard Samples	10
C. Neutron Radiography of Standard Samples	12
IV. ULTRASONIC INSPECTION AND COMPARISON WITH PHOTOMICROGRAPHS, X RADIOGRAPHY, AND NEUTRON RADIOGRAPHY	15
V. COMPARISON OF X-RAY AND NEUTRON RADIOGRAPHY ON UNSHARPNESS FACTORS	22
A. Scattering and Secondary Radiation Effects	24
VI. CONCLUSIONS	26
ACKNOWLEDGMENTS	28
REFERENCES	29

LIST OF FIGURES

<u>No.</u>	<u>Title</u>	<u>Page</u>
1.	Typical Brazing Specimen	8
2.	Brazing Furnace	9
3.	Hole Arrangements Used in Brazing Foils Used as Standard Faults for Radiographic Studies	9
4.	Hole Diameters in Various Thickness Easy Flow 35 Brazing Foils Which Could Be Observed by X Radiography of an Assembly Made by Sandwiching a Test Brazing Foil between Two Plates of 304 SS	11
5.	Data Similar to Those in Figure 4 Except That the Brazing Foil Material is BAg8	11
6.	Data Similar to Those Shown in Figure 4 and 5 Except That Neutron Radiography of Easy Flow Brazing Test Foils and 304 SS Base Metal Is Involved	13
7.	Data Similar to Those Shown in Figure 6 But Obtained by a Direct Neutron-exposure Method in Which 0.0127-mm Gadolinium Back Screens Were Used with Single-emulsion Type M X-ray Film	13
8.	Data Similar to Those Shown in Figure 7, a Direct-exposure Neutron Radiographic Method	14
9.	Test Results, Ultrasonic Through-transmission Test and Direct-exposure and Transfer-exposure Neutron Radiographs, Left to Right, of a 304 SS Specimen Brazed with Easy Flow . . .	16
10.	Metallographic Results for the Sample Shown in Figure 9, Shown at 100X	17
11.	Ultrasonic Paper Recording and Radiographic Results for a Copper Specimen Brazed with Easy Flow	17
12.	Metallographic Results for the Copper-Easy Flow Brazed Specimen Whose Test Results Are Shown in Figure 11	18
13.	An Ultrasonic Paper Recording of a Carbon Steel Specimen Brazed with Ni-Mn-Si High-temperature Brazing Alloy	18
14.	Micrograph and Ultrasonic Pen Recording of a Portion of the Dotted Line Area of the Carbon Steel, Ni-Mn-Si Brazing Specimen Shown in Figure 13	19
15.	Test Results of a Brazed Sample Using Ni-Cr-B High- temperature Brazing Alloy	20

LIST OF FIGURES

<u>No.</u>	<u>Title</u>	<u>Page</u>
16.	Metallographic and Ultrasonic Pen Recording Results for the Brazed Sample Shown in Figure 15	20
17.	Micrographs of a Copper, Easy Flow Specimen Showing Good Bond on the Left (as indicated by maximum amplitude of the ultrasonic pen recording) and Fine Dispersed Faults within the Braze on the Right	21
18.	Micrograph and Ultrasonic Pen Recording for a Diffusion-bonded Zirconium, 304 SS Sample	21
19.	Calculated Values of Unsharpness for a 4-mm X-ray Focal Size for Various Film-focal-spot Distances	22
20.	Changes in Slope in the Density vs Thickness Curves Are Observed in X Radiography of Easy Flow Brazing Foil Sandwiched between Various Thicknesses of 304 SS Base Metal . . .	24
21.	Arrangement of Specimens Used to Determine Experimentally the X-ray Scattering Factor	25
22.	Data Similar to Those Shown in Figure 20, Except These Results Are for Neutron Radiography (indium transfer method) of 304 SS Base Metal Pieces Sandwiched around Easy Flow Brazing Alloy	25
23.	Characteristic Curves of Several X-ray Films	26

LIST OF TABLES

<u>No.</u>	<u>Title</u>	<u>Page</u>
I.	Base Metals	8
II.	Brazing Alloys	8
III.	Characteristics of Thermal-neutron Beam for Neutron Radiography	12
IV.	Unsharpness Results Obtained for Neutron Radiographic Facility at Juggernaut Reactor	23
V.	Measurement of $1 + (S/D)$ for 304 Stainless Steel Plates	25

THE NONDESTRUCTIVE TESTING OF BRAZED JOINTS

by

Akira Kannō

I. INTRODUCTION

Although brazing is one of the important methods for joining metals, nondestructive methods of inspecting such joints have not been studied thoroughly, one reason being the wide variety of base materials, brazing alloys, and brazing methods in use. Because of this variety, no single nondestructive test method appears capable of supplying all the desired inspection information. This study is intended to compare three different nondestructive testing methods: X-ray radiography, neutron radiography, and ultrasonic testing.

The strength of a brazed joint is considered to depend upon many factors, such as defects inside the joint, the type of alloy formed between base metal and brazing alloy, and the clearance of the brazed parts.

The relation between the strength and the joint clearance has often been investigated. The most favorable clearance is 0.0254 mm for Easy Flow type brazing alloys⁽¹⁾ and less than 0.0254 mm for Microbrazing type alloys.⁽²⁾ This clearance setting is related to the alloy tensile strength. If the clearance is favorable for this alloy, the tensile strength can be several times higher than the brazing alloy strength itself under a three-dimensional force.⁽¹⁾ Therefore, this study was made to check the detectability of several nondestructive testing methods for faults in brazed samples having a 0.0254-mm clearance between the parts joined.

It is very difficult to make artificial standard faults in such thin brazes, so the standard brazing faults were introduced by making holes, of various specified diameters, through brazing alloy foils, which were then sandwiched between the base metals, to study the detectability of these faults. The radiographs of real brazed parts were compared with these results and also with photomicrographs of brazed samples.

The results of ultrasonic testing, which were recorded either on electrosensitive paper in two dimensions or pen recorded, were also compared with these radiographs and with photomicrographs.

Brazing alloys that contain thermal-neutron-sensitive elements, such as boron, silver, and cadmium, were used in this study. As base metal, ASTM 304 stainless steel was mainly used.

II. TESTING SPECIMENS

The compositions of base metals and brazing alloys used are shown in Tables I and II. The brazing specimens had dimensions shown in Figure 1. Brazing clearances were made by inserting steel foil at the four corners.

Table I

BASE METALS

ASTM	C	Mn	P	S	Si	Cr	Ni	Mo
304	0.030 Max	2.00 Max	0.045 Max	0.030 Max	1.00 Max	18.00 20.00	8.00 12.00	
4023	0.20 0.25	0.70 0.90	0.040	0.040	0.20 0.35			0.20 0.30
Others:	Copper, Zirconium plate							

Table II

BRAZING ALLOYS

Alloy No.	Cr	Fe	B	C	Si	Ni	Ag	Cu	Zn	Cd
Standard Microbraz AMS 4775	13.5	4.5	3.5	0.8	4.5	Bal				
Microbraz 60	17.0 Mn			0.15 Max	8.0	Bal				
Easy Flow 35							35	26	21	18
BAG8							72	28

Fig. 1

Typical Brazing Specimen

The brazing furnace and crucible are shown schematically in Figure 2. This system permits rapid heating and cooling in an argon atmosphere. The specimen container, argon filled, could be inserted into the furnace and heated rapidly by virtue of the heat capacity of the retort made of stainless steel.

Fig. 2. Brazing Furnace

Artificial faults for study and evaluation were made either by applying carbon powder mixed with alcohol to certain areas of the specimens, by scratching the surface of mating plates, or by oxidizing partially the specimen surface mating plates.

As a standard brazing fault for radiography, brazing foil containing many holes with different diameters was sandwiched between base metals as explained in the introduction.

III. TESTING BY X-RAY AND NEUTRON RADIOGRAPHY

A. Standard Fault

The brazing-alloy foils containing various holes were sandwiched between base metals, but not brazed. Figure 3 shows these hole diameters and locations.

Fig. 3

Hole Arrangements Used in Brazing Foils Used as Standard Faults for Radiographic Studies

Foils of BAg8 and Easy Flow alloy were chosen because both contain some neutron-absorbing elements. Cadmium has a linear absorption coefficient of 97.0 cm^{-1} for thermal neutrons and of 9.4 cm^{-1} for 126.5-kV X radiation. Similar values for silver are 2.5 cm^{-1} for thermal neutrons and 11.0 cm^{-1} for X rays. Boron, which has a linear absorption coefficient of 60 cm^{-1} for thermal neutrons, is contained in the powder alloy. This powder alloy was not available as foil.

Stainless steel (304) samples of thickness of 6.35 mm, 3.18 mm, and 1.59 mm were used as base metal.

B. X-ray Radiography of Standard Samples

The X-ray apparatus used was a Westinghouse 250-kV Constant Potential Therapy Unit. The generator had a 4×2.5 -mm focal-spot size. The film-focus-distance (FFD) was set at 1.22 m, large enough to decrease geometrical unsharpness caused by the finite focus size. This will be discussed in more detail later.

X radiographs were taken on Kodak Type M film through 0.127-0.254-mm lead screens. The standard fault samples were considered to be at least somewhat similar to hole-type radiographic penetrameters, and a comparison between these results and radiographic reports on hole-type penetrameters^(3,4) may therefore be possible.

For hole-type penetrameters it has been shown ⁽⁴⁾ that if a penetrameter of thickness T_1 and a hole in the penetrameter of diameter N_1T_1 can be seen radiographically on a given thickness of material, a calculation of the radiographic visibility of another penetrameter thickness T_2 containing holes of diameter N_2T_2 can be made from the relation

$$T_1(N_1)^{1/2} = T_2(N_2)^{1/2}, \quad (1)$$

where the hole size $\phi_a = T_a N_a$.

Using this relationship one can calculate hole sizes in brazing material of various thickness that should be radiographically detectable, based on the radiographic results for a particular thickness of brazing material. In Figures 4 and 5, the dotted lines show the expected relation from this equation based on experimental results with brazing foils 0.0508 mm thick. The solid lines show observed spots. Figure 4 gives results obtained with Easy Flow and Figure 5 those obtained with BAg8.

Because of resolution limitations, a minimum diameter was observed between 0.0762 mm to 0.1016 mm in 0.0762-mm-thick foil.

When small-diameter holes were not clear but larger-diameter holes were observed clearly, the datum spot was chosen at the average of these diameters.

Observed spots satisfied the relation of equation (1) when the foil thickness was between 0.0762 and 0.0254 mm. But to be visible, holes in 0.01270-mm foil must be larger than those predicted by equation (1). As may be seen by comparison of Figure 4 with 5, smaller hole visibility was exhibited by BAg8 than Easy Flow. This is explained by the larger content of silver in BAg8 than in Easy Flow.

Fig. 4

Hole Diameters in Various Thicknesses of Easy Flow 35 Brazing Foils Which Could Be Observed by X Radiography of an Assembly Made by Sandwiching a Test Brazing Foil between Two Plates of 304 SS. The thicknesses of the stainless steel pieces were 1.58, 3.17, and 6.34 mm, respectively, for curves 1, 2, and 3. The dashed curves are calculated hole-visibility values based on equation (1) and experimental values for 0.05-mm-thick foils. Kodak Type M X-Ray Film, with 0.127-0.254-mm lead screens was used at 150 kV and a 1.22-m distance.

Fig. 5

Data Similar to Those in Figure 4 Except That the Brazing Foil Material is BAg8. All other conditions are the same.

The voltage of the X-ray tube was 150 kV for all the specimens, and the density of the film was kept within the linear part of a density-to-log relative exposure relationship. In these experiments, the base metal acted as a filter of the X rays and as a source of scattering. This is discussed later.

C. Neutron Radiography of Standard Samples

A neutron-radiography facility is located at Argonne's Juggernaut Reactor. The details of this apparatus for neutron radiography have been described by Berger.⁽⁵⁾ The conditions of the neutron source for this experiment are given in Table III.

Table III

CHARACTERISTICS OF THERMAL-NEUTRON BEAM FOR NEUTRON RADIOGRAPHY

Reactor	Juggernaut Reactor (Light Water Moderation)
Total Neutron Intensity	4.5×10^7 n/cm ² -sec
Graphite Thickness (Additional)	12.7 cm
γ -ray Intensity	120 R/hr
Beam Coverage	6.35 x 10.16 cm
Cadmium Ratio	2.4

The detecting methods used, the indium transfer method and the gadolinium direct-exposure method, have been described.⁽⁶⁾

The standard foil specimens as used with the X-ray inspection were neutron radiographed by a direct-exposure gadolinium technique in which 0.0127-mm screens were used with Kodak Type M (single-coated) X-ray film, and by a transfer method in which 0.254-mm indium screens were used with Kodak Type AA X-ray film. Film densities were kept in a linear part of the density-to-log of the relative exposure relation. The exposure times for the neutron exposures were as follows: indium screen exposure for 1.27-cm (total) specimen thickness was 2.5 min, 2.0 min for 6.35-mm material, and 1.5 min for 3.18-mm specimens. Transfer exposure times to AA film were 2 hr.

The radiographic results for the indium transfer method are shown by the solid lines in Figure 6 for Easy Flow brazing material. The dashed lines are calculated values based on experimental results for brazing material 0.0508 mm thick and equation (1). This neutron technique yields results for Easy Flow very similar to those found with X radiography. Very poor results were found for BAg8 brazing alloy.

For gadolinium and single-emulsion Type M film, exposures were 1.75 min for 1.27-cm specimens, 1.33 min for 6.35-mm specimens, and 1 min for 3.18-mm specimens.

Fig. 6

Data Similar to Those Shown in Figures 4 and 5 Except That Neutron Radiography of Easy Flow Brazing Test Foils and 304 SS Base Metal is Involved. The neutron technique was a transfer method in which a 0.254-mm-thick indium foil was transferred to Type AA X-Ray film.

The gadolinium direct-exposure methods gave the best hole-detectability results of all the radiographic methods for Easy Flow. These results are shown in Figure 7. The observed diameters of the holes actually

Fig. 7

Data Similar to Those Shown in Figure 6 But Obtained by a Direct Neutron-exposure Method in Which 0.0127-mm Gadolinium Back Screens Were Used With Single-emulsion Type M X-Ray Film. Samples were 304 SS and Easy Flow brazing alloy.

detected were smaller than expected from equation (1), based on experimental results at 0.0762 mm. This inspection method also could detect holes in BAg8 foil, but not so well. The experimental data are shown in Figure 8.

Fig. 8. Data Similar to Those Shown in Figure 7, a Direct-exposure Neutron Radiographic Method. Samples were 304 SS and BAg8 brazing alloy.

IV. ULTRASONIC INSPECTION AND COMPARISON WITH PHOTOMICROGRAPHS, X RADIOGRAPHY, AND NEUTRON RADIOGRAPHY

Methods of ultrasonic testing have been applied to brazed joints and diffusion-bonded joints.⁽⁸⁻¹⁰⁾ Brazed specimens of different base metals, brazing alloys, brazing clearances were inspected by a through-transmission method and compared with photomicrographs. Most specimens were 1.27 cm thick (total) and had dimensions shown in Figure 1. Both transmission and reflection techniques were considered applicable for this thickness. A reflection technique was used in preliminary tests. In this case a focused transducer, 2.25 Mc and 5.72-cm focal length, was used.

A through-transmission technique, which provided a two-dimensional recording on electrosensitive paper, was applied. A Sperry UR Reflectoscope Type 50E480 (modified for high gain and pulse-repetition rate) and Type RA monitor attachment and electrosensitive recording system (ANL manufactured amplifier and recorder) were used.

The details of this technique and apparatus have been described.⁽¹¹⁾ The yoke assembly, which holds the transmit and receive transducers, moves vertically, and the carriage, which carries the yoke assembly, moves horizontally. The vertical and horizontal speeds, distance between lines on electrosensitive paper, and amplitude of vertical stroke were as follows:

Vertical scan rate	-	92 strokes/min;
Horizontal speed	-	191.6 mm/min;
Distance between lines	-	0.11 cm;
Vertical stroke	-	14 cm.

A test frequency of 2.25 Mc was chosen since higher frequencies are more heavily absorbed by stainless steel. A 1.59-mm-diameter collimator made of Teflon was attached to the transmit transducer and a 3.18-mm-diameter collimator to the receive transducer. Although the line separation was small and the beam was also collimated to a small diameter, the through-transmission paper recording system would not always detect small faults of the order of 1.5-mm diameter. Diffraction of the beam, roughness of surface, etc., sometimes limit the fault area that can be detected.

In addition to the electrosensitive-paper recordings, pen recordings were taken of each specimen. This pen recording gave more precise information about amplitude differences corresponding to fault sizes than did the electrosensitive-paper method. Sperry Type 50E366 UR (modified for a constant repetition rate of 600 pulses/sec) and a pen recording system (Brush amplifier and Brush recorder) were used. The absolute sizes of faults could not be estimated from these amplitudes in this study, but the amplitude shows relative soundness of brazing bond, e.g., the higher the amplitude the sounder the bond.

Figure 9 shows an ultrasonic paper recording and neutron radiograph of the 304 SS specimen brazed by Easy Flow. The defect therein recorded could not be detected by X rays. Neutron radiography, both by direct and transfer methods, could detect this fault slightly. The pen recording across the specimen at the dotted line shown in Figure 9 and the micrograph of the same part are compared in Figure 10. The sound brazing part was 0.0254 mm wide, and the low-amplitude ultrasound corresponded to areas for which the brazing clearance was less than 0.0127 mm. It is possible that this part was only partially brazed. However, the micrograph (at 100X) does not show this condition clearly. The paper recording, as shown in Figure 9, does not give an exact outline of the specimen because of energy scattering at the edges.

Figure 11 shows the comparison of fault images of a copper specimen brazed by Easy Flow. Figure 12 shows a micrograph and a pen recording of the specimen of Figure 11 at the dotted line. The brazed part had a 0.0508-mm width, so this difference is detected by all radiographic methods.

Figure 13 shows a plane carbon steel specimen brazed by Ni-Mn-Si high temperature brazing alloy. The micrograph and pen recording of ultrasonic inspection are shown in Figure 14. The change in absorption is very small for this thickness of brazing alloy. X-ray and neutron radiographs could not detect the faults.

Fig. 9. Test Results, Ultrasonic Through-transmission Test and Direct-exposure and Transfer-exposure Neutron Radiographs, Left to Right, of a 304 SS Specimen Brazed with Easy Flow. The flaw detected by the ultrasonic test (slightly above the center of the recording) can be detected as a slightly darker area (greater neutron transmission) on the neutron prints. Metallographic results from this specimen are shown in Figure 10. Metallographic results were obtained along the dotted line through the fault area.

Fig. 10

Metallographic Results for the Sample Shown in Figure 9, Shown at 100X. Ultrasonic pen recordings of these two areas are also given. The thicker brazing material layer shown on the left sample is indicative of better bond quality. The pen recording indicates this by the increased pen deflection, corresponding to improved ultrasound transmission. The valley in the pen recording corresponds to decreased ultrasonic transmission through the area shown in the micrograph on the right.

Fig. 11. Ultrasonic Paper Recording and Radiographic Results for a Copper Specimen Brazed with Easy Flow. The radiographs are direct and transfer neutron radiographs, and an X radiograph from left to right. All the images are shown with the same sample orientation (except that the X-radiographic image is reversed in the left to right sense). The brazing faults can be detected by all the techniques illustrated, the poorest result in this case being obtained with X radiography. Metallographic results along the dotted line are illustrated in Figure 12.

Fig. 12. Metallographic Results for the Copper-Easy Flow Brazed Specimen Whose Test Results Are Shown in Figure 11. An ultrasonic pen recording trace for this sample is also shown, and the valley in the trace corresponds to the small brazing clearance width at the right of the micrograph. Good bond is shown on the left of the micrograph and confirmed by good ultrasonic transmission.

Fig. 13

An Ultrasonic Paper Recording of a Carbon Steel Specimen Brazed with Ni-Mn-Si High-temperature Brazing Alloy. Metallographic results along the dotted line are shown in Figure 14. Radiographic results are not shown.

Fig. 14. Micrograph and Ultrasonic Pen Recording of a Portion of the Dotted Line Area of the Carbon Steel, Ni-Mn-Si Brazing Specimen Shown in Figure 13. Good bond is indicated on the left of the micrograph and confirmed by good ultrasonic transmission shown on the pen recording. The valley on the pen recording corresponds to the poor bond area on the right of the micrograph.

Figure 15 shows a 304 SS-405 SS specimen brazed by Ni-Cr-B high temperature brazing alloy. The ultrasonic paper recording is not clear for these faults. The micrograph (see Figure 16) indicates diffusion of a trace of boron to 405 SS through the grain boundary. This would reduce the content of boron in the brazing part, but still the image of the fault was indicated by neutron radiography.

Figure 17 shows copper brazed joints of which one is almost complete and the other has finely dispersed faults. Since the ultrasonic pen recording showed only a difference in amplitude, it would have been impossible to detect the fault area unless a comparison with a sound area were available. Figure 18 shows diffusion bonding of zirconium and 304 SS. The left-half side is completely bonded; the right half is not bonded because of mating difficulties. In this case only the ultrasonic method could detect this fault.

Fig. 15. Test Results with a Brazed Sample Using Ni-Cr-B High-temperature Brazing Alloy. Type 304 SS was brazed to 405 SS. The faults indicated along the dotted line on the ultrasonic paper recording are detectable on the two neutron prints shown, a direct exposure (center result) and a transfer exposure (right). Metallographic results are shown in Figure 16.

Fig. 16

Metallographic and Ultrasonic Pen Recording Results for the Brazed Sample Shown in Figure 15. Boron from the brazing alloy apparently has diffused through the grain boundary of the 405 SS, as shown on the right of the micrograph. Poor ultrasonic transmission on the pen recording was obtained in that area.

Fig. 17. Micrographs of a Copper, Easy Flow Specimen Showing Good Bond on the Left (as indicated by maximum amplitude of the ultrasonic pen recording) and Finely Dispersed Faults within the Braze on the Right. This area showed less ultrasonic transmission. The portions of the neutron radiographs of these two areas show slightly increased neutron transmission, as evidenced by more film darkening through the poorer bond area.

Fig. 18. Micrograph and Ultrasonic Pen Recording for a Diffusion-bonded Zirconium, 304 SS Sample. Good bond is indicated on the left of the micrograph. Poor bond is indicated on the right by the black void area. This is confirmed by the decreased ultrasonic transmission in that area, as shown by the pen recording.

V. COMPARISON OF X-RAY AND NEUTRON RADIOGRAPHY ON UNSHARPNESS FACTORS

The results of X and neutron radiography are affected by many factors, such as geometrical unsharpness and scattered radiation. For neutron radiography there are additional factors, such as effects of resonance neutrons and prompt γ rays emitted from the specimens. These factors are discussed and compared later in the report.

The X-ray apparatus had a focal-spot size of 4×2.5 mm at the center of the beam. For a focal spot based on the 4-mm dimension, the unsharpness that is caused by the specimen-to-film distance as determined from geometrical calculations is shown in Figure 19. The film-to-specimen distance was almost equal to the thickness of base metal. The improved results at larger FFD indicate that good radiographic resolution results can be obtained for specimens of the thicknesses used in this study.

Fig. 19. Calculated Values of Unsharpness for a 4-mm X-ray Focal Size for Various Film-focal-spot Distances. Results are shown for three different film-specimen distances, the values used being approximately equal to the base metal thicknesses studied. Little improvement can be obtained for FFD values in excess of 120 cm. The three film-specimen distances are 1.58 mm for curve 1, 3.17 mm for curve 2, and 6.34 mm for curve 3.

The geometrical unsharpness for neutron radiography was examined by using a cadmium plate, of 0.508-mm thickness with a hole of 4.77-mm diameter, held parallel to the cassette at different distances from the cassette. The change of hole diameter of the radiographic image was measured by a recording microphotodensitometer (Jarrell-Ash). The gadolinium direct-exposure method with the use of Type M single-emulsion film was employed to make the neutron radiographs. The film background caused by the prompt γ radiation from the cadmium test object was neglected.

Table IV shows the results. Object-detector distances were 0, 1.27, 2.54, 5.08, and 7.62 cm. The image hole diameter parallel to the long part of the beam hole is denoted as D_L , that in the short direction by D_T . The result shows that unsharpness in the long direction was 2 per cent of film-to-specimen distance, and that for the short direction 1 per cent.

Table IV

UNSHARPNESS* RESULTS OBTAINED FOR NEUTRON RADIOGRAPHIC FACILITY AT JUGGERNAUT REACTOR

Object-detector Distance, mm	$U_L, \frac{1}{2}(D_L - D_0), \text{ mm}$	U_L/t	$U_T, \frac{1}{2}(D_T - D_0), \text{ mm}$	U_T/t
0	0	0	0	0
12.7	0.296	0.023	0.138	0.011
25.4	0.532	0.021	0.335	0.013
50.8	1.14	0.024	0.65	0.013
76.2	1.65	0.022	1.05	0.014

Unsharpness of neutron radiograph caused by diverging neutrons.

D_L : Diameter of hole shadow parallel to a long side of the beam hole

D_T : Diameter of hole shadow parallel to a short side of the beam hole

D_0 : Actual diameter of hole

t : Distance of object from detector

U_L : Geometric unsharpness in the long direction of the beam opening

U_T : Geometric unsharpness in the short direction of the beam opening

*Unsharpness values measured are primarily due to geometric unsharpness. Some effect of other factors, however, such as movement, screen, and inherent unsharpness, will be observed in the data.

These results can be explained on the basis of the finite area of the collimated beam, a fact that permits neutrons other than those parallel to the collimator walls to emerge. The experimental results are in reasonable

agreement with the geometric factors of the collimator (2.44 m long, and 6.35×10.16 cm in area) and with previous experimental studies of this beam.⁽⁵⁾

Upon comparison of these results with those for the X-ray inspections, the values are seven times larger for a specimen-to-film distance of 6.35 mm.

A. Scattering and Secondary Radiation Effects

In X radiography, the relation between film density and a sufficiently small change in material thickness can be expressed by a straight line. The tangent of this line will be varied by the ratio of scattering ray intensity S to the direct ray intensity D . Figure 20 shows that the tangent changes as the base metal thickness changes when 0.0127-mm variations in Easy Flow brazing material is radiographed through various stainless steel thicknesses. The density was measured by a Macbeth-Ansco Densitometer, and each film density was normalized to a value of 2.00 at the zero thickness point. Although film-density differences observed are near the sensitivity limit of the apparatus, a tendency for a decreasing tangent as the material thickness increases was observed. Table V shows the ratio of $1 + (S/D)$ which was measured by the method shown in Figure 21.

Fig. 20. Changes in Slope in the Density vs Thickness Curve Are Observed in X Radiography of Easy Flow Brazing Foil Sandwiched between Various Thicknesses of 304 SS Base Metal. The base metal thicknesses were 1.58 mm for curve 1, 3.17 mm for curve 2, and 6.34 mm for curve 3. The decreasing slope as the base metal thickness increases is attributed to increased radiation scattering within the specimens and some change in absorption coefficient as the beam is filtered by specimen thickness.

Concerning neutron radiography, the relation between film density and Easy Flow foil thickness for each thickness of base metal is shown in Figure 22. According to these results, the change in scattering of neutrons by the specimen is much less than that observed for X rays for the thin plates given in Figure 22.

The γ -ray effect, both incident and secondary, on film must also be considered for the direct-exposure neutron radiographic method. If Kodak Type M single-emulsion film is used with gadolinium, the effects of this radiation becomes lessened. For example, when 3.18-mm 304 SS (total) with 0.0762-mm BAg8 was imaged on Type M film without a gadolinium

screen, the density outside the specimen area by direct γ was 0.22. Prompt γ from the specimen and the direct γ combined yielded a density of 0.27, whereas the density of film of the Gd-M neutron radiograph of this specimen showed a density of 1.84 for the same exposure time. Therefore, little problem with gamma radiation should be encountered with the use of this detection method.

Table V

MEASUREMENT OF $1 + (S/D)$ FOR 304 STAINLESS STEEL PLATES

Plate Thickness, mm	Exposure Time, min	Density				Ratio of Scattering*
		(D+S) Direct + Scatter	(D) Direct	$1 + (S/D)$	$1 + (S/D)$ Mean	
6.35 + 6.35	12	1.80	1.01	1.78	1.81	1.50
	10	1.60	0.87	1.84		
3.18 + 3.18	3.5	1.90	1.23	1.54	1.49	1.23
	2.5	1.27	0.89	1.43		
1.59 + 1.59	1.5	1.90	1.56	1.22	1.21	1
	1.0	1.26	1.06	1.19		

*Thinner samples were arbitrarily rated 1.0. The thickest samples, therefore, had a scattering factor 1.5 times as great as the thin ones.

Film Type M (Double Emulsion)

Fig. 21

Arrangement of Specimens Used to Determine Experimentally the X-ray Scattering Factor. The film density obtained with the arrangement on the left will be caused by both direct and scattered radiation, $D + S$, while the density obtained with the arrangement on the right, D , will be due primarily to direct radiation

Fig. 22. Data Similar to Those Shown in Figure 20, Except These Results Are for Neutron Radiography (indium transfer method) of 304 SS Base Metal Pieces Sandwiched around Easy Flow Brazing Alloy. The upper curve is for 6.34-mm thicknesses of base metal; the lower curve for 1.58-mm thicknesses. No change in slope is observed, and the conclusion, therefore, is that no appreciable change in neutron scattering is obtained over this range of steel thickness.

When faster films were used (see Figure 23), densities were much higher because exposure times could not be reduced to the low values necessary for these films. The slow movement of the shutter used to control exposures presented difficulties for exposure times of less than about 30 sec.

Fig. 23
Characteristic Curves of Several X-ray Films

Resonance neutrons in the thermal-neutron beam can give variations in contrast on the neutron radiograph because resonance neutrons may pass through material that is sensitive to thermal neutrons and these neutrons may be detected. The Juggernaut reactor beam has a cadmium ratio of 2.4 in the condition⁽⁵⁾ used in these tests. A similar ratio was measured by film density. A film-density ratio of 2.5 was found by using indium transfer methods and of 3.0 by using the Gd-M direct-exposure method. For the transfer method, In^{115} is activated by resonant neutrons of 1.44-eV energy. Therefore, the indium transfer method will be more affected by resonant neutrons than the gadolinium direct-exposure method.

VI. CONCLUSIONS

Nondestructive testing of brazing joints having a width of 0.0254 mm was studied. Base metals used were ASTM 304 SS mainly. Brazing alloys containing thermal-neutron-sensitive elements were chosen. As standard

brazing faults, brazing-alloy foils with thicknesses ranging from 0.0127 to 0.0762 mm and containing various holes were sandwiched between base metals with thicknesses in the range from 1.59 to 6.35 mm.

X-ray and neutron radiographs were compared for these standards and for actual brazed specimens. With 0.0254-mm brazing foils, the hole diameters that could be radiographically detected were as follows: for Easy Flow foil, 0.305, 0.61, and 0.99 mm by X-radiography; 0.127, 0.152, and 0.305 mm by Gd-M direct-exposure neutron radiography, and 0.457, 0.61 and 1.27 mm by indium transfer neutron radiography. The values correspond to total brazed-specimen thicknesses of 3.18, 6.35, and 12.7 mm, respectively. The brazed-joint fault diameter and width were compared with hole-type radiographic penetrameters and the relation between hole diameter and width given by Equation (1) for thickness between 0.0254 to 0.0762 mm.

Neutron radiography showed excellent detectability when a Gd-0.127-mm M (single) direct-exposure method was applied to Easy Flow brazing alloy. The In-AA transfer method was comparable with X radiographs for the detectability of Easy Flow faults. Both neutron methods produced poor sensitivity with BAg8 foil, which contains no neutron sensitive element but silver.

Concerning geometrical unsharpness, the Juggernaut reactor beam facility shows an unsharpness of 2% (maximum) of distance between specimen and film. Although this value is larger than in X radiography, the fault detectability for the gadolinium direct-exposure method for the 12.7-mm specimen thickness was better than observed for X radiography. This may be a result of increased scattering in the X-ray case.

The high-temperature brazing alloy with 3.5% boron content showed poorer detectability than expected, because of diffusion of boron into the base metal.

Ultrasonic methods have superior sensitivity to nonbonds in diffusion-bonded samples, areas that cannot be detected by radiography. Although such methods are very sensitive, the resolution is rather poor, so small faults around 1.6-mm diameter cannot be indicated clearly for 12.7-mm-thick specimens, particularly faults near edges. It is also considered that ultrasonic results must be always compared with suitable standards. To get precise information of faults, the Gd-M direct method would be recommended for thermal-neutron-sensitive brazing alloys.

ACKNOWLEDGMENTS

It is a pleasure to acknowledge the assistance of people of the Non-destructive Testing Group of Argonne National Laboratory, especially the help and guidance of Harold Berger for radiographic studies and of Ronald Selner for ultrasonic inspection.

REFERENCES

1. Nikolajs Bredzd, Investigation of Factors Determining the Tensile Strength of Brazed Joints, The Welding Journal, 545-S-563-S (1954).
2. W. H. Chang, Basic Characteristics of Some Heat-resisting Brazing Filler Materials, The Welding Journal, 431-S-443-S (1956).
3. D. T. O'Connor and E. L. Criscuolo, The Quality of Radiographic Inspection, ASTM Bulletin (TP63) (April 1956).
4. E. L. Criscuolo and D. Polansky, The Application of Radiographic Specifications, Nondestructive Testing (March-April 1962).
5. Harold Berger, Characteristics of a Thermal Neutron Beam for Neutron Radiography, International Journal of Applied Radiation and Isotopes, 15, 407-414 (1964).
6. Harold Berger, "Neutron Radiography," Symposium on Physics and Nondestructive Testing, Argonne National Laboratory, October 1960, ANL-6346, pp. 12-37.
7. Harold Berger, "Neutron Radiography as an Inspection Technique," The Fourth International Conference on Nondestructive Testing, London, September, 1963.
8. H. Greenberg, Ultrasonic Inspection Checks Quality of Brazed Joints, Material and Method (1952).
9. K. V. Cook and R. W. McClung, Development of Ultrasonic Techniques for the Evaluation of Brazed Joint, The Welding Journal (Sept 1962).
10. Hans Krächter, Versuche Zur Zerstörungsfreien Prüfung von Hartgelöteten Stumpfstößen an Kupfer, Materialprüf. 3 (1961).
11. W. N. Beck and W. J. McGonnagle, Development of Ultrasonic Techniques for Inspecting Experimental Boiling Water Reactor Cast Uranium Alloy Cores and Fuel Plates, ANL-5653 (Dec 1957).
12. Eastman Kodak Company, Radiography in Modern Industry (1957).