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by

W. R. Kanne, Jr.

E. I. du Pont de Nemours and Company
Savannah River Laboratory
Aiken, South Carolina 29808

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HELIUM EMBRITTLEMENT CAUSED WELD TOE CRACKING ON THE IRRADIATED WALL OF A NUCLEAR REACTOR TANK

A repair patch was welded to the wall of a nuclear reactor tank using remotely controlled thirty-foot long robot arms. Further repair was halted when gas tungsten Arc (GTA) welds joining type 304L stainless steel patches to the 304 stainless steel wall developed toe cracks in the heat-affected zone (HAZ). The role of helium in cracking was investigated using material with entrapped helium from tritium decay. As a result of this investigation, and of an extensive array of diagnostic tests performed on reactor tank wall material, helium embrittlement was shown to be the cause of the toe cracks.

SAVANNAH RIVER REACTORS

Nuclear reactors at the Savannah River Plant produce radioactive materials for national defense and for peacetime applications. No electricity is generated. Five reactors were built in the early 1950's, three of which remain in operation. All are heavy water moderated, are unpressurized, and operate at temperatures below the boiling point of water.

One of the reactors not presently operating is uniquely different from the other four in that it has a curved knuckle transition piece joining the tank side wall to the bottom. This region was sensitized during tank fabrication and developed stress corrosion cracks during service (Fig. 1). Cracks resulted in leaks that were first repaired in 1968 (Ref. 1) using GTA welding to place 0.25-inch-thick patches on the tank wall. The tank leaked again in 1984 and a program was initiated to repair the new leaks.

The reactor tank is 18.5 feet in diameter and 15.3 feet high. Access to the tank for repair is through 4.4-inch-diameter holes in the reactor top. The tank is made from 304 stainless steel with high carbon content (~0.07%) by today's standards. Side walls are 0.5-inch-thick joined to the 1.0-inch-thick bottom by the knuckle transition piece.

Leaks were first indicated by the loss of heavy water moderator, at a rate of less than one drop per second, during reactor operation. Leak sites were located by a combination of visual examination, helium leak testing, bubble testing, and ultrasonic testing. Leaks were found to be through the knuckle region. Placement of patches over crack areas in the knuckle was, as in 1968, determined to be the best repair method. Repair was carried out in the 10^5 R/hr radiation field of the reactor.

ROBOTIC PATCH PLACEMENT

Westinghouse Electric Corporation was contracted to make the repair. Thirty-foot-long robot arms with six axes of motion were designed by Westinghouse and used by them for the repair. Westinghouse ROSA (Robotic Operated Service Arm) controllers were used to operate the robot arms. Approximately twenty types of end effectors, including those for welding, were designed and built for use on the robot arms. Four robots were built, any two of which could be used in the tank at one time. Location of the robot arms in the reactor is shown schematically in Fig. 2.

Autogenous and wire feed weld heads with fiber-optic fore and aft viewing devices were designed and fabricated for use by the robot arm through the holes in the reactor top. Each weld head has its own rotation, cross-seam, and arc length motor drives. A weld head being operated by a robot arm is shown in Fig. 3. To weld a seam the robot arm is first programmed to track the seam. The welding operator initiates the arc, makes any cross-seam adjustments for precise tracking during the weld and initiates current downslope to complete the weld. The weld is inspected using TV monitors and with the fiber-optic system while retraversing the seam.

Design of the patches evolved as identification of the IGSCC crack sites progressed. Initially, small 0.25-inch-thick patches similar to those used in 1968 were planned. Ultrasonic and dye-penetrant testing showed more extensive cracks although they did not go through the wall. In addition, there was concern that further welding on the knuckle region could aggravate future sites for IGSCC. The final patch design was chosen to cover the entire knuckle region so that the top and bottom welds would not be on the knuckle. The patch had to be made up of curved segments that could fit through the 4.4-inch-diameter-holes in the reactor top and then conform to the curved knuckle area. Final design of segments is shown in Fig. 4. Segments were only 0.070-inch-thick in the center to accommodate thermal stresses and were 0.25-inch-thick along the patch segment perimeter.

Seven segments were welded together to form the first patch. Patch segments were individually fitted to the complex tank wall configuration twenty feet below the tank top (Fig. 5). Autogenous GTA welding was used to join the patch segments to the wall and to each other, except where wire feed was required to close gaps between the patch segments and the tank wall. Patch segments were first tack welded to the tank wall as shown in Fig. 6. Welding of the lap joints joining patch segments to each other and of the fillet weld joints joining segments to the tank wall was demonstrated by extensive testing in a mockup facility. Design and configuration of the lap and fillet welds are shown in Fig. 7 and 8. Welds were made with pulsed current of 190/90 amperes (fillet welds) or 120/80 amperes (lap welds) for 0.5 second at each level at a travel speed of 2.0 inches per minute using argon, or argon - 25% helium, torch gas.

REACTOR WALL WELD TOE CRACKING

Bubble tests were performed on the completed patch by pressurizing the space between the tank wall and the patch with gas, raising the water level in the tank, and monitoring for bubbles. Several leak sites were present. Repair welding of the leak sites eliminated some sites but introduced new sites. Dye-penetrant testing showed the presence of cracks around half the circumference of the patch in the weld HAZ on the tank wall side. The extensive nature of the dye indications showed that the leaks were not isolated but were part of a crack network. Cracks were along the edge of the weld bead on the tank wall side. No cracks were found on the patch side of the welds. Parallel bead test welds were made on the tank wall in both the knuckle and in unsensitized material above and below the knuckle. In all areas the test welds showed dye-penetrant indications (Fig. 9A) that, along with direct camera observations of the cracks, showed them to be toe cracks in the heat-affected zone of the welds. A piece of the tank wall was later removed and metallographically examined (Fig. 9B) showing the intergranular nature of the cracks.

Cause of the leaks was first thought to be incomplete fusion to the tank wall, but the repeated failure of the repair attempts by the appearance of new leak sites eliminated this as a possible cause. Other possible causes such as hydrogen embrittlement, IGSCC not detected by dye-penetrant or ultrasonic testing, intergranular attack from pickling during tank fabrication, or radiation-induced segregation were investigated during an extensive diagnostic program and shown not to be the cause. These investigations will be reported elsewhere.

WELDABILITY OF IRRADIATED STAINLESS STEEL

Helium is present in the type 304 stainless steel reactor tank wall in the knuckle region at concentrations of approximately 3 appm. Helium resulted from irradiation of boron and nickel during the thirty years of reactor service. The role that helium may play in weld toe cracking was previously undemonstrated.

There is extensive information in the literature on mechanical properties of neutron irradiated stainless steel (Ref. 2). Mechanical property studies on stainless steel containing helium from ion implantation and from decay of tritium are also plentiful (Ref. 3). Helium is known to reduce the high temperature ductility of 304 stainless steel at concentrations as low as 0.1 appm (Ref. 4). This result leads to the suspicion that difficulties may be encountered when materials containing helium are being welded since the high stress and high temperature present in the heat affected zone of welds, combined with the loss of ductility due to helium, sets up the conditions for cracking. Irradiation increases the low temperature strength and reduces ductility, but not to the point of concern about material integrity (Ref. 5) for helium concentrations up to about 70 appm (Ref. 6). This result indicates that helium at low concentrations will not degrade the integrity of irradiated tank walls at the operating temperatures (less than 100°C) of Savannah River Reactors.

Very little experience on welding irradiated stainless steel has been reported in the literature. The observation of occasional porosity and cracking has been reported (Ref. 7) when GTA welding irradiated 304L stainless steel with helium concentrations calculated to be 10-50 appm (Ref. 6). A high density of porosity has been reported in shallow electron beam welds in 316 stainless steel containing cyclotron-implanted helium at concentrations from 200 to 600 appm, but no cracks were reported (Ref. 8). Porosity, but no cracks, was also reported when GTA welding rapidly solidified 304 stainless steel with 7.1 appm helium entrapped during processing (Ref. 9).

WELDING HELIUM CHARGED TYPE 304L STAINLESS STEEL

To demonstrate the role of helium in reactor repair weld toe cracking, test welds were made on 304L stainless steel that contained dissolved tritium and deuterium with helium present from tritium decay. The helium concentration was high on the tritium exposed surface and decreased to zero within the material. A pre-existing (therefore helium charged) gas tungsten arc (GTA) weld was present across the center of the samples. Parallel bead GTA test welds, Fig. 10A, were made at parameters chosen to duplicate the test weld conditions in the reactor tank.

GTA welds on the helium-containing surface of this material produced cracks identical to those observed during reactor tank repair. Compare the dye-penetrant results in Fig. 10B with those shown for the reactor tank in Fig. 9A. The cracks were largest toward the end of the weld, but did not necessarily occur on both sides of the weld. Cracks were not visible with the unaided eye, but were visible at magnifications above about 25X, Fig. 11. Cracks were present in the pre-existing GTA weld where the double bead welds crossed it , but these cracks were not continuous. Welds on the back surface of the sample, with no helium, did not crack.

Microscopically (Fig. 12), the cracks were intergranular and generally perpendicular to the material surface. Porosity was present within the weld beads. The similarity of the crack microstructure in the test samples to that in the reactor tank can be seen by a comparison with Fig. 9B.

Heating of samples to remove deuterium and tritium without removing helium did not reduce cracking susceptibility nor did it noticeably reduce porosity. This result, combined with previous work with hydrogen-charged material where no cracking was produced, confirmed that helium alone, rather than a combination of helium with hydrogen isotopes, was responsible for the cracking. Low heat input welds that just barely melted the surface and spot GTA welds also produced cracks.

Cracks were not produced by resistance welds or by a low heat GTA pass that did not produce melting. Resistance welds were made by projection welding tubes (Ref. 10) to the surface. No cracks formed in either the solid-state-bonded region or around areas of molten weld flash (Fig. 13). This result is consistent with successful solid state welding of 304 stainless steel with entrapped helium reported previously (Ref. 9). Low tensile stress techniques (e.g., resistance welding) or nonmelting techniques (e.g., brazing) may therefore be satisfactory for joining material with entrapped helium.

The conclusion that helium embrittlement caused the patch leaks was supported by additional diagnostic tests to be reported elsewhere. These tests included ambient and elevated temperature tensile and fracture toughness tests, weld strength tests, and TEM analysis of material irradiated to different helium concentrations (0.07 to 35 appm He).

CONCLUSIONS

Technology exists for remote repair of nuclear reactor tanks. This was demonstrated by the placement, by Westinghouse Electric Corporation, of a welded stainless steel patch approximately 13 inches high by 21 inches long on the inside wall of a Savannah River Plant reactor tank. The repair was made in a 10^5 R/hr radiation field from a distance of approximately 20 feet through a 4.4-inch-diameter hole.

Heat affected zone (weld toe) cracks that occurred during welding of patches to the tank wall were caused by small amounts of helium (~3 appm) present in the wall. At higher helium concentrations, 304L stainless steel test pieces developed cracks even with very small weld beads. No cracking occurred when test pieces were locally heated to temperatures slightly below the melting point, but not melted. Joining processes creating only low tensile stresses, such as brazing or solid state resistance welding, may therefore eliminated cracking in helium containing materials.

The identification of helium as the cause of weld toe cracking has impact on any fusion welding program involving stainless steel containing helium. Helium may be present from irradiation in high flux neutron fields (as in nuclear reactors), from decay of dissolved tritium (as in the samples used for this study), or from other sources. These results will have increased industrial significance as the welding of aging nuclear reactors and of tritium exposed materials becomes more frequent.

Acknowledgments

Contributors to the welding repair and investigative programs reported herein included: R. F. Mittelberg, B. W. Schaaf, B. J. Eberhard, and C. L. Angerman of Du Pont; D. A. DelSignore, D. L. Welker, and E. R. Haberman of Westinghouse; and E. A. Franco-Ferreira, consultant. Many others participated in the overall repair and diagnostic programs.

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REFERENCES

1. Maloney, J. P., et al. 1969. Repair of a nuclear reactor vessel. DP-1199, E. I. du Pont de Nemours & Co., Savannah River Laboratory, Aiken, SC.

2. Marshall, P. 1984. Austenitic stainless steels: microstructure and mechanical properties. Elsevier.

3. Caskey, G. R., Jr. 1985. Tritium-Helium Effects in Metals. Fusion Technology (8): 2293-2298.

4. Kramer, D., et al. 1968. Helium embrittlement in type 304 stainless steel. Journal of Nuclear Materials (25): 121-131.

5. Joseph, J. W. 1960. Mechanical properties of irradiated welds in stainless steel. DP-534, E. I. du Pont de Nemours & Co., Savannah River Laboratory, Aiken, SC.

6. Caskey, G. R., Jr. Unpublished calculations. E. I. du Pont de Nemours & Co., Savannah River Laboratory, Aiken, SC.

7. Hall, M. M., Jr., et al. 1978. Fusion welding of irradiated AISI 304L stainless steel tubing. Weldments: Physical Metallurgy and Failure Phenomena. Proc 5th Bolton Landing conference: 365-378.

8. Schiller, P., et al. 1987. Structure of helium loaded stainless steel after short heat pulses. Journal of Nuclear Materials, (148): 224-226.

9. Clark, D. E.; Einerson, C. J.; and Loop, R. B. 1986. Weldability of rapidly solidified type 304 stainless steel. Advances in Welding Science and Technology. ed S. A. David: 817-820.

10. Kanne, W. R., Jr. 1986. Solid state resistance welding of cylinders and spheres. Welding Journal 65 (5): 33-38.

FIGURE 1. SAVANNAH RIVER NUCLEAR REACTOR SCHEMATIC SHOWING LOCATION OF MODERATOR WATER LEAKS THROUGH "KNUCKLE" REGION.

FIGURE 2. ROBOT ARM ARRANGEMENT IN REACTOR TANK. ARM EXTENDS FROM SHEATH SUPPORTED AT TOP OF TANK AND CENTERED ON MONITOR PIN AT BOTTOM. TWO ARMS AND SEVERAL CAMERAS AND LIGHTS CAN BE USED IN THE TANK AT ONE TIME. SURFACE PREPARATION FOR WELDING WAS DONE USING A GRINDING END EFFECTOR ON THE ROBOT ARM.

FIGURE 3. AUTOGENOUS WELD HEAD HELD BY ROBOT ARM IN PREPARATION FOR WELDING SMALL PATCHES OF INITIAL DESIGN IN MOCKUP FACILITY.

FIGURE 4. PATCH DESIGN COVERING KNUCKLE AND OLD PATCH.

FIGURE 5. PLACEMENT OF FIRST TWO PATCH SEGMENTS IN REACTOR TANK. PHOTO FROM TV MONITOR SHOWS PATCHES (LEFT) HELD BY GRIPPING END EFFECTORS ON TWO ROBOT ARMS.

FIGURE 6. WELD HEAD HELD BY ROBOT ARM WHILE TACK WELDING PATCH SEGMENTS TO TANK WALL MOCKUP.

FIGURE 7. LAP WELD JOINING PATCH SEGMENTS TO EACH OTHER.

A. JOINT DESIGN

B. METALLOGRAPHIC SECTION (8x).

FIGURE 8. FILLET WELD JOINING PATCH TO TANK WALL.

A. JOINT DESIGN

B. METALLOGRAPHIC SECTION (8x).

FIGURE 9. TOE CRACKS IN THE HEAT AFFECTED ZONE OF TEST WELDS ON IRRADIATED NUCLEAR REACTOR TANK WALL.

A. DYE PENETRANT TEST OF PARALLEL BEAD TEST WELDS ON TANK WALL (2x).

B. METALLOGRAPHIC SECTION OF TEST WELD CUT FROM TANK WALL (20x).

FIGURE 10. TEST WELDS ON HELIUM CHARGED 304L TEST PIECE (2x).

A. VERTICAL TEST WELDS. (HORIZONTAL WELD MADE PRIOR TO CHARGING.)

B. DYE PENETRANT TEST.

FIGURE 11. SURFACE APPEARANCE OF WELD TOE CRACK (40x).

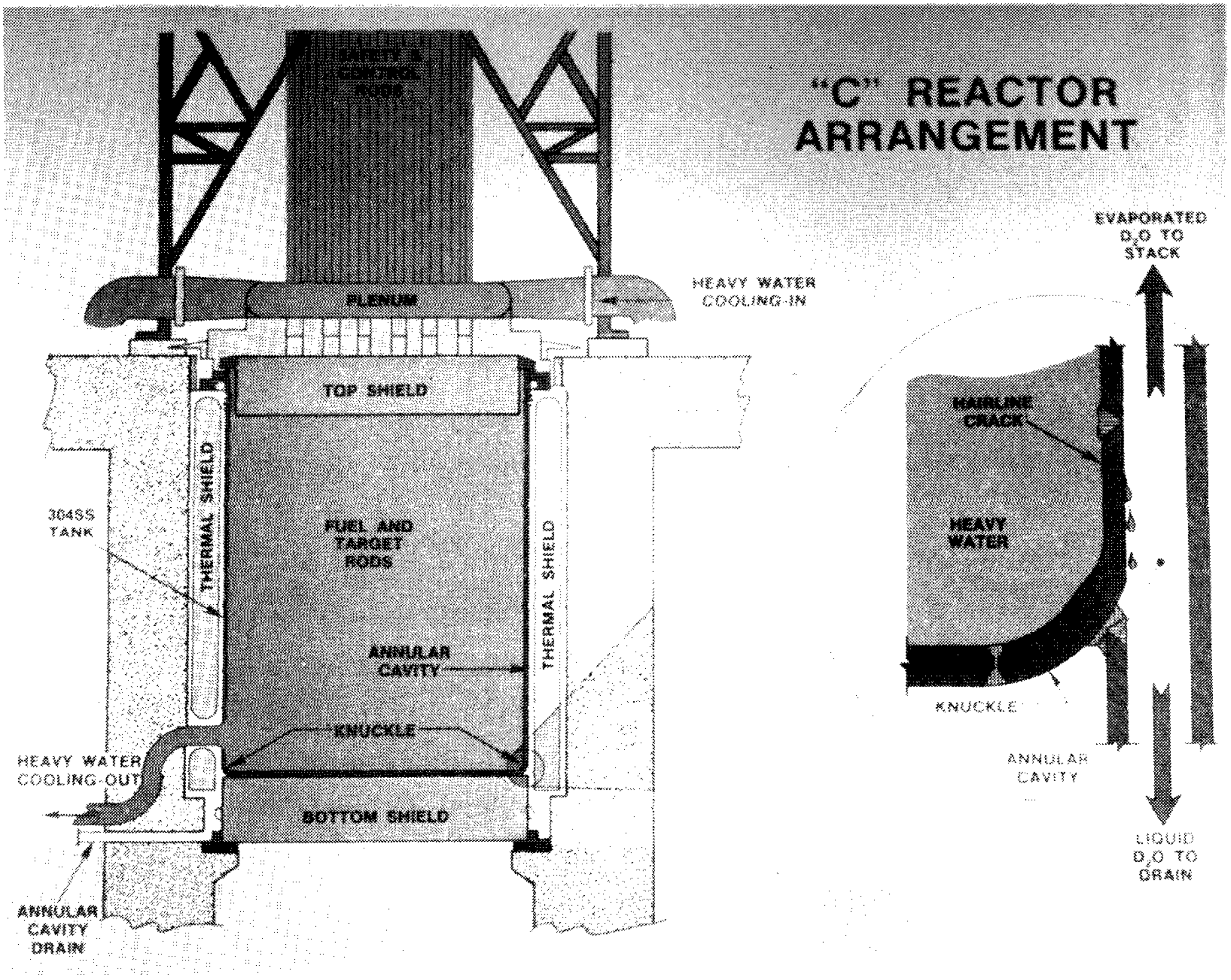
CRACK WELD METAL

FIGURE 12. POROSITY AND TOE CRACKS IN TEST WELD ON HELIUM CHARGED MATERIAL (8X, 100X, 100X).

FIGURE 13. CRACK FREE RESISTANCE WELD.

A. TUBE PROJECTION WELDED TO HELIUM CHARGED SURFACE (2X).

B. METALLOGRAPHIC SECTION OF ONE SIDE OF WELD SHOWING SOLID STATE WELD WITH FLASH OF MOLTEN METAL AT OUTER EDGE (40X).



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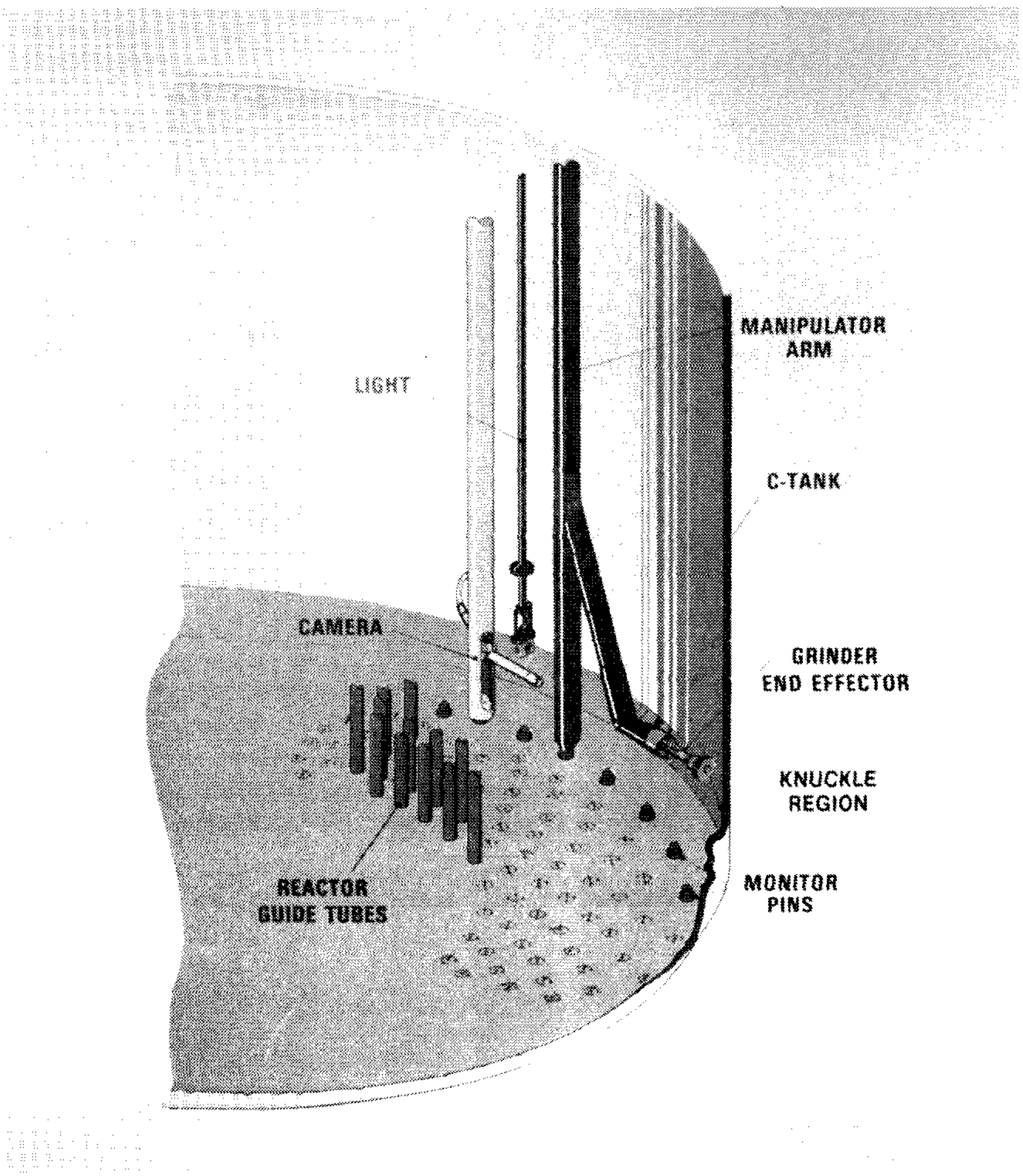

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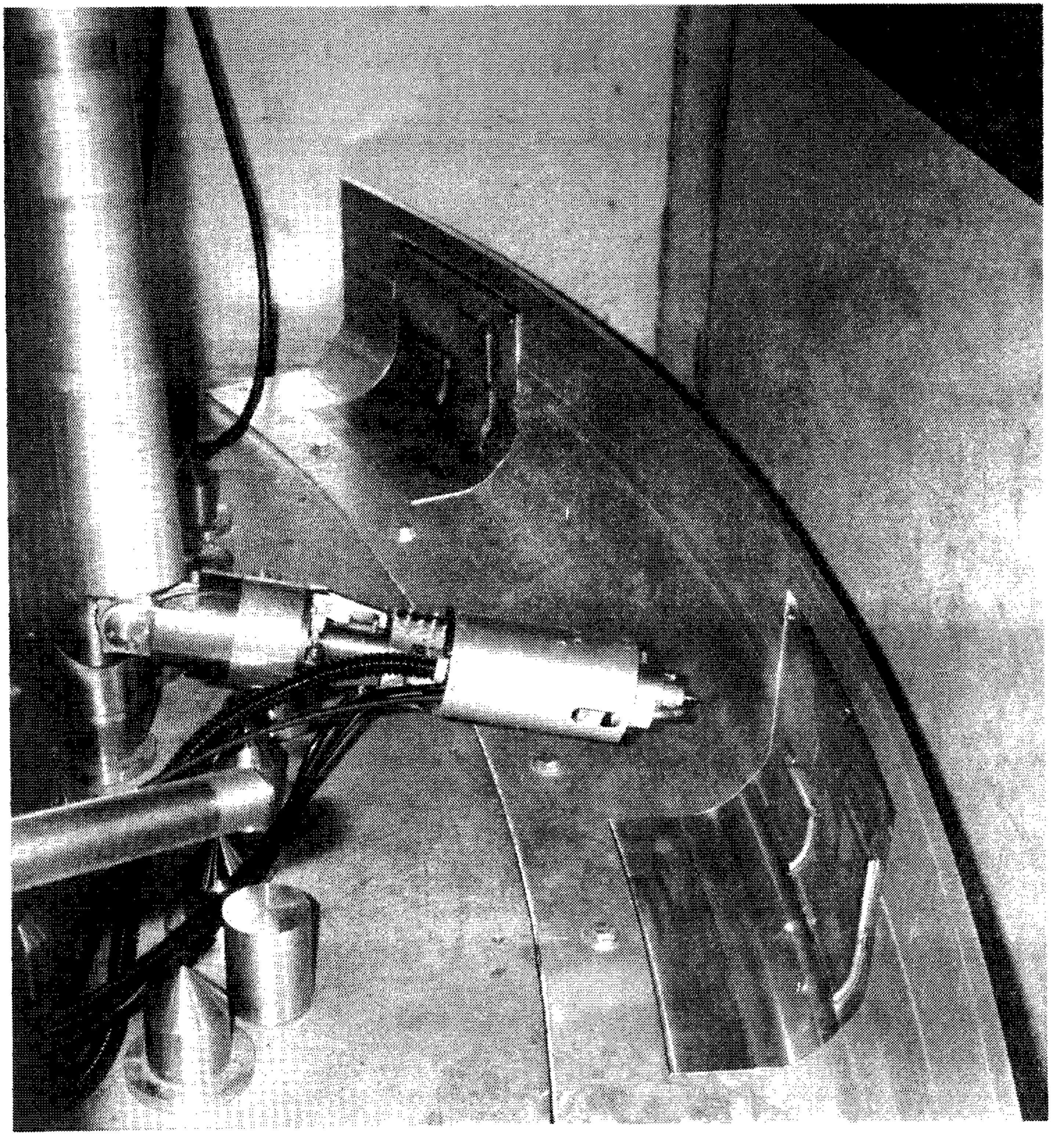

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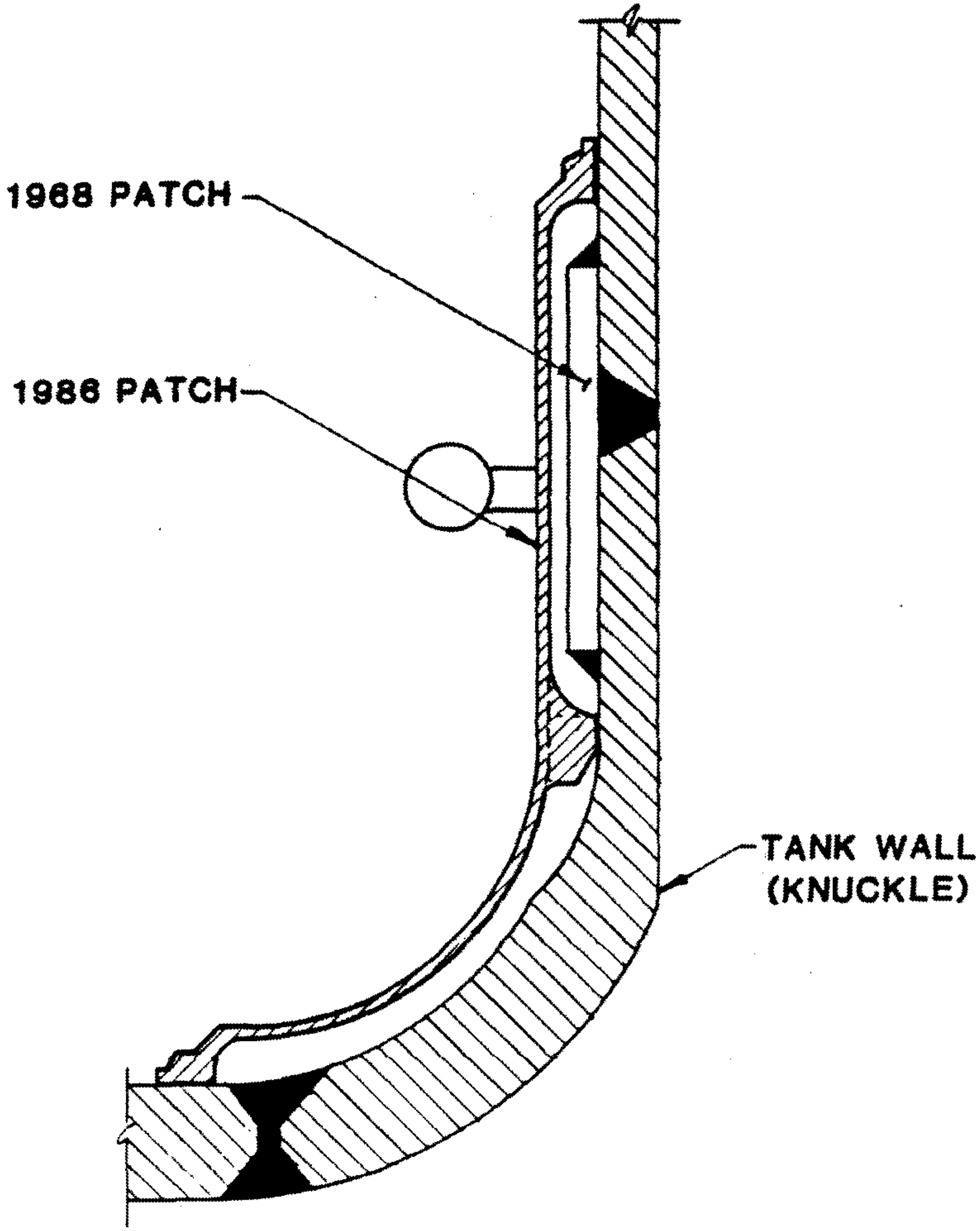

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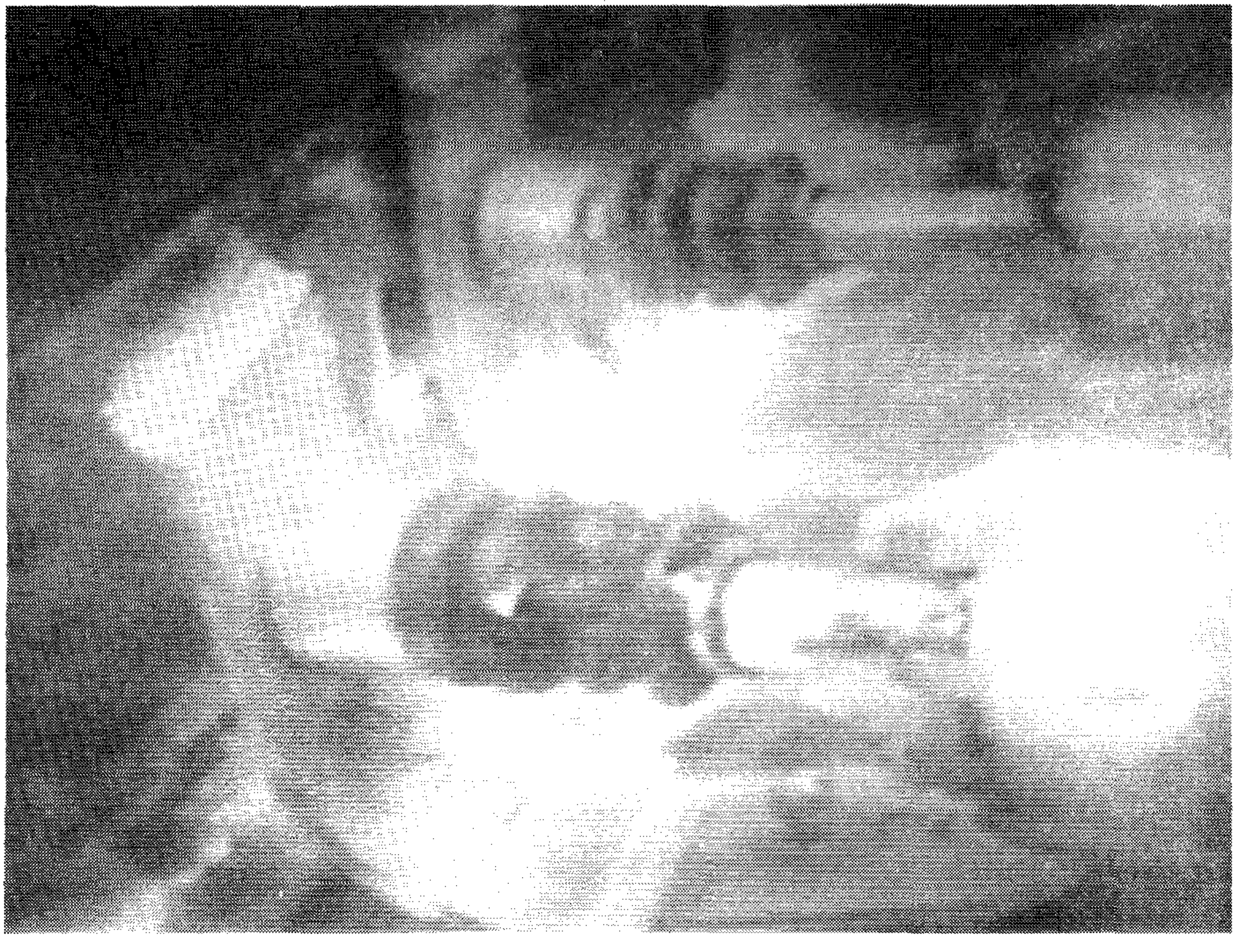

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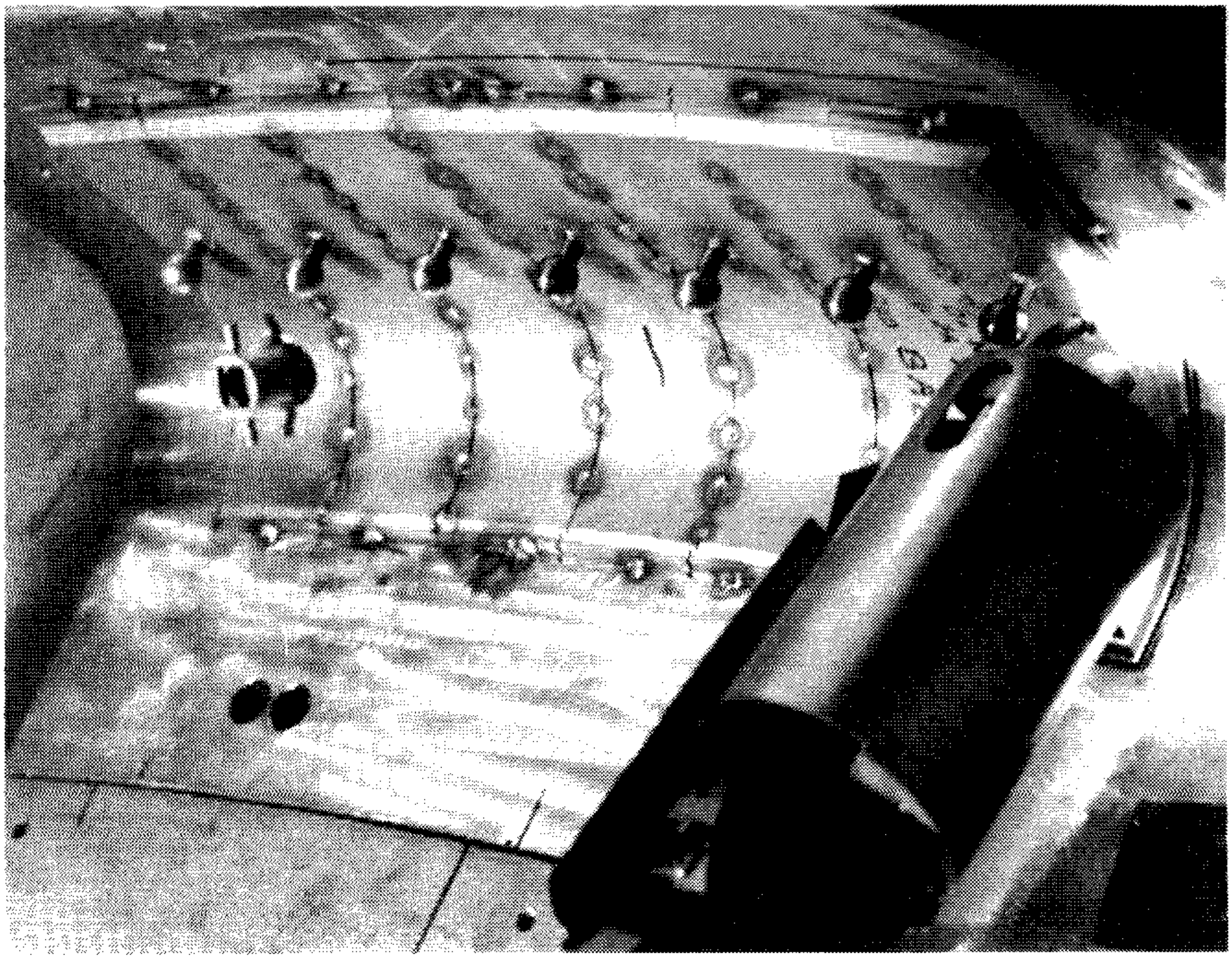

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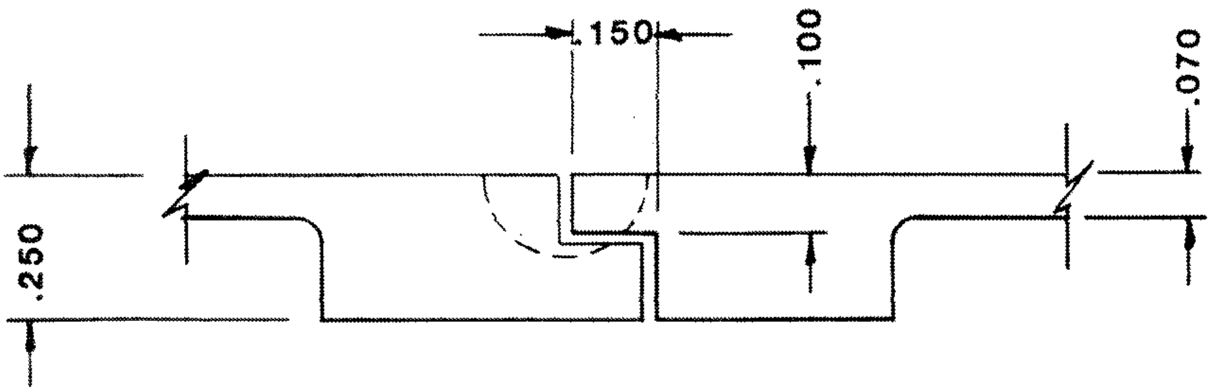
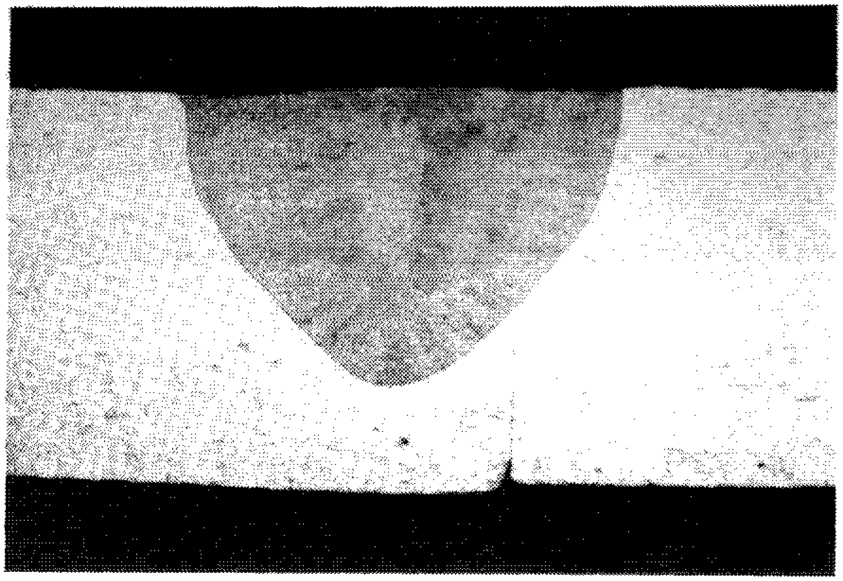
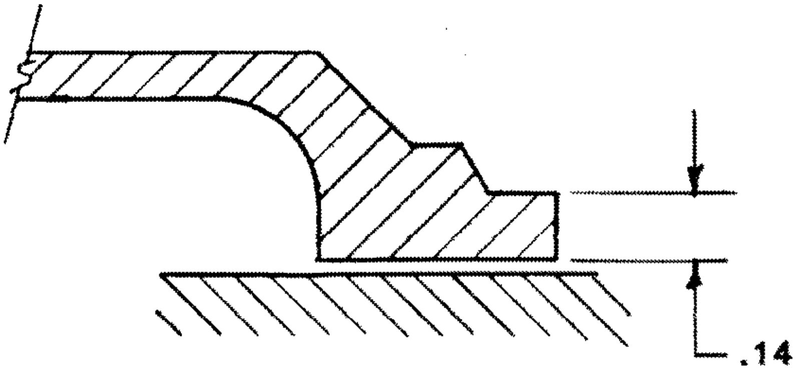


A. JOINT DESIGN



B. METALLOGRAPHIC SECTION (8x).

FIGURE 7. LAP WELD JOINING PATCH SEGMENTS TO EACH OTHER.



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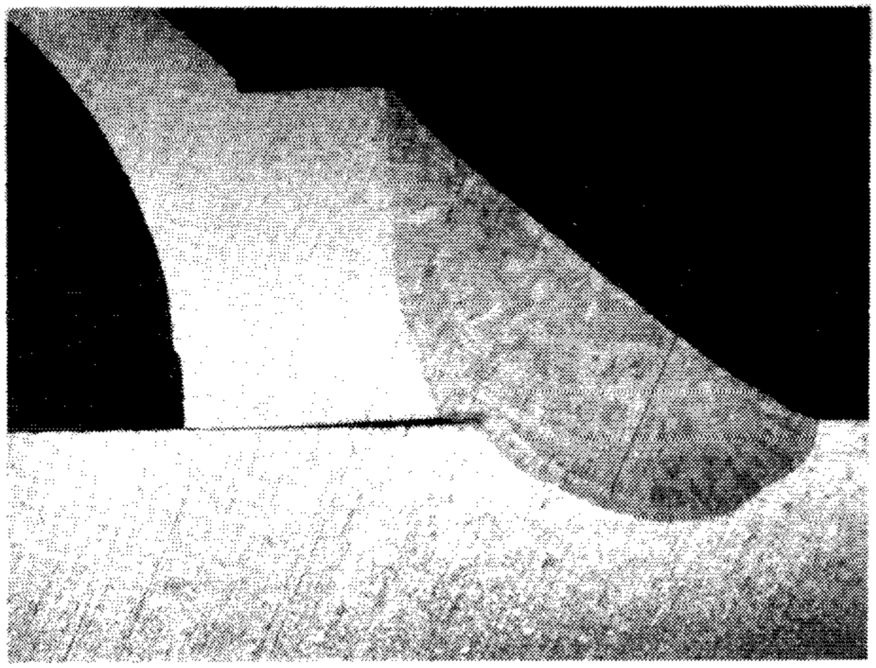
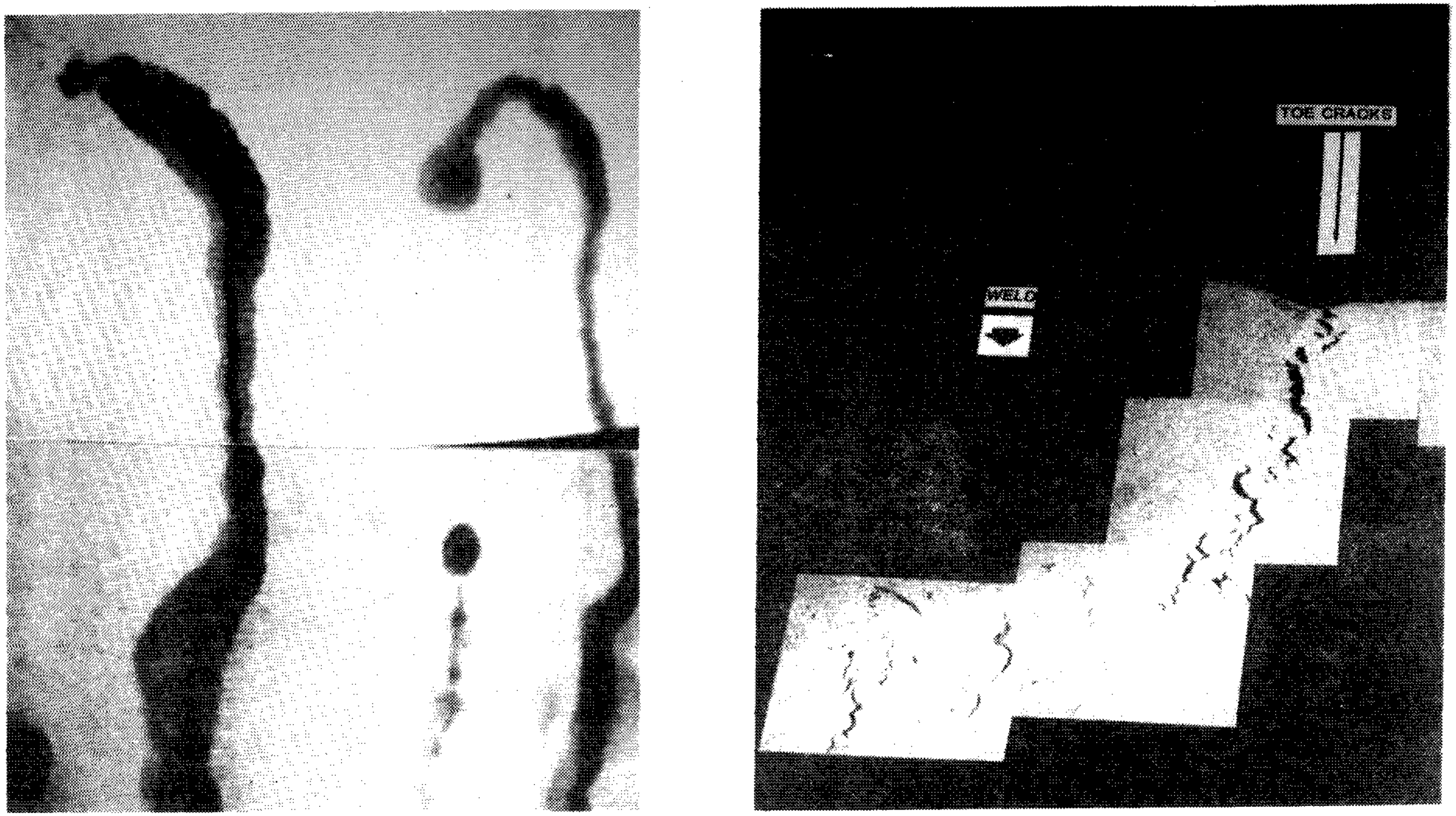


B. METALLOGRAPHIC SECTION (8x).

FIGURE 8. FILLET WELD JOINING PATCH TO TANK WALL.



A. DYE PENETRANT TEST OF PARALLEL BEAD TEST WELDS ON TANK WALL (2x).

B. METALLOGRAPHIC SECTION OF TEST WELD CUT FROM TANK WALL (20x).

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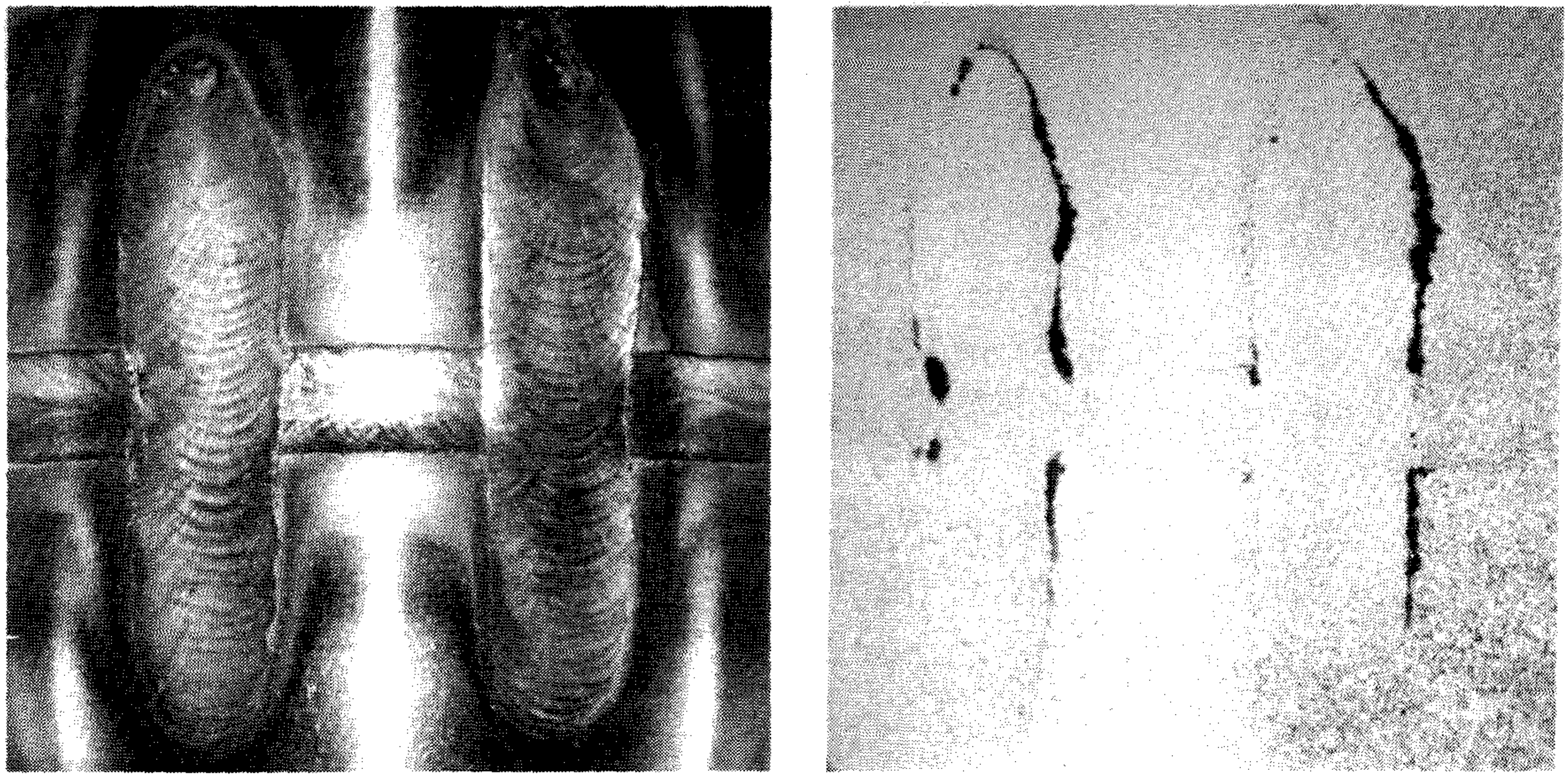

A. VERTICAL TEST WELDS.
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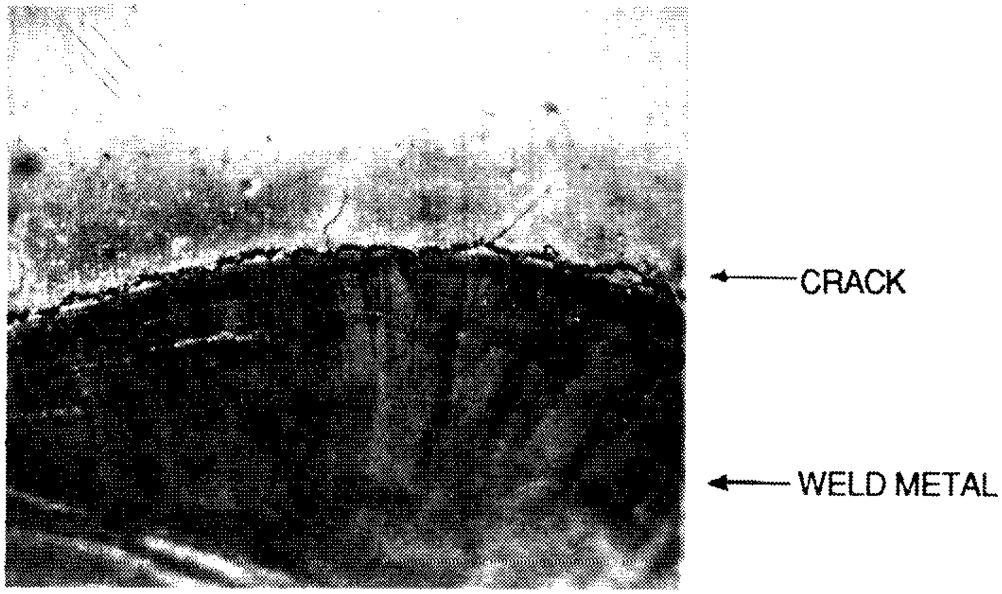
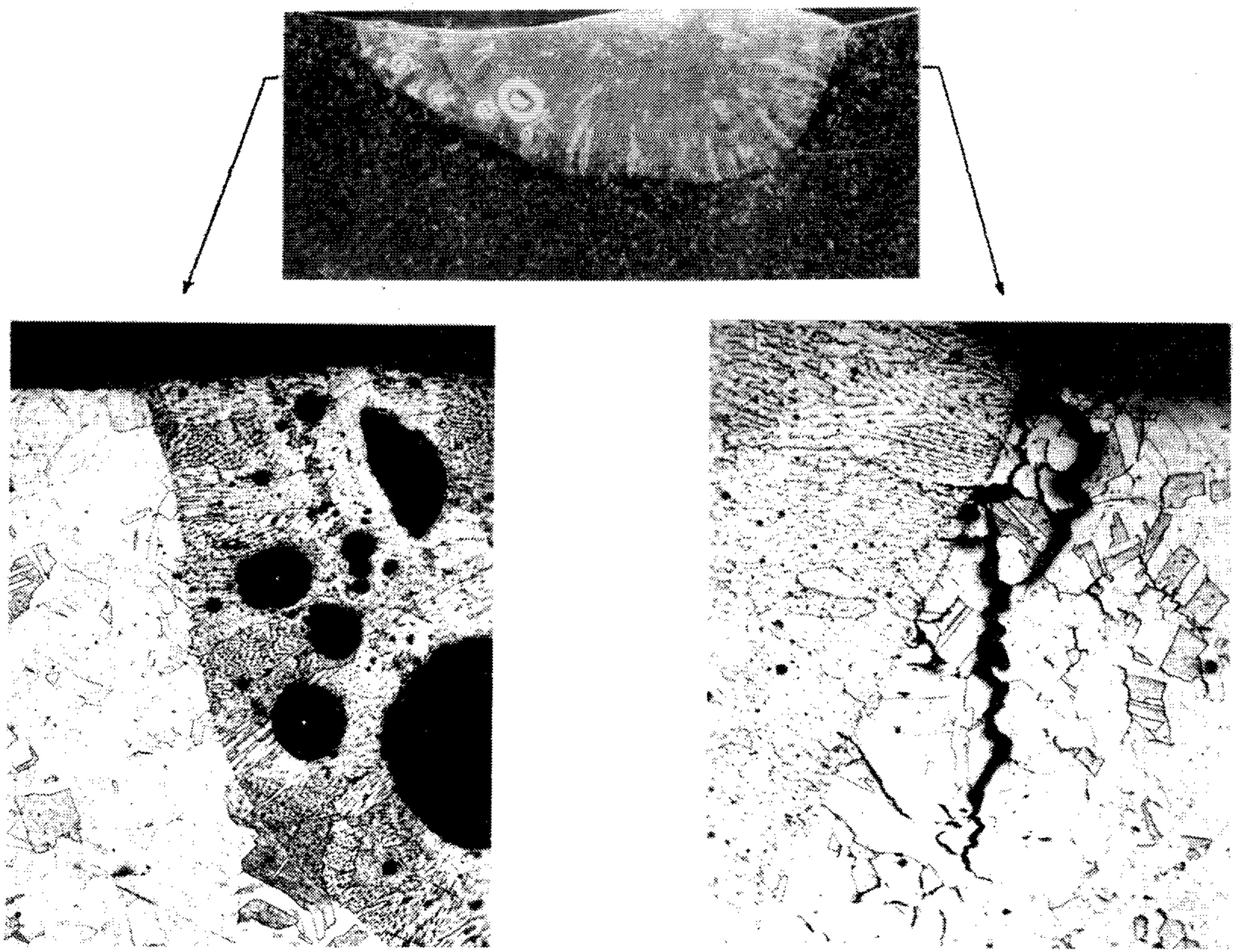


FIGURE 11. SURFACE APPEARANCE OF WELD TOE CRACK (40x).



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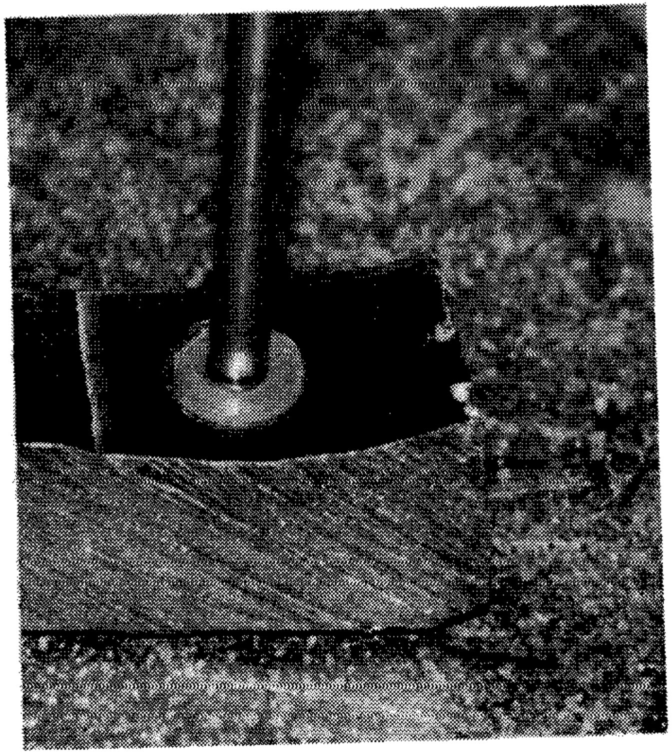
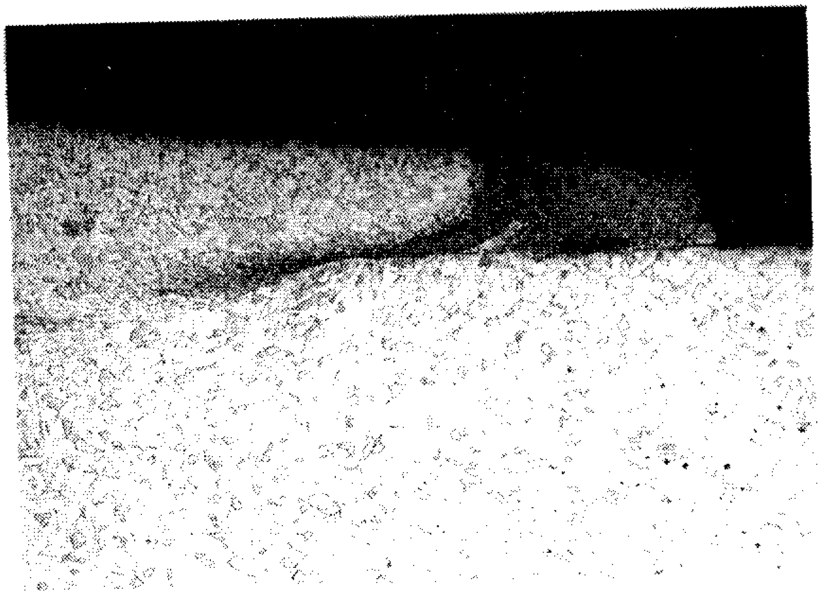


A. TUBE PROJECTION WELDED TO HELIUM CHARGED SURFACE (2X).



B. METALLOGRAPHIC SECTION OF ONE SIDE OF WELD SHOWING SOLID STATE WELD WITH FLASH OF MOLTEN METAL AT OUTER EDGE (40X).

FIGURE 13. CRACK FREE RESISTANCE WELD.